DOT/FAA/TC-23/8

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts – 2022 Revision

January 2023

Final report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-23/8		

4. Title and Subtitle	5. Report Date
Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts – 2022 Revision	January 2023
	6. Performing Organization Code
7. Author(s) AIA Rotor Manufacturing Team	8. Performing Organization Report No.
9. Performing Organization Name and Address Aerospace Industries Association 1000 Wilson Blvd., Suite 1700 Arlington, VA 22209	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Federal Aviation Administration Engine and Propeller Standards Branch 12 New England Executive Park Burlington, MA 01803	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code AIR-621

15. Supplementary Notes

The Federal Aviation Administration Representatives were Dan Kerman, Tim Mouzakis, and David Galella

16. Abstract

This report was developed by a partnership of the Aerospace Industries Association (AIA) Rotor Integrity Steering Committee (RISC) member company manufacturing experts and the Federal Aviation Administration (FAA) in response to accidents and incidents caused by Manufacturing Induced Anomalies in Critical Rotating Parts. According to a 2017 summary from the AIA Rotor Integrity Steering Committee, slightly fewer than 30% of rotor cracks/events are caused by post-forging Manufacturing Induced Anomalies. However, the data indicate a significant reduction in cracks and events over the last decade from such causes as more robust Manufacturing Methods such as those recommended within this report have been introduced.

The guidelines contained herein represent an industry consensus on the currently available best practices to minimize Manufacturing Induced Anomalies in Critical Rotating Parts consistent with the AIA RoMan team charter and vision. Recommendations for rotor Manufacturing Process development and control, including Process Validation, quality assurance, disposition of suspect parts, Process Monitoring, Human Factors and training, and Non-Destructive Evaluation, are included to provide an overall framework for a highly reliable Manufacturing Process.

To address Special Cause Events, a section containing industry lessons learned is included to provide guidance on such issues common in the industry. The term "lessons learned" generally refers to useful pieces of practical wisdom acquired by experience or study. The combination of Manufacturing Induced Anomaly root causes and industry lessons learned was used to create a list of Manufacturing Methods for inclusion in this report revision. With these additions, the primary Manufacturing Methods used to produce Critical Rotating Components is captured within the appendices of this document.

The appendices include the team charter and vision along with information and guidance concerning: Process Monitoring of holes, Non-Destructive Evaluation Techniques, and Manufacturing Methods including Edgebreak, Axial Blade Slot, mechanical finishing of titanium, Turning, Marking, Milling, and Grinding. Manufacturing credits for damage tolerance assessments promoting introduction of improved Manufacturing Methods are also provided.

17. Key Words	18. Distribution Statement
Rotor manufacturing, Critical rotating parts, Manufacturing guidelines, Manufacturing induced anomalies, Process monitoring, Lessons learned, Circular holes, Axial blade slots, Design credit approach, Titanium spark impingement, Titanium polishing and blending, Turning, Milling, Part Marking, Grinding.	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	180	

Executive Summary

This report was developed by a partnership of the Aerospace Industries Association (AIA) Rotor Integrity Steering Committee (RISC) member company manufacturing experts and the Federal Aviation Administration (FAA) in response to accidents and incidents caused by Manufacturing Induced Anomalies in Critical Rotating Parts. According to a 2017 summary from the AIA Rotor Integrity Steering Committee, slightly fewer than 30% of rotor cracks/events are caused by post-forging Manufacturing Induced Anomalies. The data indicate a significant reduction in cracks and events over the last decade from such causes as more robust Manufacturing Methods such as those recommended within this report have been introduced.

This report summarizes guidelines useful to ensure the Manufacturing Process minimizes the likelihood of Manufacturing Induced Anomalies reaching service usage. The following topics are presented:

- Process Validation
- Quality Assurance
- Process Monitoring
- Human Factors and Training
- Non-Destructive Evaluation (NDE)
- Process Validation.

- Process Validation. Two approaches to Process Validation are used in the industry. The first approach is defined as the Part Specific Process Validation (PSPV) while the second is known as the Generic Manufacturing Process Validation (GMPV). In PSPV, a manufactured part is evaluated against the Design Intent and subsequent production is controlled to deliver product consistent with the evaluation. In GMPV, those Manufacturing Methods that are identified as being sensitive, i.e., as needing a high level of control if the manufactured product is to meet the Design Intent, are controlled by specifications and/or validated parameter limits. GMPV ensures that any product manufactured within the parameter windows will meet the Design Intent.

    Validation of the Manufacturing Process may include, but may not be limited to:

    − Best practices (e.g., speed, feed and use of tool)
    − Process monitoring requirements
    − Product Definition requirements
    − NDE method requirements
    − Metallurgical examination to the materials standard
    − Residual stress measurement
    − Special design requirements
    − Fatigue testing (specimen, sub-element or component)

    When changes in the Manufacturing Method are proposed, it is first necessary to assess the extent of the change. In GMPV, the lowest level of change is one within the parameter limits defined for the Manufacturing Process. In this case, since the whole process window has been demonstrated to yield product that meets the Design Intent, change within the window can be allowed with no further process validation. However, change beyond the parameter limits in GMPV and all change in PSPV must be carefully evaluated before being accepted.

- Quality Assurance. To ensure that Critical Rotating Parts have been produced in accordance with the Design Intent, the Production Certificate Holder should have a written procedure that seeks to prevent non-conforming parts from entering service. Process Validation, the Manufacturing Control Plan (MCP), and manufacturing Change Control should be covered by written procedures. The Material Review process evaluates suspect or confirmed non-conforming material, part, or process. A non-conformance is defined as a part characteristic that does not meet or conform to the requirements specified in the contract, Product Definition, MCP, or other approved product description.

- Process Monitoring. Nominal Manufacturing Methods that are properly qualified do not cause Machining Induced Anomalies. It is when Special Cause Events take place that such Anomalies are most likely to occur. Currently, the best method to detect Special Cause Events is by Process Monitoring.

  Ideally, Process Monitors should operate on a real-time basis and be capable of interrupting the process prior to the occurrence of a Machining Induced Anomaly. In the event a Manufacturing Method varies outside its acceptable parameter limits; the Process Monitor should act automatically.

- Human Factors and Training. The manufacturing of Critical Rotating Parts typically involves many methods, inspections, and transportation steps. While robust processes and process oversight (such as Process Monitors) can, and should, be put in place, people cannot be eliminated from the process. The machine operators, inspectors, material handlers, engineers, and others that work with the parts every day as they are being manufactured are a vital link in the process of identifying and responding to a Special Cause Event. What may appear to be an unimportant observation during part processing (different surface appearance, unusual tool wear or noise, etc.) can indicate the presence of a Manufacturing Induced Anomaly. All such observations and events should be reviewed and documented. Training and motivation are the keys to enable those directly involved to react correctly. To minimize the impact of Human Factors on the output of a Manufacturing Process, it is important that everyone involved is adequately trained. The training should be designed to ensure that both hard and soft elements are addressed. This training should be part of current programs and should be included in the initial training given to people that are new to an area and as part of a regular refresher training.

- Non-Destructive Evaluation. The purpose of an inspection should be defined prior to selecting the inspection method. There are fundamentally two ways NDE methods can be used: (1) as a qualitative tool to evaluate control of the Manufacturing Process or (2) as a quantitative inspection method, which takes flaw sizing capability into account. The term quantitative is being used here to describe the statistical capability of a method to detect anomalies, although it can also be defined as a specific numerical reading taken during the inspection process, such as amplitude shown on an NDE instrument. However, before the NDE method can be considered quantitative, it must be proven that the reading has a quantitative correlation to the indicated anomaly of a specified type.

Aerospace Industries Association

Rotor Integrity Steering Committee Rotor Manufacturing (RoMan) Report

November 15th, 2022

Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts – 2022 Revision

DISCLAIMER

This report is a revision to report DOT/FAA/TC-19/14, "Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts – 2019 Revision" Report, dated May 2019 and is the response of the Aerospace Industries Association (AIA) Rotor Integrity Steering Committee (RISC) to a continuing FAA initiative on Critical Rotating Part manufacturing for gas turbine aero engines. It has been written by manufacturing experts drawn from engine manufacturers in both North America and Europe and is the result of a series of meetings and work since the completion of the above report. While the report describes the summation of the experience and practices used in the participating companies, no liability for the validity or for the views expressed here can be accepted by either the AIA or the participating organizations or companies.

Contents

1 References

1) DOT/FAA/TC-19/14, "Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts – 2019 Revision" dated May 2019.

2) FAA Advisory Circular 33.70-1, Change 1, "Guidance Material for Aircraft Engine Life-Limited Part Requirements," February 24, 2017.

3) FAA Advisory Circular 33.70-2, "Damage Tolerance of Hole Features in High-Energy Turbine Engine Rotors," August 28, 2009.

4) Klocke, F.; Gierlings, S.; Veselovac, D.; Tamayo-Osorio, L.; Cherubini; M.; Pizzi, M., "Intelligent Sensor System Supporting Set-Up Processes in Manufacture of Safety-Critical Components," 21st International Computer-Aided Production Engineering Conference (CAPE), Edinburgh, Scotland, 2010.

5) Gierlings, S., "Model-Based Temperature Monitoring for Broaching Safety-Critical Aero Engine Components," Apprimus Verlag, Aachen, 2015, ISBN 978-3-86359-344-5.

6) Brockmann, M., "On the Use of Potential Theory for Thermal Modeling in Metal Cutting," Apprimus Verlag, Aachen, 2015, ISBN 978-3-86359-391-9.

7) Klocke, F.; Brockmann, M.; Gierlings, S.; Veselovac, D., "Thermal Investigations for Finishing Conditions in Broaching Nickel-Based Turbine Components for Aero Engines," 30th International Manufacturing Conference (IMC30), Dublin, Ireland, 2013.

8) C.T Olofson, F.W. Boulger and J.A.Gurklis, "Machining and Grinding of Titanium and its Alloys", NASA Technical Memorandum TM X-53312, Dated August 4th, 1965.

9) "Hazards and Safety Precautions in the Fabrication and Use of Titanium", TML Report No. 63, January 25, 1957, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, Contract No. AF 18(600)-1375 (RSIC 0205).

2 Introduction and Recommendations

2.1 Introduction

This report is a year 2022 revision to the Reference 1 report which adds new sections for Turning, Marking, Milling and Grinding Manufacturing Methods and creates a separate section for the edgebreak Manufacturing Method.

This report was developed by a partnership of the Aerospace Industries Association (AIA) Rotor Integrity Steering Committee (RISC) member company manufacturing experts and the Federal Aviation Administration (FAA) in response to accidents and incidents caused by Manufacturing Induced Anomalies in Critical Rotating Parts. According to a 2017 summary from the AIA Rotor Integrity Steering Committee, slightly fewer than 30% of rotor cracks/events are caused by post-forging Manufacturing Induced Anomalies. The data indicate a significant reduction in cracks and events over the last decade.

- An example of a Holemaking caused accident or incident is the Delta Airlines non-contained JT8D-200 series engine titanium fan disk in Pensacola, Florida on July 6, 1996. During takeoff roll, an engine fan disk on the MD-88 ruptured and resulted in two fatalities. The cause of the fan disk rupture was traced to a severely worked material surface layer in one tie-rod bolt hole introduced during the hole machining of the disk (i.e., a Machining Induced Anomaly).
- An example of an Axial Blade Slot Manufacturing Method caused accident or incident is the American Airlines non-contained CF6-80A series engine high pressure turbine disk in Los Angeles, California on June 2, 2006. During a high-power ground run, an engine high pressure turbine disk on the CF6-80A ruptured, resulting in a fire damaging the airplane and engines. The cause of the high pressure turbine disk rupture was traced to a fatigue crack initiating at a small depression in the aft corner radius of a blade slot bottom, likely introduced during the slot-making process (i.e., a Manufacturing Induced Anomaly).

A summary of Axial Blade Slot Manufacturing Method strategies useful for establishing improvements (also known as manufacturing credits) relative to legacy methods is included. These strategies were provided to the AIA RISC for consideration within the damage tolerance assessment methodology.

The information and guidelines contained herein represent an industry consensus on the currently available best practices to minimize Manufacturing Induced Anomalies in Critical Rotating Parts consistent with the AIA RoMan team charter and vision, see Appendix A. The RoMan team function is currently performed by a team of manufacturing experts from the AIA RISC member companies. Recommendations for nominal process development and control are included to provide an overall framework for a highly reliable Manufacturing Process. Because Critical Rotating Part reliability has demonstrated particular sensitivity to certain manufacturing practices (e.g., the Pensacola event), recommendations for Holemaking, edgebreak, Axial Blade Slot, Turning, Marking, Milling, and Grinding Manufacturing Methods are included. Recommendations for other Critical Rotating Part feature Manufacturing Methods will depend on a detailed review of industry gathered service experience and associated manufacturing practices. If needed, recommendations for other processes will be included in future revisions of this report.

Although this report is aimed at part manufacture, it should be noted that the same disciplines and skills should be applied for approving sensitive processes in the overhaul, maintenance, and repair of Critical Rotating Parts.

2.2 Recommendations for the Manufacturing of Critical Rotating Parts

2.2.1 Manufacturing Process Validation and Change Control

2.2.1.1 Identification of Parts Subject to Special Control

Rotating parts whose primary failure is identified by FMEA as immediately leading to a potentially hazardous engine condition should be designated as CRITICAL or some other suitable designation such as FLIGHT SAFETY PART or LIFE CONTROLLED PART. This designation should be conveyed to all parties involved in the processing of the part.

2.2.1.2 Process Validation Approaches

Process Validation should be by one of the two routes described in Section 5.2, these being either the Part Specific Process Validation (PSPV) or the Generic Manufacturing Process Validation (GMPV). In PSPV the specific Manufacturing Process is shown to deliver a part which meets the Design Intent. In GMPV it is shown that parts produced using Manufacturing Methods which may be defined by specifications and/or validated parameter limits will meet the Design Intent.

2.2.1.3 The Process Validation Function

A Process Validation Function (PVF) should be established that consists of the following key skills:

Engineering (Design and Lifing)

Material Engineering

NDE

Quality Assurance

Manufacturing Engineering

Manufacturing Development Engineering (Method owner)

The Process Validation Function is a cross-functional group that should evaluate and approve Process Validation and the rules for Change Control, non-conformance disposition and Preliminary Review (including disposition of Special Cause Events) to ensure that the product of manufacturing is consistent with the Design Intent. The Process Validation Function group should make decisions by consensus. If consensus cannot be achieved, then the final decision should be made to ensure the part Design Intent/quality is met.

2.2.1.4 Manufacturing Control Plan (MCP)

A Manufacturing Control Plan that defines the key parameters for all steps and methods of the Manufacturing Process should be produced for all Critical Rotating Parts. Any change in the Manufacturing Process defined in the MCP should require an update of the MCP.

2.2.2 Human Factors and Training

A training program should be established that includes everyone involved in the manufacturing of Critical Rotating Parts: machine operators, material handlers, inspectors, shop supervision and management, manufacturing engineers both in-house and at suppliers. The training should convey how the recommendations of this report are met and should include elements of both background education and training in the necessary skills. The training should be included in the initial training for new hires and in a regular refresher for current employees.

2.2.3 Recommendations for Further Work

Research work in the following areas is recommended: Process Control, Process Monitoring and Non-Destructive Evaluation aimed at improving the reliability of Manufacturing Processes. A detailed review of service experience and associated production practices is recommended. It is anticipated that this review would result in additional research and development activities and a potential revision of this report.

2.2.4 Recommendations for Holemaking

Holemaking has been identified as a Sensitive Manufacturing Process. An assessment of the degree of Manufacturing Process Control required for all holes in Critical Rotating Parts should be performed based on the feature stress and design life, the difficulty of manufacture (e.g., High L/D Holes) and the material. The Critical Rotating Part surface damage tolerance methodology presented in FAA AC 33.70-2 (Reference 3) is considered an acceptable means, but not the only means, to decide whether further Manufacturing Process Control should be required. In addition to Process Validation and Change Control, other process improvement strategies for holes are recommended which may include but may not be limited to:

2.2.4.1 Process Monitoring

Real-time Process Monitoring with automated machine shutdown is recommended for all holes identified in Section 2.2.4.

2.2.4.2 Non-Destructive Evaluation (NDE)

The Process Validation Function (PVF) should evaluate and select appropriate NDE Methods, with particular attention to all High L/D Holes and edge breaks. The PVF should base their recommendations on the specific Detection capabilities and other inspection characteristics of NDE Methods commonly used by the industry as summarized in Tables 9.1 and 9.2 in Section 9 of this report.

2.2.5 Recommendations for Edgebreak

An edgebreak Manufacturing Method strategy is essential to meet the Design Intent of Critical Rotating Parts. Edgebreak methods are applied to remove burrs and condition or round edges according to the part drawing or to prepare the edge for subsequent processing such as shot peening. A discussion of the edgebreak Manufacturing Method is provided in Appendix H.

2.2.6 Recommendations for Axial Blade Attachment Slots

The combination of Manufacturing Methods used to produce axial blade attachment slots has been identified as a Sensitive Manufacturing Process. An assessment of the degree of Manufacturing Process Control required for all axial blade attachment slots in Critical Rotating Parts should be performed based on the feature stress and design life, the difficulty of manufacture and the material. The Critical Rotating Part surface damage tolerance methodology presented within an FAA Advisory Circular is considered an acceptable means, but not the only means, to decide whether further Manufacturing Process Control should be required. A detailed discussion for an axial blade attachment slot Manufacturing Process is provided in Appendix I.

2.2.7 Recommendations for Other Manufacturing Methods

Appendices J through N provide information and guidance for mechanical finishing of titanium, Turning, Marking, Milling, and Grinding Manufacturing Methods, respectively. A summary of each Manufacturing Method and the necessary attributes for development of a robust method suitable for Critical Rotating Parts is provided. Guidance on Process Monitoring is included, where applicable.

2.2.8 Recommendations for Promoting Improved Manufacturing Methods

Appendix O includes a discussion of manufacturing credits for damage tolerance assessments to promote introduction of improved Manufacturing Methods. The Manufacturing Method strategies provided in this appendix should be considered a good starting point for the development of improved Manufacturing Methods.

3 Definitions

The definitions provided in this report are not official regulatory definitions. Official regulatory definitions are those provided by regulatory material such as 14CFR Part 33.70 or associated Advisory Circular material.

Anodic Etch	Electrolytic etching where the part (workpiece) is the anode. Can be used as a visual inspection method to Detect surface Anomalies.
Anomaly	An abnormal Surface Condition with chemical or physical properties that do not meet the Design Intent.
Approved Lifing Method	A regulatory agency approved method for calculating a material's low cycle fatigue (LCF) capability for use in lifing Critical Rotating Parts.
Axial Blade Slot Manufacturing Method	A Manufacturing Method which removes material from the rim of a rotating part/disk to produce axial slots that constrain removable blades. In the context of this report, the method includes processes used to produce an edgebreak where the slots intersect the axial faces and/or OD of the disk.
Blue Etch Anodize (BEA)	An anodizing/inspection process which deposits a bluish conversion coating on titanium surfaces, providing a high visual contrast distinction for certain Anomalies.
Broaching	A machining Manufacturing Method where a cutting tool with multiple successively larger cutting edges/teeth moves linearly through the workpiece to produce a slot. Each tooth cutting edge removes a small amount of material, with the final part geometry produced by the last tooth cutting edge.
Change Control	A process in which changes to the Manufacturing Process are evaluated, validated, and documented.
Critical Rotating Parts (i.e., Engine Life-Limited Parts)	Refer to the Engine Life-Limited Part definition provided in Federal Aviation Administration (FAA) Chapter 14 of the Code of Federal Regulations, Part 33.70.
Cutting Fluid	Also known as coolant or metalworking fluid. Commonly it is a liquid used within Manufacturing Methods to reduce the friction between the chip and the cutting tool. It also removes heat and helps to transport chips/swarf away from the cutting zone.
Design Intent	Part material, geometry, and material Surface Condition that delivers the form, fit and function required by the part design to meet the Service Life of the part. Design Intent is recognized as including more than those requirements noted by the Product Definition or quality control document.

Detect, Detection, etc.	A threshold-driven identification process in which the existence of an Indication is of interest or worthy of further investigation.
Discontinuity	An interruption in the physical structure or configuration of a material or component.
Electromagnetic Induction	The process of introducing a magnetic field or electrical current in a part or test piece from a contacting or non-contacting probe.
Engineering Requirement	Engineering Product Definition including all associated specifications and standards, and purchase orders.
False Indication	An NDE Indication that is interpreted to be caused by a condition other than an Anomaly or imperfection.
Generic Manufacturing Process Validation (GMPV)	A route to Process Validation using a manufacturing specification and/or validated parameter limits defining a process window for manufacturing rather than a specific manufacturing set-up. GMPV demonstrates that any product manufactured within the process window will meet the Design Intent.
Geometric Anomaly	An Anomaly possessing finite physical dimensions, surface connected and non-metallurgical in nature such as abnormal surface finish, nicks, dents, scratches, and burrs. (See also Non-Geometric Anomaly).
Grinding	A machining Manufacturing Method where abrasives are used to remove workpiece material. In most aerospace applications, the abrasives are in the form of a grinding wheel which rotates at high speed as it passes through the workpiece, but some applications employ abrasive belts. Applications which use loose abrasives are not considered to be Grinding in the context of this report.
Heat Affected Zone (HAZ)	A material degradation mechanism which can occur during machining or processing in which the workpiece surface temperature is high enough to change the material microstructure or properties in the surface region. In extreme cases the near-surface material can be overheated to the point that it is visible as a “white layer” (or amorphous layer) in a metallographic examination. Rapid quenching of the heated material by the Cutting Fluid can also lead to microhardness changes in the near-surface region.
Holemaking	A machining Manufacturing Method where the cutting tool rotates as it translates through the workpiece to produce a hole. Most commonly, a drill is plunged axially to make a round hole, but other types of cutters and toolpaths may be used to finish a drilled hole or to produce shaped holes. In the context of this report, the Holemaking method includes processes used to produce an edgebreak where the holes intersect the hole entrance and exit features of the disk.

Human Factors	The mental and physical makeup of the individual, the individual's training and experience and the conditions under which the individual must operate that influence the ability of the Manufacturing Process or NDE system to achieve its intended purpose.
Indication	A response from an NDE Method which is different from the background.
Interpretation	The determination of whether Indications are relevant, Non-Relevant, or False.
Legibility	The quality of the characters, Marks or symbols with which a reader (person or equipment) can recognize the individual pieces of the information. Aspects that affect legibility include character height / depth, shape, contrast, and size.
Low L/D Hole	Any hole which is not a High L/D Hole.
Machining Induced Anomaly	See Anomaly. A type of Manufacturing Induced Anomaly created during a machining process. Factors which could cause Machining Induced Anomalies include excessive cutting speeds, dull cutting tools, improper tool design, and inadequate cooling.
Manufacturing Control Plan (MCP)	A detailed plan to manufacture and inspect a certain feature or part. The plan should identify Sensitive Manufacturing Processes and where appropriate establish parameter limits, specify Process Monitoring and inspection requirements and outline the reaction plan for Special Cause Events.
Manufacturing Induced Anomaly	See Anomaly. Manufacturing Induced Anomalies rarely occur, and as used in this report, are either in-process or end product Non-Geometric Anomalies (e.g., white layer, bent grains, work hardened material, tears, embedded tool tips, inclusions, etc.), Geometric Anomalies (e.g., abnormal surface finish, nicks, dents, scratches, and burrs, etc.) or cracks caused during machining and finishing processes.
Manufacturing Method	As used in this report: A Manufacturing Method is a single operation, e.g., Turning, drilling, shot peening, etc.
Manufacturing Process	As defined in this report: A Manufacturing Process is a sequence of Manufacturing Methods which produces a part or part feature.
Mark or Marking (noun)	Words, information, characters or symbols applied to a part surface for subsequent communication of information such as part identification, serialization, assembly alignment, etc. This includes both engineering-required and process-use Markings.

Mark or Marking (verb)	The act or process conducted to apply a Mark or Marking to the part. "Marking Method" is used to indicate the process of applying a Mark.
Material Review (MR)	Evaluation and disposition of non-conforming or Special Cause Event parts.
Milling	A machining Manufacturing Method where the cutting tool rotates as it translates through the workpiece to remove material. The cutting tool may have multiple cutting edges and may be designed to cut with the end of the cutter (plunge Milling), periphery of the cutter (peripheral Milling) or both.
NDE Method	A NDE Method is a discipline of applying a physical principle in Non-Destructive Evaluation, e.g., eddy current.
NDE, NDI, NDT	Non-Destructive Evaluation (NDE), Non-Destructive Inspection (NDI) or Non-Destructive Testing (NDT) - the application of technical methods to examine materials or components in ways that do not impair future usefulness and serviceability in order to Detect, locate, measure, and evaluate Anomalies; to assess integrity, properties, and composition.
NDE Technique	A specific way of utilizing an NDE Method, e.g., eddy current rotating probe hole inspection.
Non-Geometric Anomaly	An Anomaly that does not possess sharply defined boundaries and is typically associated with material structure or processing such as inclusions, overheated surface layers, microstructural Segregation, detrimental residual stresses, micro-cracking and smeared surface layers. A special type of Non-Geometric Anomaly is an embedded inclusion from a broken tool tip which has a sharply defined boundary that may not be open to the surface. (See also Geometric Anomaly)
Non-Relevant Indication	An NDE Indication that is caused by a condition or type of Anomaly that is not rejectable to the acceptance criteria. False Indications are Non-Relevant Indications.
Part Specific Process Validation (PSPV)	A route to Process Validation in which it is demonstrated that a specific Manufacturing Process produces a part which meets the Design Intent.
Predicted Fatigue Life	The low cycle fatigue life calculated by applying the Approved Lifing Method.

Preliminary Review	A procedure, defined by the PVF, in which a part with a suspected non-conformance or Special Cause Event is initially evaluated and dispositioned: • Accept to Engineering Requirements, • Forward to Material Review • Rework - This requires rework procedures approved by the PVF • Scrap
Probability of Detection (POD)	The probability of detecting an Anomaly of specified characteristics, which is achieved using a specified NDE Method. It is commonly represented as a function of POD versus flaw size.
Process Control	A procedure for maintaining a process within nominal limits due to anticipated Process Variability.
Process Failure Mode and Effects Analysis (PFMEA)	A procedure used to assess elements of any process that could lead to process failure. The PFMEA highlights the relative importance of the process elements and the required control mechanisms needed to maintain high process reliability.
Process Monitoring	Manufacturing Process oversight methodology used to Detect and automatically interrupt the Manufacturing Method when variations outside acceptable parameter limits occur.
Process Validation	A procedure in which it is demonstrated that the Manufacturing Process delivers parts consistent with the Design Intent.
Process Validation Function (PVF)	A cross-functional group with specialized skills which evaluates and approves the Manufacturing Process.
Process Variability	As used in this report, Process Variability is the normal variation that arises from fluctuations of the Manufacturing Process within the validated parameter limits, in contrast to Special Cause Events.
Product Definition	This includes the part geometric definition and all associated specifications, standards, and quality requirements.
Production Certificate Holder	The regulatory agency approved manufacturer of serviceable (i.e., acceptable for flight) parts. The Production Certificate Holder is the organization responsible for ensuring manufactured parts meet the Design Intent.
Readability	The ability to understand the information to be acquired from characters, Marks or symbols that make up the information presented. Aspects that affect readability include proximity, linearity, exposure time, contrast, patterns and variation from a standard.
Segregation	A non-uniform distribution of alloying elements, impurities or micro-phases found in materials.

Sensitive Manufacturing Process	Any Manufacturing Process which requires a high level of control to meet the Design Intent.
Service Life	The published life limit for a Critical Rotating Part, which is stated in operating cycles or operating hours, or both. When a part reaches its published life limit (as provided in the airworthiness limitations section of the engine manual), it is retired from service.
Special Cause Event	A generic term that applies to validated parameter limit exceedance or other process abnormality that could lead to a Manufacturing Induced Anomaly.
Surface Condition	The combination of material microstructure, finish, and residual stress at or very near the surface.
Tool Breakage	Minor chipping of the cutting edge, in which case the cutting process may or may not be continued, or total failure of a tool where it breaks into pieces and continuing the cutting process is impossible.
Tool Change Point	The designated life of the tool. Generally expressed as the maximum number of like features permitted to be machined using a single tool.
Turning	A machining Manufacturing Method where the workpiece rotates as a cutting tool translates axially and/or radially to remove material. The cutting tool may remove material from the outer diameter, inner diameter, or axial face of the workpiece. Turning machines are commonly called "lathes".

4 Background

It is inevitable that there will be scatter in the performance of parts made by a controlled process due to Process Variability. This Process Variability can be not only in the final dimensions of the part but just as importantly in the material condition, residual stress, etc. Fatigue, for example, is particularly sensitive to the material condition and especially the material Surface Condition. Process Variability within a controlled process must be accommodated when establishing the part Service Life. An illustration of Process Variability impact to part Service Life is presented in Figure 4.1. Parts that do not have sufficient properties to meet or exceed the Service Life because of the Manufacturing Process are at risk to initiate fatigue cracks.

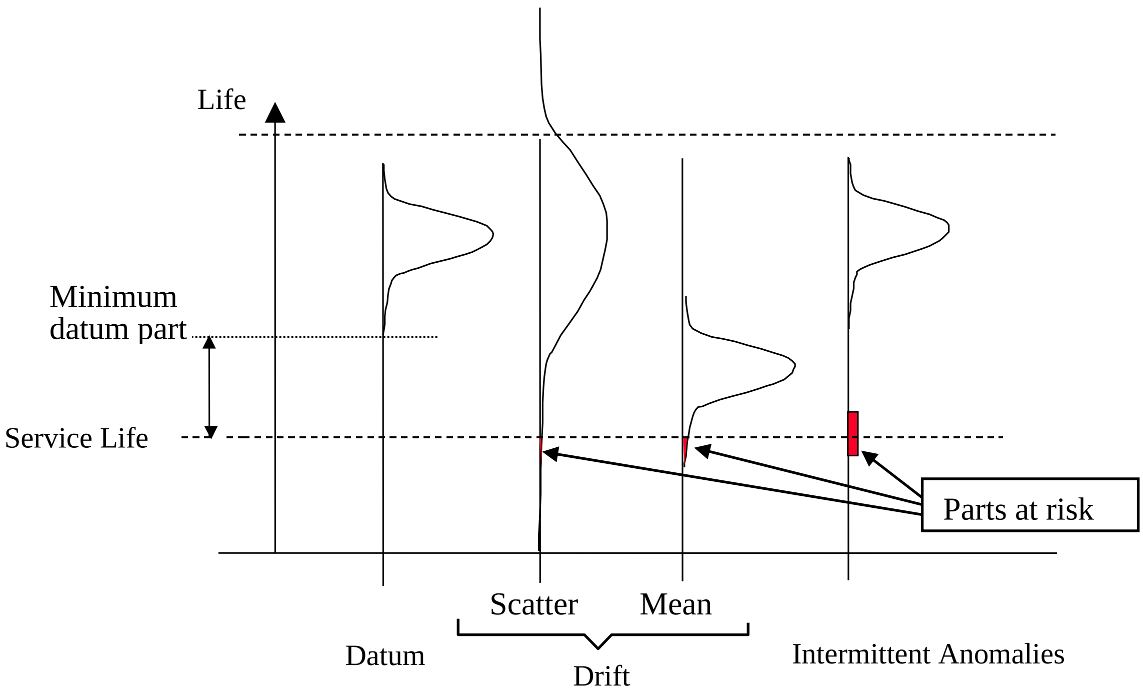


Figure 4.1: The Effect of Variation in the Product of a Manufacturing Process

4.1 Minimizing Parts at Risk

To eliminate manufactured parts that do not have sufficient properties to meet or exceed the Service Life due to process drift, it is necessary to:

- Relate the fatigue capability of the product of the Manufacturing Process to the Service Life.
- Control the Manufacturing Process and changes to ensure that the part meets the Service Life while accounting for the combination of drift in the mean and the scatter of the process such as from tool wear. For example, the impact of tool wear must be evaluated by the Process Validation Function and included within the Process Control strategy.

However, it is possible for even well developed and controlled Manufacturing Processes to have Special Cause Events. Examples of Special Cause Events are Tool Breakage, unexpected tool wear, loss of Cutting Fluid, chip packing, machine failure, validated parameter limit exceedance, etc. The vast majority of these are immediately apparent, but on rare occasions they may give rise to undetected Manufacturing Induced Anomalies. Unlike drift in the Manufacturing Process described above, such Anomalies can arise in both isolated incidences or in small outbreaks without necessarily impacting the process mean and scatter. This condition is shown by the fourth distribution in Figure 4.1, labelled “Intermittent Anomalies”. Sampling the fatigue capability delivered by the process (i.e., within the validated parameter limits) is not likely to be effective in capturing the fatigue impact of intermittent Manufacturing Induced Anomalies since it is unlikely that a part with an Anomaly will be examined. To address such Manufacturing Induced Anomalies, it may be necessary to use a combination of Process Controls, Process Monitoring and inspection to ensure that the probability of a life limiting intermittent Manufacturing Induced Anomaly escaping into service is minimized.

4.2 Content and Organization of the Report

The remainder of the report is organized as follows:

- Section 5 describes practices that address the integration of the Manufacturing Process into the Service Life declaration process.
- Section 6 describes Quality Assurance best practices.
- Section 7 describes Process Monitoring best practices.
- Section 8 emphasizes the importance of Human Factors and Training in the Manufacturing Process.
- Section 9 describes Non-Destructive Evaluation best practices with tables to aid in choosing NDE Methods for holes.
- Section 10 lists some "Lessons Learned" to date by the industry.
- Section 11 is Appendix A which provides the RoMan charter and vision statements and lists the RoMan participants
- Sections 12-20 include Appendices B through O which provide details and guidance for:
    - 12 - Process Monitoring of circular holes
    - 13 - Current NDE criteria and capabilities
    - 14 - The edgebreak Manufacturing Method
    - 15 - Producing axial blade attachment slots
    - 16 - Mechanical finishing of titanium
    - 17 - The Turning Manufacturing Method
    - 18 - The application of part Marking
    - 19 - The Milling Manufacturing Method
    - 20 - The Grinding Manufacturing Method
    - 21 - Manufacturing Process credit development and Manufacturing Method strategies which support damage tolerance assessments

5 Integrating the Manufacturing Process into the Structural Integrity of the Part

5.1 Identifying Parts Subject to Special Controls and Feature Gradation

It is accepted that it is impossible to design all modern gas turbine engines with total redundancy so the failure of any single component can be accommodated by alternative load paths, containment of high energy debris, etc. Rotating parts for which a high level of integrity in the source material and manufacturing quality is required to avoid primary failures whose consequences may hazard the airframe should be subject to special controls and designated as CRITICAL or some other suitable designation such as FLIGHT SAFETY PART or LIFE CONTROLLED PART. The part designation is intended to convey the need for special controls to all parties who will handle the part. Hence, the part designation should be systematic and may go beyond the Product Definition.

Although the Product Definition is a means of transferring geometrical dimensions from engineering to manufacturing, it is not necessarily a complete set of instructions needed to successfully manufacture the part. These instructions can be defined by the Product Definition or can be a collection of generic and part specific instructions and documentation approved by the PVF as discussed in the following sections. Providing gradation of specific features within the Product Definition enhances the awareness of the manufacturer to the sensitivity of these features. In order not to overwhelm manufacturing with information, it is recommended to limit the classes of gradation for a specific feature (based on, for example, material, feature geometry such as L/D in holes, Service Life, etc.).

With feature gradation, the design authority can easily call out special requirements/controls within the Product Definition for the:

- Forging
- Manufacturing Process (e.g., MCP)
- Process Controls (e.g., inspections plans, Process Monitoring, training)

5.2 Approaches to Manufacturing Process Validation

To ease the discussion of how Process Validation is accomplished, the following is assumed:

- Initially all Manufacturing Methods are examined to establish a set of operational parameters which will deliver acceptable quality. In machining, for example, this could be an acceptable range of cutting speeds, feedrates, tool shape including sharpness, etc.
- A Manufacturing Process is a sequence of Manufacturing Methods which produces a part or part feature.

Two approaches to Process Validation are used in the industry. The first approach is defined as Part Specific Process Validation (PSPV) while the second is known as Generic Manufacturing Process Validation (GMPV). In PSPV, a part is evaluated against the Design Intent and subsequent production is controlled to deliver product consistent with the evaluation. In GMPV, those Manufacturing Methods that are identified as being sensitive, i.e., as needing a high level of control if manufactured product is to meet the Design Intent, are controlled by specifications and/or validated parameter limits. GMPV ensures that any product manufactured within the parameter windows will meet the Design Intent.

In practice, sometimes PSPV and GMPV are used in combination to validate the Manufacturing Process for a part. For example, specific features, such as holes, can be controlled through GMPV using a specification or validated parameter limits, while Turning operations may be controlled by PSPV. Over time the investigation and validation of a range of Turning parameters may allow the development of a specification or validated parameter limits defining a process window for Turning and then such Turned features may be controlled by GMPV. Because it is much easier to validate small features by sub-element tests than general areas such as disc bores, it is easier to develop a fully validated specification or parameter limits for local features and use GMPV from the outset.

The route to Process Validation and the issues that require consideration are described in Table 5.1.

Table 5.1: The Route to Process Validation

<table>
<tr><th>Who</th><th>#</th><th colspan="4">Activity</th><th>HOW / COMMENTS</th></tr>
<tr><td>Engine design, i.e. Type Certificate Holder</td><td>1</td><td colspan="4">Identify rotor parts which must maintain a high level of integrity to avoid hazardous engine effects per FAR Part 33.75 and designate such parts as described in Section 5.1.</td><td>FMEA of the engine leads to part classification, ¶5.1
The critical nature of the part should be conveyed to all parties concerned with manufacturing the part, ¶5.1</td></tr>
<tr><td>PVF, ¶5.3</td><td>2</td><td colspan="4">Review all part features and identify the features made by Sensitive Manufacturing Processes.</td><td>A PFMEA or other disciplined method should be used to help identify Sensitive Manufacturing Processes. It is generally accepted that the feature Manufacturing Process and fatigue life should be considered in the identification process (e.g., FAA AC 33.70-1, Reference 2). For example, an identification process may capture features with both
a. Sensitive Manufacturing Processes
b. Predicted fatigue lives that are either less than four times the Service Life or less than 100,000 cycles.</td></tr>
<tr><td rowspan="2">PVF</td><td rowspan="2">3</td><td colspan="4">Validate the Manufacturing Process for those features identified in #2 above.</td><td rowspan="2">The Process Validation can be a combination of PSPV and GMPV.</td></tr>
<tr><td colspan="2">PSPV ¶5.4.1</td><td colspan="2">GMPV, ¶5.4.2</td></tr>
<tr><td>Manufacturing Engineering (ME)</td><td></td><td>3A.1</td><td>Define Manufacturing Process</td><td>3B.1</td><td>Define parameter limits</td><td>Based on validated Manufacturing Methods, ¶5.4.3</td></tr>
<tr><td>PVF</td><td></td><td>3A.2</td><td>Establish fatigue capability</td><td>3B.2</td><td>Investigate the fatigue behaviour of parameter limits including consideration of the most adverse parameter combinations</td><td>By fatigue test using part, sub-element or specimen which captures material, Surface Condition and geometry
Or
Metallurgical evaluation where experience defines an acceptable material Surface Condition.
Or
A combination of the above.</td></tr>
</table>

Who	#	Action				How / Comments
PVF		3A.3	Declare the Service Life within established fatigue capability using Approved Lifing Method.	3B.3	Confirm the fatigue life determined in 3B.2 is consistent with the Approved Lifing Method.	
PVF		3A.4	Manufacturing Process is defined for the part	3B.4	Specification or validated parameter limits defined	
Manufacturing Engineering	4	Capture the Manufacturing Process into the Manufacturing Control Plan, ¶5.5				The MCP defines all the steps & methods for manufacturing Critical Rotating Parts.
PVF	5	Change Control, ¶5.6				
		PSPV-A		GMPV-B		
		Who	Action	Who	Action	
		PVF	Identify substantial change If change is not substantial, allow If change is substantial, go to #2 above	ME	Is change within Specification or validated parameter limits? If so, allow If not, go to #2 above	The PVF should determine whether a proposed change in the Manufacturing Process may reduce the capability of the part to meet the Design Intent. If that is the case the change should be considered as a substantial change, see ¶5.6 All change, substantial or not substantial, should be recorded in the MCP.

5.3 The Process Validation Function (PVF)

The PVF is a cross-functional group with specialized skills that evaluates and approves the Manufacturing Process by consensus. If consensus cannot be achieved, then the final decision should be made to ensure the part Design Intent/quality is met. The PVF may be a standing committee or an ad-hoc working team and/or teams that evaluates/certifies the Manufacturing Processes for a specific feature and/or part.

The PVF should include individuals with the following skills:

- Engineering (Design and Lifing)
- Materials Engineering
- NDE
- Quality Assurance

- Manufacturing/Production Engineering
- Manufacturing Development Engineering (Method owner)

The main purpose of the PVF is to ensure that the Manufacturing Process for the part is consistent with the Design Intent. To do this, the PVF should understand the Manufacturing Process and its impact on the part's capability to meet the Design Intent. The PVF should address and ensure control of those aspects of the Manufacturing Process that could sensibly lead to a substantial reduction in the integrity of the part. The PVF may help to develop the MCP and will approve it as shown in steps 2 through 5 in Table 5.1.

Another important role of the PVF is to control and approve manufacturing changes and differentiate between changes that are substantial and not substantial. The PVF should determine what level of detail is required to qualify a manufacturing change or new technology.

Validation of the Manufacturing Process may include but may not be limited to:

- Best practice (e.g., speed, feed, and use of tool)
- Process Monitoring requirement
- Product Definition requirements
  - NDE Method requirements
  - Metallurgical examination to the materials standard
  - Residual stress measurement
  - Special design requirements
  - Fatigue testing (specimen, sub-element, sub-component, or component)

Finally, the PVF should evaluate and approve the rules for Preliminary Review and non-conformance disposition, including the disposition of Special Cause Events.

5.4 Manufacturing Process Validation

A PFMEA or other disciplined method is useful in Manufacturing Process evaluation for identifying Sensitive Manufacturing Processes and their key parameters requiring tight control to avoid producing Anomalous product. PFMEA (or other disciplined method) can form the basis of Process Monitoring and inspection strategies for Sensitive Manufacturing Processes.

5.4.1 Guidelines for Manufacturing Process Evaluation – Part Specific Process Validation (PSPV) Approach

Manufacturing Process evaluation should be performed on a full-size part that is manufactured by a process representing all Manufacturing Methods, such as Turning, drilling, Milling, Broaching etc. required in the MCP. The validation part may be the first part made according to the part MCP and should represent the production standard in every detail such as tooling, fixtures, machining devices, etc.

An appropriate NDE Method may be helpful to determine the cutting locations for metallurgical investigations.

Full size component tests such as spin pit or Ferris wheel testing should be considered if a life critical feature is produced in a new material or using a new manufacturing technique. The test article should be manufactured according to the MCP and should represent production standards in details such as tooling, fixtures, machining devices, etc. although controlled geometric differences may occur when using model disks for fatigue testing and evaluation of the Manufacturing Process.

The results derived from testing should comply with the company's Approved Lifing Method fatigue database. If a single test is conducted, the achieved life values should be equal to or better than an average of the appropriate fatigue life distribution. If not, more tests to demonstrate compliance with the appropriate fatigue life distribution should be required.

5.4.2 Guidelines for Manufacturing Process Evaluation – Generic Manufacturing Process Validation (GMPV) Approach

Manufacturing Process limits should be defined and documented such as in a specification. This document should define manufacturing limits such as maximum permissible cutting speeds. These maximum cutting speeds should be dependent on the Manufacturing Method used (drilling, reaming, Milling etc.), geometry (hole L/D), and part material. Other process requirements such as minimum stock removal, Cutting Fluid application, NDE requirements and Process Monitoring requirements can be included in the document.

The extremes of the Manufacturing Process should be assessed as discussed in Section 5.4.3 for each Manufacturing Method like drilling, reaming, and Milling, etc. This should be done for the various types of materials and various feature geometries.

5.4.3 Guidelines for Manufacturing Method Evaluation

The objective of this step is to understand the qualitative and quantitative Manufacturing Method impact on the fatigue life (or life influencing elements such as microstructure, residual stress, and surface finish) of the features of Critical Rotating Parts. The Manufacturing Method may be assessed as part specific or generic. For generic assessment, a common industry practice, the data may be obtained via internal development work and/or industry studies. Alternatively, industry best practices may be used, and the step may be eliminated altogether as a "stand alone element" for part specific evaluation.

The Manufacturing Method examined should demonstrate, within the window of manufacturing parameters anticipated for the material, compliance with the company's standards, set by experience of:

- Microstructure (e.g., highly distorted grain boundaries, slip lines, cold work, white layer)
- Surface finish (e.g., surface roughness, surface contamination)
- Residual stress profile
- Lifing system/database

The following is a guideline on what areas should be addressed in Manufacturing Method evaluation.

Near-Surface Microstructure

Several specimens, cut and polished, representing the following should be evaluated:

- Materials condition anticipated
- New and worn/dull tools
- Extremes of the anticipated manufacturing parameter window
- Adverse manufacturing parameters, if applicable (max. speed/min. feed; min. speed/max. feed)
- Tool characteristics, material and geometry (if applicable)

Where possible, the cutting location should be determined by means such as NDE, part life capability assessment, or sensitivity to Manufacturing Method variations.

Surface Finish

Surface finish quality evaluation should consider:

- New and worn/dull tools
- Minimum and maximum Manufacturing Process parameters

Residual Stress Profile

Residual stress profile measurements should consider new and worn/dull tools.

Fatigue Testing

An appropriate number of fatigue tests should be required to undertake statistical assessments for a minimum property part (per Reference 2) and should consider:

- New, worn/dull, and reconditioned tools
- All rotor materials involved
- Range of Manufacturing Process parameters (e.g., cutting speeds and feeds)
- Adverse Manufacturing Process parameters (if applicable)
- Tool characteristics

Results should be within the company's Approved Lifing Method fatigue database. The fatigue specimens may be cut from parts using a process like those used in production or may be manufactured in a lab using production-like Manufacturing Processes. These fatigue specimens should be prepared by using selected extremes, either singly or in combination, of the Manufacturing Method such as dull cutting tools, maximum cutting speed, maximum cutting speed and feed, etc.

It is necessary to ensure an allowance is made for the minimum standard of microstructure and surface finish.

Residual stress and fatigue testing are recommended since not all life influencing effects can be detected by metallurgical investigations. Fatigue tests should be required if metallurgical examinations across the anticipated machining parameter limits are borderline or outside those of the Approved Lifing Method fatigue database.

5.5 The Manufacturing Control Plan (MCP)

The MCP is a technical plan that defines the steps and methods of manufacturing for Critical Rotating Parts. The key elements of this MCP may include, but may not be limited to:

- Manufacturing Process steps and sequence
- Manufacturing parameters and allowable range
- Tool design, make and material(s)
- Cutting parameters and scatter allowed
- Machining device
- Cutting Fluid type, flow, and change requirements
- Tool wear limits and/or tool change requirements
- Inspection methods and acceptance criteria
- In-process control techniques, including monitoring, and acceptance criteria.
- Reaction plan (what to do if something goes outside validated process limits allowable range)
- Part protection during handling and storage

The level of detail in the MCP will depend on the sensitivity of the process.

After satisfactory process evaluation, the MCP is approved by the PVF.

The MCP is a control document and should be "Change Controlled" through the individual company's PVF procedures.

Deviation from the MCP should be considered as a potential non-conformance.

5.6 Guidelines for Manufacturing Change Control

5.6.1 Identifying Substantial Change

When changes in Manufacturing Method are proposed, it is first necessary to assess the extent of the change. In GMPV the lowest level of change is one within the parameter limits defined for the Manufacturing Process. In this case, since the whole process window has been demonstrated to yield product which meets the Design Intent, change within the window can be allowed with no further Process Validation. However, change beyond the parameter limits in GMPV and all change in PSPV should be carefully evaluated before being accepted. An appropriate program of work should be identified by the PVF to ensure that the changed Manufacturing Process continues to meet the Design Intent.

The PVF should define whether a proposed change in the Manufacturing Process has the potential to change the integrity of the part such that it would not meet the Design Intent. If so, the change should be considered a substantial change.

Below is a guideline to what could be considered as a substantial change. It includes, but is not limited to, changes to the:

- Manufacturing sequence
- Process parameters
- Machine, fixtures, tooling etc.
- Part or tool material
- Manufacturing source or equipment

The change evaluation should be documented, and all changes should be recorded in the MCP.

5.6.2 Guidelines to Validate Manufacturing Change

Pre-requisite: The old (or current) Manufacturing Methods are known to deliver a part feature which meets the Design Intent.

1. Manufacture the feature using both the old and new Manufacturing Methods. Cut-up and evaluate the microstructural condition of the material.
2. If the microstructural and Surface Condition of the material is identical, or if the new Manufacturing Method can be shown to deliver an improved microstructural and Surface Condition, then the change may be accepted as equivalent to the former Surface Condition. As in method evaluation, Section 5.4.3 above, not only metallography but also residual stress measurement may be necessary to demonstrate equivalency. In establishing equivalency or improvement, it is necessary to show that this judgement is based on previous experience with the material, the Surface Condition, and the fatigue performance.
3. Where substantial differences in the microstructural and Surface Condition can be identified, it is necessary to undertake further validation such as:
   - 3.1 Demonstrating equivalent fatigue capability by testing specimens representing the Surface Condition delivered by the new and the old Manufacturing Methods. In such cases special attention should be paid to ensuring that the specimen Surface Condition captures the old and new Surface Conditions in the part.
   - 3.2 Demonstrating the fatigue capability of a part or parts. This can be used either to demonstrate equivalent fatigue capability (GMPV or PSPV) or to establish a different fatigue capability (PSPV). If a lower fatigue life capability is determined, the part feature must maintain the part published life in the airworthiness limitations section of the instructions for continued airworthiness and the lower fatigue life capability must be documented and used going-forward for future life assessments of the feature.

6 Quality Assurance

6.1 Quality Assurance in Manufacturing

To ensure that Critical Rotating Parts have been produced in accordance with the Design Intent, the Production Certificate Holder should have a written procedure that seeks to prevent non-conforming parts from entering service. Process Validation (Sections 5.2 to 5.4), the MCP (Section 5.5) and manufacturing Change Control (Section 5.6) should be covered by written procedures.

All manufacturing parameters identified in Section 5.4 should be controlled by documented work instructions. The work instruction may be a part of the MCP. Preliminary Review and Material Review (MR) should be controlled by written procedures aimed at preventing non-conforming parts from entering service.

The manufacturing of Critical Rotating Parts should be subject to periodic audits to ensure that the current Manufacturing Process is consistent with the approved MCP and PVF procedures. There should be a written procedure of how and when such audits will be conducted. In the audit procedures, special attention should be paid to how changes in manufacturing are controlled.

Personnel with audit skills commensurate with the PVF should conduct all audits.

6.2 Material Review (MR)

6.2.1 Introduction

The MR evaluates suspect or confirmed non-conforming material, part, or process. A non-conformance is defined as a part characteristic that does not meet or conform to the requirements specified in the contract, Product Definition, Manufacturing Control Plan, or other approved product description.

MR is performed by a board or a group of individuals responsible for the evaluation and disposition of non-conforming material. As a minimum, MR should be performed by one representative from Engineering and one from Quality Assurance (QA) but in general should call upon the same skill mix as identified for the PVF. Since high-energy rotor manufacturing is critical to the safety of aircraft, a special set of qualifications (in addition to other company specific requirements) are recommended for persons performing MR. These qualifications may consist of:

- Educational qualifications such as an engineering degree or equivalent experience
- Adequate work experience related to the proposed MR function with a focus on rotor component specific experience
- Training related to materials review and corrective action including exposure to regulatory agency requirements
- Passing grade on a MR exam or a regulatory agency recognized program

A list of approved MR individuals should be maintained.

6.2.2 Disposition of Non-Conforming Hardware

There are four common types of disposition of non-conforming hardware: use as-is, rework, repair and reject. Disposition of non-conformance on critical features manufactured by sensitive processes should be by consensus and should require special attention and scrutiny utilizing the skill mix of the PVF. If consensus cannot be achieved, then the final decision should be made to ensure the part Design Intent/quality is met.

- Use As-Is: Generally, use "as-is" disposition is discouraged for non-conformance that could affect the fatigue capability of the rotor.
- Rework: This requires rework procedures approved by the PVF that restores the part to Engineering Requirements.
- Repair: This requires repair procedures approved by the PVF that restores the part to meet the Design Intent.
- Reject (Scrap): This is used when the other three options are not feasible.

7 Process Monitoring of Machining

7.1 Introduction

Field experience and laboratory results have demonstrated that Machining Induced Anomalies can result in reduced fatigue life leading to early part failure.

Machining can cause damage to rotor parts by, for example:

Heat build-up

- Dull cutting tools
- Poor Cutting Fluid delivery
- Excessive metal removal rates – over-speed

Excessive mechanical work

- Wrong tool geometry
- Dull tools (over-use or wrong tool material)
- Tool breakage

"Murphy's Law"

- Power loss
- Loss of Cutting Fluid delivery
- Machine breakdown
- Program loss / error

Nominal machining processes that are properly qualified do not cause Machining Induced Anomalies. It is when Special Cause Events take place that such Anomalies are most likely to occur. Currently, the best method to detect when a Special Cause Events happens is by Process Monitoring.

The following are examples of Special Cause Events that Process Monitoring can detect:

- Broken tools
- Improper tool Grinds
- Wrong tool material
- Excessive tool wear
- Loss of Cutting Fluid
- Wrong feeds and speeds due to a machine malfunction
- Wrong feeds and speeds due to machine operator intervention

Ideally, process monitors should operate on a real-time basis and be capable of interrupting the process prior to the occurrence of a Machining Induced Anomaly. If a Manufacturing Method varies outside its acceptable parameter limits, the process monitor should act automatically.

7.2 Purpose

The primary purpose of Process Monitoring is to prevent Manufacturing Process induced damage to the part. Process Monitoring oversees a Manufacturing Method to detect and automatically interrupt the method and take control of the process when variations outside acceptable parameter limits occur. Process Monitoring prevents most Machining Induced Anomalies from occurring, therefore reducing scrap and rework costs as well. In addition, Process Monitoring can be used for adaptive parameter control and for method development by helping select the optimum tool geometry and machining parameters resulting in optimized tool life.

7.3 Description

Process Monitoring systems should be real-time so most Machining Induced Anomalies can be prevented while machining the part. To be effective, Process Monitoring systems should interface with the machine numerical control to provide automatic machine shutdown when a process Special Cause Event occurs. Process Monitoring systems that generate alarms or warning lights are generally ineffective since machine operators are often required to perform multiple tasks such as running more than one machine, performing part inspections, or doing tool kitting while machines are running. Process Monitoring systems should be easily installed in a production manufacturing environment, and they should be user-friendly at the machine operator level.

Process Monitoring systems should be calibrated. The PVF should define a procedure for evaluating and dispositioning the work piece when a monitor output indicates a Special Cause Event has occurred. Process monitor output data should be available and retained when a Special Cause Event occurs.

Process Monitoring may not be required for all components, features, materials, or Manufacturing Processes. A PFMEA (or other disciplined method) or surface damage tolerance analysis (e.g., FAA AC 33.70-2, Reference 3) should be performed to determine which combinations of components, features, materials, and Manufacturing Processes require Process Monitoring. It is recommended that Process Monitoring requirements be applied to components and features as a Product Definition requirement. Process Monitoring requires training of the machine operators, shop supervisors, quality personnel, and shop management. In addition, design engineers also need to be instructed when to apply the requirements for Process Monitoring within the Product Definition. Machine operators and their management should be trained on the need for process monitors, the operation of the monitors, the need to follow operating procedures, and most importantly, what to do when a process monitor signals a Special Cause Event or automatically shuts down the process. Shop management and Quality should be clearly instructed on the work piece evaluation process when a process monitor detects a Special Cause Event. Whenever possible, directed disposition procedures should be approved by the PVF and provided for use by quality and shop management. Periodic training is beneficial, and it is recommended that refresher training occur at regular intervals.

7.4 Recommendation

Over the years there have been several cracks and fractures of Critical Rotating Parts attributed to Machining Induced Anomalies in holes. An assessment of the degree of Manufacturing Process Control required for all holes in Critical Rotating Parts should be performed based on the duty (stress and design life), the difficulty of manufacture (e.g., High L/D Holes) and the material. The Critical Rotating Part surface damage tolerance methodology presented in FAA AC 33.70-2 (Reference 3) is considered an acceptable means, but not the only means, to decide whether Process Monitoring should be required. Process Monitoring has been demonstrated as an effective production method to detect the onset of many types of Machining Induced Anomalies in holes and is therefore recommended on holes thus identified. See Appendix B: Process Monitoring for Holemaking for detailed guidance on the application of Process Monitoring for holes.

Process Monitoring for most other Manufacturing Methods has yet to be demonstrated in a production environment. Monitoring other Manufacturing Methods as discussed above will depend on the result of a detailed service experience review and the outcome of current or future Process Monitoring development activities. A discussion of Process Monitoring, where applicable, for Axial Blade Slot, Turning, Marking, Milling, and Grinding Manufacturing Methods are included within each Manufacturing Method Appendix.

8 Human Factors and Training

8.1 Human Factors

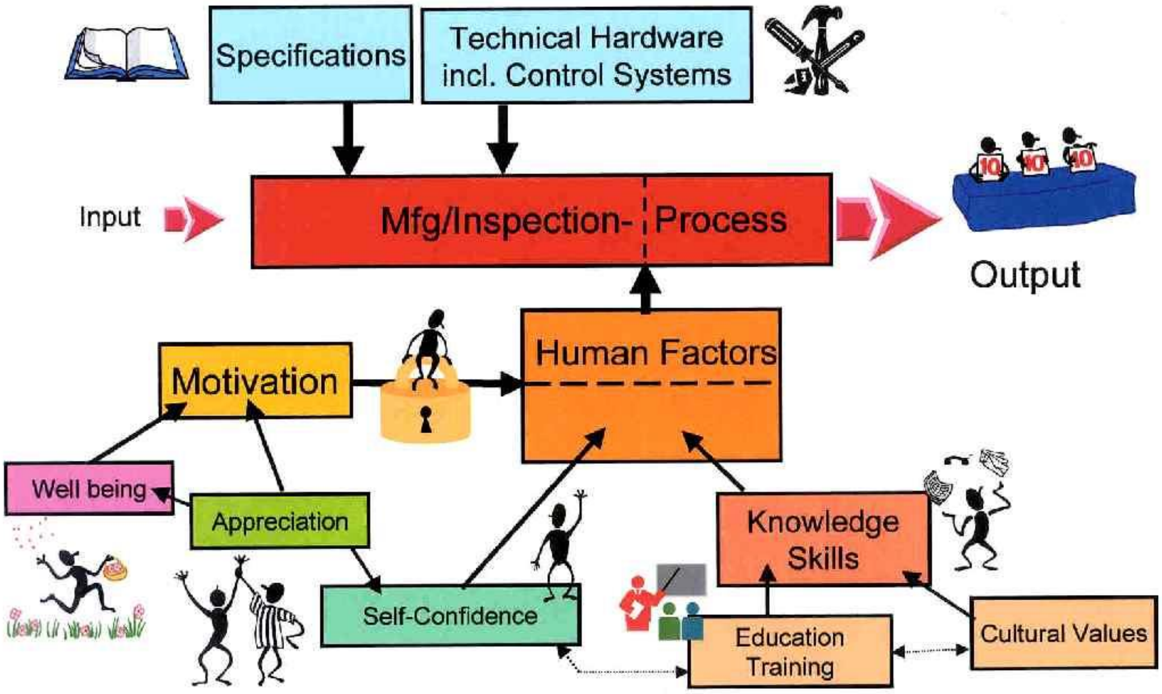


Figure 8.1: How Different Human Characteristics Influence the Manufacturing / Inspection Process

It is apparent from other sections of this report that our ability to minimize Manufacturing Induced Anomalies is dependent on our ability to control the Manufacturing Process. There are two elements that should be considered to ensure control: the Manufacturing Process and Human Factors. The manufacturing of Critical Rotating Parts typically involves many methods, inspections, and transportation steps. While we can, and should, put in place robust processes and process oversight (such as process monitors) we cannot completely eliminate the people from the process. The machine operators, inspectors, material handlers, engineers and others that work with the parts every day as they are being manufactured are a vital link in the process of identifying and responding to a Special Cause Event. What may appear to be an unimportant observation during part processing (different surface appearance, unusual tool wear or noise, etc.) can indicate the presence of a Manufacturing Induced Anomaly. Even if a similar Special Cause Event has occurred before and been accepted, subsequent occurrences may still indicate the presence of a Manufacturing Induced Anomaly. All such observations and events should be reviewed and documented. Training and motivation are the keys to enable those directly involved to react correctly.

As presented in Figure 8.1, there are a number of factors that influence the behavior of people. It is the role of company management to make sure that everyone involved in the manufacturing of Critical Rotating Parts is able to make the right choice. While in concept this is clear and simple, in practice it is more complex.

Human Factors can be divided into "hard" and "soft" elements. Hard elements include the work environment (temperature, light, space, noise, and arrangement), training (level of experience) and business practices. Soft elements are dependent on management actions and their influence on workplace culture (recognition, appreciation, information) and ownership (first shift vs. second shift, machine operator vs. inspector). The hard elements are easier to assess and correct, while the soft elements, although much more difficult, can ultimately be more influential.

It is recommended that management address the following:

- Environmental conditions (e.g., housekeeping, light, noise and temperature)
- Problem reporting culture (i.e., don't shoot the messenger!)
- Worker ownership, recognition, and training

  It should be stressed that the machine operator is crucial to the control of the process. Operators are the eyes and ears of the process. Everything else is just a clinical measurement of the results. The machine operator can hear changes in the cutting, see the proper amount and location of Cutting Fluid flow, determine if tools are wearing properly, etc. Even if the machine operator is running multiple machines, they are still the first person to notice a change in the process. The machine operator is on duty to report the changes in the process.

It is emphasized that the above applies to everyone involved with, and influencing, the manufacturing of Critical Rotating Parts.

8.2 Human Factors Consideration in NDE

Human Factors can have a major effect on inspection capability, cost, and productivity depending on their degree of involvement in the NDE process, their potential effect on the results, and their personal characteristics. In general, more human involvement in a process introduces a greater potential for variation in the process results. The quantitative effect of this variation is generally demonstrated by comparing POD curves for manual and automated inspections – typically the higher the human involvement, the lower the inspection confidence. The complexity of the Human Factors and the key role of motivation to the inspection process is highlighted in Figure 8.1.

Etch, visual and FPI/MPI processes rely on human eyes to Detect and interpret Anomalies on the hardware. The results obtained by each human depend on a large number of factors, including training, experience, physical and mental condition, attitude, environment, etc. Because of their dependence on humans whose performance is affected by a large number of variables, etch, visual and FPI/MPI are inherently limited in Detection reliability. The influence of Human Factors on these NDE processes tends to decrease as the Indication size of interest increases. However, under certain circumstances large Indications have been interpreted as Non-Relevant when the size of the Indication is outside the experience of the inspector and their judgement overrules the test result.

The impact of Human Factors on eddy current (EC) results is generally considered to be lower than for etch, visual or FPI/MPI. This is due primarily to the reduced human involvement in obtaining inspection data. Once the electronic EC equipment is properly set up and calibrated, the human involvement is reduced to moving the probe on the part (manual inspection) and/or reading the probe response from a meter. Factors such as inspector eyesight, physical and mental condition, attitude, and environment have a smaller effect on the inspection results. Semi-automated and automated EC further reduce inspector involvement by providing repeatable probe movement.

8.3 Training

To minimize the impact of Human Factors on the output of a Manufacturing Process it is important that everyone involved is adequately trained. The training should be designed to ensure that both hard and soft elements are addressed. This training should be a portion of current programs and should be included in the initial training given to people that are new to an area and also as a portion of a regular refresher training. Encourage the use of real examples including failed and cracked parts, highlighting the consequences of Critical Rotating Part failure, along with using a variety of training techniques and locations. Manufacturing Induced Anomalies are rare and, for people to understand the potential impact of such Anomalies, information should be provided in a way that enhances retention. Some suggestions would be to do the training on the factory floor, to break it up into short sessions given more frequently, etc.

Training for hard elements should include specific skills and knowledge necessary to understand and use the process, methods, tools, and equipment. Regarding the manufacture of Critical Rotating Parts this training should include:

1. **<u>The importance of remaining within the validated parameter limits</u>**

    - Follow the operation sheets <u>exactly</u>
        - Use approved cutting tools and media
        - Change tools as directed
        - Do not override programmed process parameters (e.g., speeds or feeds)
    - Ensure proper Cutting Fluid application for machining and Grinding operations
        - Maintain continuous Cutting Fluid flow along the tool shank and at the cutting edge(s)
        - Do not allow chip ‘birds nests’ to form
        - A minimum Cutting Fluid concentration and quality are required (reference process sheets)
    - Report any Special Cause Events such as:

- Chip packing, wrapping and/or welding to the tool
- No Cutting Fluid flow to the cutting edge(s)
- Dull or improperly ground tools
- Broken or squealing tools
- Abnormal indications of heat build-up on the tool or part such as smoke or discoloration

2. **Change Control process**

   Explain the company's manufacturing Change Control procedures, the reasons for the procedures and the importance of following the procedures.

3. **Process Monitoring equipment**

   Describe the monitors used by the company, their purpose and operation, the importance of following the operating procedures and what to do when a process monitor shuts down the Manufacturing Method.

Training records should be kept that demonstrate the people have the necessary skills to perform the work. Rotor manufacturing operations should not be performed by untrained personnel or if the required training is not current. Company procedures for documenting, reporting, and dispositioning Special Cause Events and product non-conformance should be known and practiced.

Training for the soft elements should focus primarily on management and supervision to ensure there is a clear understanding of how soft elements influence Critical Rotating Part reliability. Encouraging people to raise questions and concerns and creating an environment where people are comfortable highlighting events that may appear to have little impact should be addressed. The people directly involved in the Manufacturing Process should also be trained to understand the function and sensitivity of the parts they make and the impact of a Special Cause Event and the consequence of a Critical Rotating Part failure.

9 Non-Destructive Evaluation (NDE)

9.1 NDE Method Selection– Key Factors to be Considered

9.1.1 Purpose of the Inspection

The purpose of the inspection should be defined prior to selecting the inspection method. There are fundamentally two ways NDE Methods can be used: a) as a qualitative tool to evaluate control of the Manufacturing Process or b) as a quantitative inspection method which takes flaw sizing capability into account. Quantitative is being used here to describe the statistical capability of a method to Detect Anomalies, although it can also be defined as a specific numerical reading taken during the inspection process, such as amplitude shown on an NDE instrument. However, before the NDE Method can be considered quantitative, it must be proven that the reading has a quantitative correlation to the indicated Anomaly of specified type. Additional details on this subject are presented in Section 13.1, Appendix C: Criteria for Selection of NDE Method.

9.1.2 Potential NDE Methods

This section will limit the discussion to consideration of the following NDE Methods that are commonly used throughout the Aircraft Engine Industry for the Detection of surface and near-surface Anomalies:

- Etch (aided and unaided)
- Visual (aided and unaided)
- Fluorescent Penetrant Inspection (FPI) and Magnetic Particle Inspection (MPI) (aided and unaided)
- Eddy Current (EC) (manual, semi-automated, and automated)

For the purposes of these discussions, etch and visual inspections refer to optical evaluations conducted in normal (white) light. Aided etch and visual and aided FPI/MPI refer to the use of enhancements such as surface preparation or visual aids such as magnification devices, mirrors or borescopes. Manual EC relies on hand-controlled scanning of the probe, and observation of Indications as deflections of a cathode-ray beam. Semi-automated EC refers to equipment, which has some automated probe scanning capability, but requires increased inspector attention to initiate and complete the inspection. Indications are likely to be read from a strip-chart recording or a cathode ray tube. Automated EC refers to equipment having extensive computer software capabilities to control key inspection functions such as the placement of the probe on the desired location on the part, initiation of the inspection, and acquisition, display, and storage of data with minimal inspector attention. Additional details on these NDE Methods are presented in Section 13.2, Appendix D: NDE Method Descriptions.

One inspection process, which is commonly used in many industries, has been intentionally left off the list of potential methods. Visible dye penetrants, such as red or black dye, should not be used to inspect Critical Rotating Parts under any circumstances.

9.1.3 Determination of Inspection Accept/Reject Criteria

The PVF should determine the accept/reject criteria for NDE. The objective should be to define criteria, which support the Design Intent of the part, that are consistent with part geometry limitations and material properties and can be achieved with reasonable assurance by the selected NDE Method.

9.1.4 Choosing the Appropriate NDE Method

Selection of the most appropriate inspection process involves consideration of many different technical and economic factors. This is often done using past experience as a guide. However, new component designs, processes and/or materials may require a reconsideration of current methods and perhaps application of improved NDE technology to meet the Design Intent. For example, new high-speed machining processes should be evaluated to ensure the Surface Condition produced is compatible with the proposed NDE Method, e.g., the surface is not smeared when FPI is to be used.

One of the most important steps in the definition of a NDE Method is the exchange of information between design and NDE engineers. In order to identify the most appropriate inspection method and associated processing parameters, the design engineer should understand the capabilities and limitations of the candidate NDE Methods and how these characteristics relate to the part design. The NDE engineer should understand how the design engineer intends to use the results of the inspection, what types and sizes of Anomalies are most critical to Detect, and if any features of the part require particular attention.

Additional factors to be considered when selecting a NDE Method are part geometry, Anomaly orientation and shape, effects of Human Factors, and data acquisition and storage capabilities. Further discussion of these factors is contained in NDE Section 13.3, Appendix E: Guidelines for the Qualification and Validation of NDE Techniques and Systems.

9.1.5 Determination of NDE Reliability

All NDE Methods are statistical in nature, and their ability to Detect Anomalies must be understood on a probabilistic basis. There are no certainties in NDE, only probabilities. In addition to the probability of Detecting an existing Anomaly, the probability of generating Indications where there are no Anomalies (i.e., False Indications) and the probability of not Detecting an existing Anomaly (i.e., a miss) must be considered to evaluate NDE reliability.

The reliability of a NDE Method can be expressed as a quantitative statistical measure of the ability of a NDE Technique under given circumstances to Detect Anomalies of specific characteristics (e.g., size, shape and/or magnitude) in a defined part. Reliability, which attempts to quantify the total variability of a NDE Method, is dependent on a number of issues, including the physical principles upon which the NDE Technique is based (theoretical Detection limit), capability of the specific equipment used, and the influence of Human Factors to name only a few. Only when a quantitative figure of reliability has been established, which can be expressed as a Probability of Detection (POD) curve or a Relative-Operating Characteristic (ROC) curve, is it possible to measure the effect of any improvements/changes that may be introduced to the NDE Method. Additional discussion of NDE reliability and quantification of NDE Detection capability is presented in Section 13.4, Appendix F: General NDE Guidelines.

9.2 Improving NDE Detection Capability

In general, there are three primary approaches to improving the capability of NDE Methods to Detect Anomalies:

1) Introduce automation to reduce the influence of Human Factors.
2) Develop a positive culture among the NDE operators and inspectors which encourages and rewards the reporting of Indications rather than considering this behavior to be counterproductive. This is especially true in situations where it is not possible to introduce automation.
3) Improve existing NDE Methods and tools as well as develop new, advanced NDE Techniques. There is substantial potential to improve the ability to Detect Anomalies produced during or after the Manufacturing Process.

9.3 Specific NDE Capabilities and Recommendations for Holes in Critical Rotating Parts

Two tables comparing the capabilities and characteristics of NDE Methods for inspection of holes in Critical Rotating Parts have been prepared. These tables reflect an Industry consensus of NDE experts and should be used by the Process Validation Function (PVF) to evaluate and select NDE Methods for inspection of holes in rotating part applications.

For the preparation of these tables, Anomaly types have been divided into three general categories: 1) cracks (which includes all material Discontinuities that are open to the surface); 2) Geometric; and 3) Non-Geometric. Geometric Anomalies have finite physical dimensions, are surface connected, and are non-metallurgical in nature. Examples of Geometric Anomalies are nicks, dents, scratches, and burrs. Non-Geometric Anomalies do not have sharply defined boundaries and are typically associated with the material structure or processing. Examples of Non-Geometric Anomalies are inclusions, overheated surface layers, microstructural Segregation, detrimental residual stresses, and smeared surface layers. A special type of Non-Geometric Anomaly are embedded inclusions from broken tool tips which have sharply defined boundaries that may not be open to the surface.

9.3.1 Relative Capabilities of NDE Methods for Low L/D Holes

Relative capabilities of NDE Methods for Low L/D Holes are summarized in Table 9.1. The ratings in this Table do not necessarily apply to other easily accessed surfaces such as planar surfaces or other surfaces where the visual line-of-sight is <45 degrees from the perpendicular to the surface (see Appendix C).

Table 9.1: Relative Capabilities of NDE Methods Considered for Inspection of Low L/D Holes

	NDE Method					
FACTORS	Etch	Visual	FPI/MPI	Manual EC[2]	Semi-automated EC[2]	Automated EC[2]
Anomaly Detection						
Cracks	3	4	3	2	1	1
Geometric Anomalies	4	4	4	2	1	1
Non-Geometric Anomalies	3 (2[1])	5	5	4[3]	4[3]	4[3]
Operator independence*	5	5	5	4	2	1
Automated process	5	5	4	3	2	1
Capital investment costs**	3	1	3	3	4	4
Throughput capability*	1	1	2	2	1	1
Data capture capability*	5	5	5	5	2	1
Ease of quantification*	5	5	5	2	1	1

KEY: 1=excellent capability, 2= good capability, 3= fair capability, 4= poor capability, 5= little or no capability
For * factors:
1=very high, 2= high, 3= average, 4= low, 5= very low
For ** factor:
1=very low, 2= low, 3= average, 4= high, 5= very high

[1] Titanium
[2] All Eddy Current inspections on holes are assumed to be conducted with high speed rotating probes.
[3] Eddy current is generally ineffective for detecting most Non-Geometric Anomalies, but it is very effective at detecting certain Non-Geometric Anomalies such as broken tool tip inclusions.

9.3.2 Relative Capabilities of NDE Methods for High L/D Holes

The relative capabilities of NDE Methods for High L/D Holes are summarized in Table 9.2. The ratings in this Table do not necessarily apply to other difficult to access surfaces where the visual line-of-sight is > 45 degrees from the perpendicular to the surface (see Appendix C).

9.3.2.1 Non-Geometric Anomalies

Etch inspection is currently the most effective method for Detecting Non-Geometric Anomalies such as Heat Affected Zones (HAZ), smeared material, Segregation, etc. Blue Etch Anodize is particularly effective on titanium alloys. Eddy current is generally ineffective at Detecting Non-Geometric Anomalies but is very effective at Detecting certain Non-Geometric Anomalies such as broken tool tip inclusions. New eddy current techniques have shown promise for more effective Detection of Non-Geometric Anomalies in titanium, but additional development is needed before they will be ready for production applications.

9.3.2.2 Cracks and Geometric Anomalies

Eddy Current is currently the most effective method for Detecting cracks and Geometric Anomalies such as scratches, nicks, dents, etc.

Table 9.2: Relative Capability of NDE Methods Considered for Inspection of High L/D Holes

	NDE Method								
FACTORS	Etch	Aided Etch	Visual	Aided Visual	FPI/MPI	Aided FPI/MPI	Manual EC[2]	Semi-automated EC[2]	Automated EC[2]
Anomaly Detection									
Cracks	5	3	5	4	5	3	2	1	1
Geometric Anomalies	5	4	5	4	5	4	2	1	1
Non-Geometric Anomalies	5	3 (2[1])	5	5	5	5	4[3]	4[3]	4[3]
Operator independence*	5	5	5	5	5	5	4	2	1
Automated process	5	5	5	5	4	4	3	2	1
Capital investment costs**	3	3	1	2	3	3	3	4	4
Throughput capability*	2	3	1	2	3	3	2	1	1
Data capture capability*	5	5	5	5	5	5	5	2	1
Ease of quantification*	5	5	5	5	5	5	2	1	1

KEY: 1=excellent capability, 2= good capability, 3= fair capability, 4= poor capability, 5= little or no capability

For * factors:
1=very high, 2= high, 3= average, 4= low, 5= very low

For ** factor:
1=very low, 2= low, 3= average, 4= high, 5= very high

[1] Titanium

[2] All Eddy Current inspections are assumed to be conducted using high speed rotating probes.

[3] Eddy current is generally ineffective for detecting most Non-Geometric Anomalies, but it is very effective at detecting certain Non-Geometric Anomalies such as broken tool tip inclusions. Special non-rotating eddy current probes and probe movement might improve capability to detect other Non-Geometric Anomalies - feasibility demonstrated for titanium, but the process is still under development.

9.3.2.3 Limitations of Visual Inspections

NDE Methods relying on optical line of sight, such as etch, visual, FPI, and MPI, are ineffective in situations where part geometry restricts the viewing angle. These methods provide some Detection capability on Low L/D Holes but are not recommended as the only inspection of difficult-to-access features such as High L/D Holes. For applications where these methods are currently being used to inspect difficult-to-access features, one (or more) of the other NDE Methods appearing in Table 9.2 should also be required. Addition of visual aids, such as mirrors or borescopes, would allow the methods relying on optical line-of-sight to be considered for features such as High L/D Holes.

A more detailed discussion of the rationale used to construct these tables, along with a description of the key process characteristics is presented in Section 13.5, Appendix G: Recommendations for Inspection of Holes.

10 Lessons Learned

The term "lessons learned" generally refers to useful pieces of practical wisdom acquired by experience or study. This phrase applied to the Rotor Manufacturing Project is intended to capture the collective experience of the industry's Critical Rotating Part manufacturers and promote the sharing of these experiences in the interest of minimizing service events from post-forging Manufacturing Induced Anomalies.

Based on the individual experiences and collaboration to date of the RoMan team members, the following lessons learned have been identified.

- Holemaking in titanium and in high strength nickel alloys has created rare Machining Induced Anomalies. High L/D Holes appear much more vulnerable than Low L/D Holes.
- Continuous Process Monitoring (power monitoring, Cutting Fluid outage detection, etc.) of hole drilling can prevent Machining Induced Anomalies in holes.
- A Holemaking study in a titanium alloy has yielded the following observations:
    1. Drilling, reaming, and Milling of holes in titanium can, on certain rare occasions, cause Machining Induced Anomalies. The Anomalies arise when there is severe friction between the tool and the workpiece. Severe chip congestion or reductions in the cutting ability of the tool are the scenarios where sufficient heat or smearing can cause Anomalies. If sufficient heat is generated over time the titanium will react with oxygen and nitrogen from the air to form a hard and brittle surface layer. The depth and extent of the Anomalies can vary considerably.
    2. Smearing between the tool and the internal diameter of the hole can leave deposits on the surface of the workpiece that can conceal the Anomaly from subsequent NDE Methods.
    3. Often the rough machining is most critical. Variation in cutting force is one of the parameters that can indicate whether there is excessive friction that can create Anomalies.
- BEA currently remains one of the few NDE Methods available to Detect titanium Non-Geometric Anomalies for the reasons discussed in Section 9. However, in the Holemaking study cited above, the ability of BEA to Detect such Anomalies was found to have the following potential limitations:
    1. Non-Geometric Anomalies that are expected to be blue/dark according to the present BEA standard may appear as light gray, making Interpretation difficult.
    2. Transformed Beta structure may appear as different shades of gray.
    3. Re-cast material structure can appear as a variation in the gray, blue or white color scale.
    4. Iron contamination (from high speed steel tooling) interferes with anodizing. This may also apply to other metallic contaminants.

5. A Non-Geometric Anomaly comprised of a local layer of increased hardness can change appearance, depending on the light source's color, heat and position in relation to the Anomaly.
6. Current BEA standards are not well adapted to the above types of Non-Geometric Anomalies.
7. The configuration of the part has a considerable effect on the readability of a possible Indication. The visual angle to the surface is important. The interior of High L/D Holes can be difficult to inspect.

- It is generally understood that compressive residual stresses on the part surface may improve the tolerance to Manufacturing Induced Anomalies. This can be achieved by controlled surface treatments such as shot peening, burnishing, laser shock peening, ultrasonic peening and cold sleeve working.
- Arc burns arising from electrical contact methods can be more detrimental to part durability than surface Anomalies arising from machining operations. Equipment or process breakdowns can create an arc burn Surface Condition. Examples include:
  - Frayed (or missing) electrical lead or contact insulation
  - Insufficient electrical contact with the part
  - Electrical power energized during contact application to or removal from the part

  An arc burned Surface Condition can quickly generate actively growing cracks.
- Based on a review of axial blade attachment slots, a contributor to Anomalies, cracks or fractures is the combination of the Axial Blade Slot Manufacturing Method (which may create large burrs) and the subsequent edge break process (which may not be capable of consistently removing large burrs).
- The industry has documented instances where damage inflicted on titanium rotating parts from hand work and re-bonded sparks has led to a detrimental Surface Condition. The appropriate combination of finishing controls and protection of surfaces is necessary to prevent finished part surface damage. A more detailed discussion of titanium mechanical finishing best practice is presented in Appendix J of this report.

11 Appendix A: The RoMan Project

- Vision: Minimize Manufacturing Induced Anomalies in Critical Rotating Parts.

- Charter: Establish industry guidelines that improve manufacturing, engineering, and quality practices towards eliminating Manufacturing Induced Anomalies in Critical Rotating Parts. Raw material processes prior to forging are not included.

The following organizations have participated in the 2022 revision of the Reference 1 report:

Organization	Address
The Aerospace Industries Association – Propulsion Sub-Committee	
The Federal Aviation Administration	Burlington, MA
GE Aviation	Cincinnati, OH
Honeywell International	Phoenix, AZ
MTU Aero Engines	Muenchen, Germany
Pratt & Whitney	East Hartford, CT
Pratt & Whitney Canada	Longueuil, Quebec
Rolls-Royce Corporation	Indianapolis, IN
Rolls-Royce plc	Derby, United Kingdom
Safran Aircraft Engines	Evry, France

Preface for Appendices B through O Contained in Sections 12 through 21

Appendices B through O are not formal recommendations but do provide information obtained by the RoMan team and are intended to help individual manufacturers develop best practices for manufacturing Critical Rotating Parts. It should be understood that this information is intended to benefit industry as a whole but does not constitute the only method(s) that may be applied to the respective disciplines described within this report.

12 Appendix B: Process Monitoring for Holemaking

12.1 General Procedure for Process Monitoring

1. Determine which parts require Process Monitoring.
    - Consider all Critical Rotating Parts and critical features.
    - Understand the effects of surface Machining Induced Anomalies for all material/feature combinations
    - Assess the material, feature stress analysis, and difficulty of producing a Machining Induced Anomaly free feature using a method such as PFMEA (or other disciplined method) or surface damage tolerance analysis (e.g., FAA AC 33.70-2, Reference 3).
    - Refer to part classification in Section 5.1.
2. Select a Process Monitoring system taking the following into consideration:
    - Real-time monitoring capability
    - Connection to a NC controller with the ability to automatically intervene in the process (e.g., withdraw the cutting tool)
    - Ability to prevent Machining Induced Anomalies
    - Ability to detect Special Cause Events that can result in Machining Induced Anomalies
    - Ability to store output data when a Machining Induced Anomaly occurs
    - Machine operator user friendliness
    - Refer to Process Monitoring best practice for Holemaking in Section 12.2.
3. The following Process Monitoring systems are currently in use for Holemaking:
    - Power, Torque or Force
    - Vibration
    - Cutting Fluid Flow
    - Cutting Fluid Pressure
    - Spindle Speed
    - Feedrate
4. Process monitors need to be under calibration control.
5. Process Monitoring requires initial and periodic training of the machine operators, shop supervisors, quality personnel, process engineers and shop management
6. Each OEM should correlate process monitor output signals to surface damage thresholds for each material/process combination or set conservative limits based on empirical data.

7. There should be a system for evaluating and dispositioning the work piece when a monitor output indicates a Special Cause Event has occurred. Reference Section 6.2, Material Review.

12.2 Determining Monitor Limits – Best Practice

12.2.1 Setting Monitoring Limits

Power monitor limits are determined by monitoring the power for a series of work-piece features produced by a controlled nominal process. For Process Validation, a minimum of three tools that are randomly acquired from the source that will be supplying production tools are utilized. If reconditioning is permitted, a reconditioned tool should be included. These tools are then run to approximately 25% beyond the Tool Change Point. The response is monitored for each machined feature to evaluate consistency between the three tools. Figure 12.1 shows a typical consistent power monitor response for three tools.

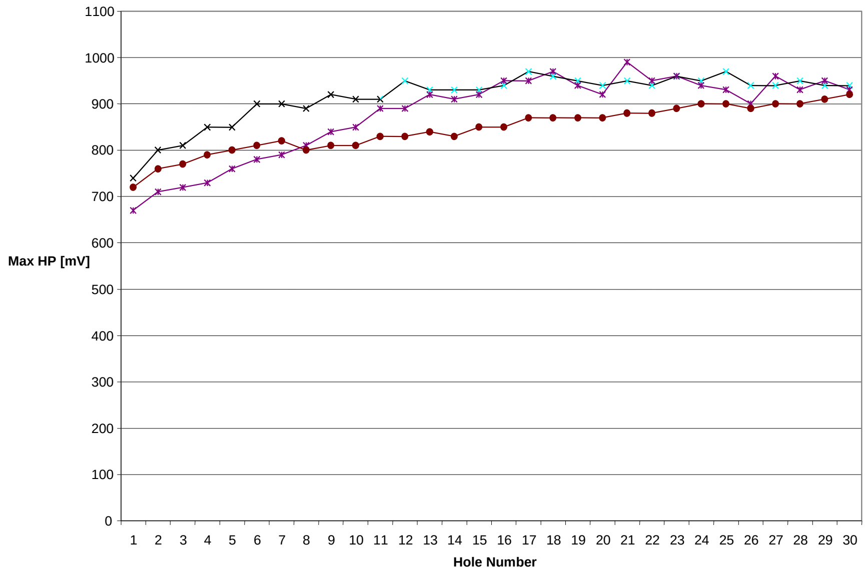


Figure 12.1: Consistent Power Response for Three Tools

Figure 12.2 shows an inconsistency between three tools. The high-power tool had poor geometry, which caused more tool rubbing.

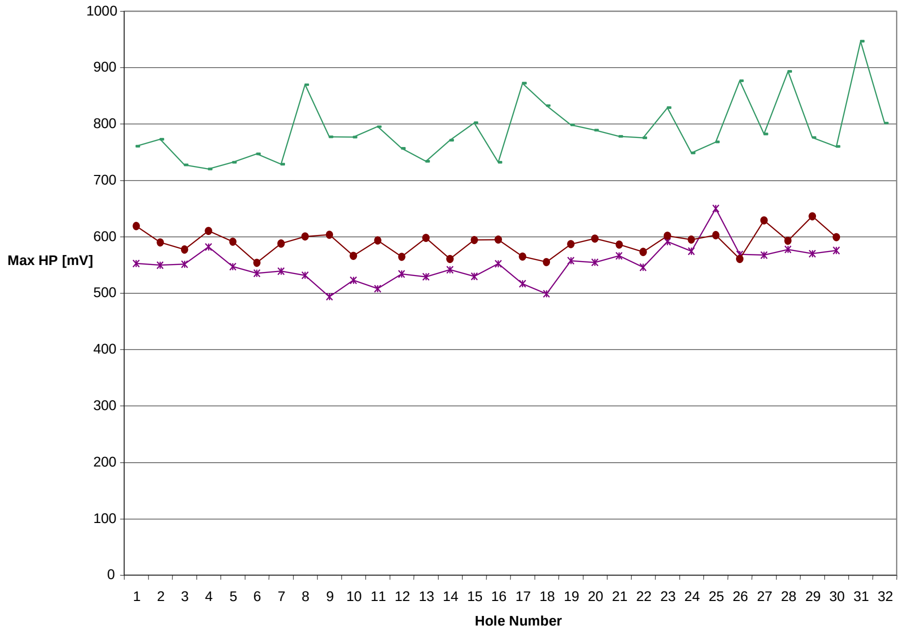


Figure 12.2: Inconsistent Power Response for Three Tools

If a bad tool is detected during validation, the cause is documented, and another tool is used in its place. When three consistent runs are achieved, the highest power, force, or torque reading within the Tool Change Point window is used to set what is known as the Tool Change Point limit.

Two working limits are typically established based on the Tool Change Point limit. The first limit is cautionary (often called a "yellow limit") and used to warn of impending problems. The yellow limit is set such that continuing the current cut to its conclusion (e.g., finishing a hole, Broached slot, or Turned feature) will not compromise the Surface Condition of the workpiece. The second limit is a reactionary limit ("red limit") which should cause immediate intervention in the process. The red limit is also typically set to prevent compromise of the Surface Condition, as long as appropriate intervention is accomplished immediately.

An example of how these two limits might be established is presented in Figure 12.3. In this example, 100 mV output of a power monitor above the Tool Change Point power has been pre-established as a robust criterion for a yellow limit. 300 mV above the Tool Change Point power was established as a robust red limit. Limits may also be established in terms of force units, torque units, direct power, or as a percentage of the nominal signal, depending on the type of monitor employed.

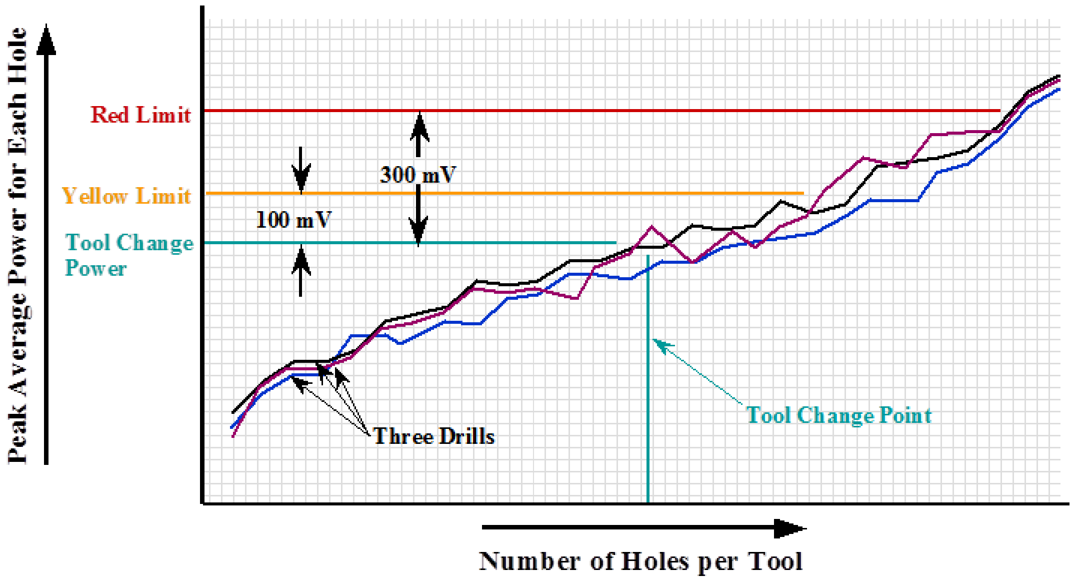


Figure 12.3: Establishing Yellow and Red Limits for Power Monitoring

12.2.2 Transferring Monitor Limits Between Different Machines

Each machine has unique characteristics, even among the same machine make and model (particularly after maintenance). For this reason, monitor limits should be uniquely determined for each machine and generally not transferred from one machine to another. In some cases, it is possible to transform limits from one machine for use on a second by comparing the properties of the machines (e.g., by comparing the spindle power curves of the machines to create a correlation factor for the limits).

12.2.3 Applying Power Monitors to Small Holes Machined on High Spindle Power Machines

The size of the machine spindle or motor vs. the diameter of the hole and amount of metal removal can cause Power Monitoring methods to be ineffective. For example, experience has shown that when cutting nickel, if the spindle motor is greater than 22 KW (30 horsepower) and the hole diameter is less than 7.6 mm (0.300 inches) and the machine has a large gear box, the effectiveness of the power monitor is greatly diminished. This is because the power needed to remove the material from small diameter holes is a small percentage of the power required to drive just the gear box. For titanium and steel parts, these limits will be even more restrictive.

12.3 Process Monitoring Questions and Answers

12.3.1 Machine Operator Training

- What machine operator intervention is allowed (or not) when using a "monitor"?

  None. The process is fixed per an approved Manufacturing Control Plan (MCP) including speed, feed, and tool selection. Only when an alarm is active is the machine operator allowed any control of the monitoring system.

- Do the operation sheets specify when to change the cutting tool?

  Yes. The manufacturing plan specifies Tool Change Points based on wear data and tool testing.

- What if the tool has been qualified to cut more than one part?

  A tracking system is required. Ideally the tracking would be automated through the machine control, but paper logs are sometimes used. In some cases, it is better to replace the tools after each part rather than rely on manual tracking.

- Can a monitor be relied on to flag when the tool needs changing?

  The monitor is in place to detect Special Cause Events. Although it will catch an overly worn tool eventually, depending on the monitor to detect when the tool should be changed is not recommended.

- How much training is required for the machine operator to understand the data?

  The machine operator is not required to understand the Process Monitoring data. The machine operator only needs to know what to do in the case of an alarm fault. This should be explained in the operation sheets.

- What kind of machine operator training is needed for monitored Holemaking operations?

  The following are some key machine operator responsibilities that should be included in the machine operator training:

  - *Machine monitoring equipment*
    - *The monitor is for Special Cause Events and is implemented so the machine operator needs to observe what is happening in the workspace and the monitoring system does the remainder.*
    - *Spindle-train maintenance requires re-setup and calibration of power monitor instrumentation.*
  - *Yellow limits*
    - *Finish the hole and then stop the operation*
    - *Change the tool*
    - *Notify the supervisor and document the event*

- *Red limits*
  - *The tool is immediately retracted by the machine*
  - *Mark the hole*
  - *Notify the supervisor*
  - *Document the event*
- *Know and practice local procedures for documenting, reporting, and dispositioning Special Cause Events and product non-conformances. MPC*

12.3.2 Process Monitoring System Requirements

- What monitoring techniques are available, and what are recommended?

Power Monitor	*recommended*
Force (Thrust)	*only recommended for drilling*
Acoustic	*good potential - technology development needed*
Thermal	*good potential - technology development needed*
Vibration	*recent commercially available systems show improved capability*

In addition to the above, one or more of the following monitoring devices are recommended:

Cutting Fluid flow

Cutting Fluid pressure

Spindle speed

Feedrate

- What attributes should be considered when:

1. Buying Process Monitoring equipment?
   - Ease of installation on the target machine
   - Machine operator friendliness
   - Robustness of sensors
   - Turnkey installation
   - Ability to interface to machine controller and numerical control (NC) program
   - Ability to output data for storage
2. Installing Process Monitoring equipment?

   Choose the machine so the spindle is not too large for the holes being drilled (Reference section 12.2.3)

Loss of production time to install monitoring system

Set up the power sensor full-scale capacity for the Holemaking process not the maximum spindle HP.

When possible, purchase power monitoring systems as an integrated package during new machine procurement.

3. Establishing Process Monitoring limits?

Simulate the actual process as closely as possible when performing the tests to establish the monitor limits.

- Is the power monitor connected to the controller to actively manage the speeds & feeds for the cutting process?

Power monitors are not intended for adaptive machining. Speeds and feeds should be fixed within validated parameter limits.

- What are the minimum controller requirements for existing equipment?

The controller should have a method for locking out the feed and speed overrides when the hole is being machined.

An external input to automatically stop the feed of the machine when a power alarm is activated is required.

The capability to automatically retract the tool through a remote input is desirable.

The capability to automatically stop the machine through a remote input is preferable.

- Where is the power monitor coupling to the machine located - i.e., spindle, spindle drive motor, spindle motor coupling, etc.?

The power-measuring cell is located in the power cabinet near the spindle drive. Wires going to the spindle motor from the drive are passed through the power cell and drive output voltage is also connected to the cell. Thus Power = Current times Voltage. See Figure 12.4.

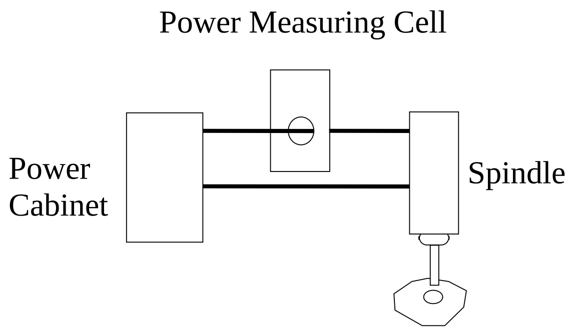


Figure 12.4: The Power Monitor Concept

12.3.3 Calibration

- Do all Process Monitoring systems require calibration?

  Yes

- What parameters are calibrated?

  This depends on the Process Monitoring system(s) in use. For example, typical Process Monitoring systems would require the following: Cutting Fluid flow, Cutting Fluid pressure, power, and rotational speed

- What is done to calibrate the power monitoring system?

  A controllable brake is mounted to the machine tool spindle in order to simulate the cutting process. A range of torques is applied to the spindle over a range of spindle speeds and the sensor and monitor outputs are evaluated against acceptance criteria (typically year-over-year consistency)

- How is calibration performed for the other monitors?

  Calibrations should be made to an established baseline. For example:

  Cutting Fluid Flow:

  A reference flow transducer is connected in series with the machine Cutting Fluid flow transducer into the Cutting Fluid feed line.

  Cutting Fluid Pressure:

  A reference pressure transducer is connected to the Cutting Fluid feed line.

  Rotational speed:

  A tachometer (e.g., infrared based) is held towards the spindle. Its output is compared to the output from the monitor as well as the output from the machine tool.

- How often is the power monitoring system calibrated?

  The frequency is set through internal tool and gage calibration procedures but should be a minimum of once per year or when any spindle maintenance is performed, either mechanical or electrical.

- What is the expected downtime associated with monitors?

  Less than 2% downtime is associated with the monitor system itself. However, Process Monitors may identify incipient spindle, drive, and Cutting Fluid flow problems, allowing proactive maintenance that can reduce machine downtime

- What are some warning signs that would indicate re-calibration is required?

  Process drift, spurious results, unexpected actions from the monitor

- Who does the calibration?

Parties independent from the machining cell usually should do calibration. Internal departments such as calibration, instrumentation, or preventative maintenance can do the calibration, or external companies can be hired

- Are there calibration standards?

  According to ISO requirements, and in addition a specification / instruction for every individual machine tool. Standards can be tied to the National Bureau of Standards or to internal procedures

- What happens if the equipment is out of calibration? Any effect on parts that recently went through that machining cell?

  Investigations according to established quality procedures should be performed. Parts machined with out-of-calibration equipment need to be evaluated

- How does a machine operator know the system is operating properly?

  Systems may include self-diagnostics, but as a minimum typically include indicators and read-outs that the operator can observe for typical behavior

12.3.4 Process Control / Certification

- Should the Manufacturing Processes be optimized for cutter life or microstructure condition or a combination of both?

  The first priority of Process Monitoring should be to establish adequate margin to protect the workpiece microstructure.

- Is there any meaningful power monitoring data produced for Low L/D Holes?

  Yes, power monitors are effective on holes with L/D < 1.0. However, some manufacturers have found that the Holemaking processes for holes with a L/D < 1.0 are very robust and power monitoring is not always applied

- Is power monitoring effective for all Holemaking processes?

  Some processes have such low material removal rates that energy-based Process Monitoring (power, force, torque) does not have sufficient sensitivity. Many Single Point Boring and some finish Milling operations are examples. While low energy processes are unlikely to cause Machining Induced Anomalies, criteria should be established based on Surface Condition as to when to implement or exempt process monitoring.

- Does a change to tool geometry or cutting fluid require new alarm limits to be established?

  Yes. It may also be necessary to establish new Tool Change Points

- Are there approved "work-arounds" during monitor down times?

  If the monitor is required, then there is no workaround except to change to another monitored machine

- If Process Monitoring involves a green/yellow/red limit scheme how are the limits established?

The limits are set based on an edge-of-envelope nominal process (usually a worn tool wear at the Tool Change Point) as described in Section 12.2.1

- How is a new process qualified with monitoring?

  Either by performing a process study (see Section 12.2.1) or from the laboratory database on the machine correlation curves

- Can Process Monitoring be relied on to identify tool problems?

  Power monitors should not be used as the only method to Detect tool problems.

  Tool control is important and should be included in the Holemaking procedure. Inspection of critical tool geometry features is required. Reground tools should be checked 100%. Tool geometry features are most consistent when NC ground. The monitor system may alarm on tooling problems

- Should visual review / understanding of tool cutting surfaces be included in a monitoring plan?

  Yes. Machine operators should compare tool geometry and condition before/after loading/unloading tools in the spindle or tool changer

12.3.5 Data Collection

- How is the data recorded for historical records?
  - *Special Cause Event data must be retained for the life of the part.*
  - *Historical records can be very useful in solving tool problems, process problems, etc. Some manufacturers retain the hole number, the alarm code, and the peak power for each hole.*

- How are process monitor alarms handled?
  - *Some manufacturers allow holes with red limits to be salvaged by removing additional material using a (monitored) rework process. This is possible only when the design can tolerate oversized holes*
  - *Holes that cannot be oversized are evaluated on Material Review. The process monitor data may be useful in evaluating the part for disposition, especially where data exist that correlate process monitor output to Surface Condition for the material and process*

- Is there a time delay between getting a power monitor reading & machine response?

  To minimize spurious alarms by filtering short duration signal spikes, a slight delay is utilized before an alarm is generated, typically 0.5 – 1.0 seconds for Holemaking operations. That is, the power signal should stay above the alarm limit continuously for the pre-defined delay period before an alarm is generated

12.3.6 Other Issues

- How are set-up changes handled?

  Through part programs. They contain all the limit and process information for the new part and material. These limits are then downloaded into the monitoring system.

Therefore, it is important to have the capability for the part program to interface with the monitor. The part programmer is responsible for setting up the monitoring system and the machine operator role is the same regardless of part, material limits, etc.

- Is the data material alloy specific?

  Yes

- Are the same monitoring techniques effective for Steel, Ti and Ni and other high temperature alloys?

  Yes

- Can a peck drilling cycle be monitored?

  Yes, in the same way as any other process

- What is "tare" power or torque?

  "Tare" refers to the power or torque consumed to run the machine at a given speed with no cutting load applied. This tare is typically subtracted from the monitor output to report (and alarm) on only cutting power or torque. Most machine power and torque curves are not linear, so systems typically reset the tare automatically at the beginning of each machining operation.

13 Appendices C, D, E, F and G for Non-Destructive Evaluation

13.1 Appendix C: Criteria for Selection of NDE Method

Selection of the most appropriate inspection method involves consideration of many different technical and economic factors. This is often done using past experience as a guide. However, new designs and new materials may require a re-consideration of old methods and perhaps application of improved technology to meet engineering and manufacturing needs. For example, new high-speed machining processes should be carefully evaluated to ensure that the Surface Condition produced is compatible with the proposed NDE Method (e.g., the surface should not be smeared when FPI is to be used). The following discussion attempts to provide some guidance for selection of the most appropriate NDE Method for Detection of surface or near-surface Anomalies.

13.1.1 Purpose of the Inspection

The purpose of the inspection should be defined prior to selecting the inspection method. There are fundamentally two ways NDE Methods can be used: a) as a qualitative tool to evaluate control of the Manufacturing Process or b) as a quantitative inspection method that defines Anomaly Detection capability as a function of Anomaly dimension. Quantitative is being used here to describe the statistical capability of a method to Detect Anomalies, usually referred to as Probability of Detection (POD), although it can also be defined as a specific numerical reading taken during the inspection process, such as an amplitude shown on an NDE instrument. However, before the NDE Method can be considered quantitative, it must be proven that the reading has a quantitative correlation to the indicated Anomaly of specified type.

a) Qualitative NDE Methods – NDE Methods are most commonly used as a monitor of Manufacturing Process control. They are widely used to evaluate and reject parts with Indications larger than a predetermined size or amplitude, or that occur with excessively high frequency. Another example of a qualitative application is establishing trends in the number of rejectable Indications found over a period of time to determine if a Manufacturing Process is providing the expected level of part consistency. For these types of applications, the NDE process parameters should be carefully controlled and, where possible, sensitivity validated by use of reference standards. The goal of such controls is to standardize the inspection so that it will have constant effectiveness. For these applications, the NDE Methods are customarily used without attempting to establish their POD.

b) Quantitative NDE Methods – Although it is not a trivial task, it is sometimes possible to empirically determine the capability of an NDE Method to Detect Anomalies. To be meaningful, the NDE Method should be carefully controlled, just as for a qualitative application. Additionally, the appropriate capability data must be generated and statistically evaluated. Since NDE Methods are influenced by factors too numerous to allow deterministic statements, the capability for the Detection of Anomalies is expressed in probabilistic terms (POD). POD data are strictly valid only for the specific inspection parameters for which they were determined – e.g., they are not applicable to a different penetrant, a different probe, a different scan index, a different material, a different Anomaly type, etc.

13.1.2 Geometric Considerations

Hardware configuration/shape plays an important role in determining the effectiveness of an inspection process. Limitations on etch, visual and FPI/MPI inspections seem obvious – one cannot inspect what one cannot see. However, it is somewhat more complicated than that simple statement. Common sense suggests that the capability of a visual inspection should decrease as the line of sight angle increases from perpendicular to the inspection surface to parallel to the surface. The consensus among the RoMan NDE team is that there is a noticeable decrease in the capability of etch and FPI/MPI inspections to Detect Anomalies once the line of sight angle exceeds about 45 degrees from perpendicular. This is illustrated in Figure 13.1.

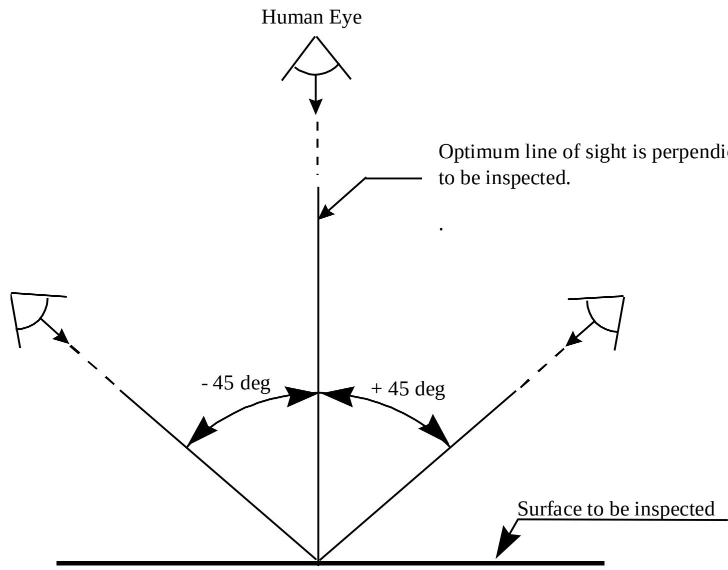


Figure 13.1: Line-of-Sight Range for Acceptable Detection Capability

Therefore, it is recommended that etch, visual or FPI/MPI inspection of cavities, holes, or other hardware features whose dimensions limit the line of sight to an angle greater than about 45 degrees off perpendicular should be avoided unless visual aids are employed to enhance the capability of Detection. As discussed in Section 13.2.4, the shape and configuration of a part can affect etch, visual, or FPI/MPI pre-processing by restricting the application of white light (visual), or the application/removal of etching agents (etch) or penetrant/emulsifier materials (FPI/MPI).

Feature geometry can also hinder the application of eddy current inspection. Complex shaped holes, very small cavities, and features with abrupt edges all present problems. In some cases, innovative probe design or the use of signal-processing techniques to reduce edge effects may provide some relief, but in many cases alternate inspection processes or more inspection friendly designs may offer the best solution.

13.1.3 Cost/Productivity Considerations

Inspection cost and productivity are important factors which should be considered before selecting an appropriate NDE Method. A common strategy is to identify all NDE Methods that are capable of supporting the Engineering Requirements of the part, then select the most productive and cost-effective process from those candidates. However, productivity and cost of the process can be influenced by a number of factors. Technical requirements, including the accept/reject limit (or, in the case of quantified inspection, the size of Anomaly and the POD and confidence level of detecting it), can have substantial effects on inspection productivity. The inspection procedure and equipment utilized are also important factors in determining cost and time of inspection. This is the reason why it is important for an NDE-specialist to be involved in early steps of the part design.

13.1.4 Data Acquisition and Storage Considerations

Data acquisition and storage techniques have a substantial effect on the long-term utility of NDE inspection results. Inspection data on Critical Rotating Parts are typically stored for very long periods of time and may need to be recalled for re-evaluation of results or conclusions. The capability to acquire and store data is typically dependent on the NDE process selected.

Generally, etch, visual and FPI/MPI data are acquired and recorded by the inspectors. The Indication information usually consists only of Indication size and general location on the part. An electronic archive of the Indication characteristics is preferred. The archive should include a permanent image (photograph or digital image) of the Indication for future recall and re-evaluation.

Eddy Current (EC) data from advanced systems is usually digital and is recorded on tape or disks for storage. The data can be recalled and re-evaluated as long as a compatible hardware and software system is available. The rapid changes in electronic developments make this a challenge when data is stored for extended periods. Data from less advanced (or simpler) EC units may be acquired digitally, on strip charts, or manually on paper, depending on the equipment. The digital units usually record data on tape or disks. Units with strip chart capability have more limited storage potential and provide less information than the digital units, but do not require compatible hardware and software for reading. The units requiring manual written data provide records which have the same constraints as the etch, visual and FPI/MPI recording and storage processes.

13.2 Appendix D: NDE Method Descriptions

13.2.1 Potential NDE Methods

This section of the report provides an overview of the NDE Methods commonly used throughout the Aircraft Engine Industry and considered to be the most suitable for inspection of Critical Rotating Parts for the Detection of surface and near-surface Anomalies. The methods are:

- Visual (unaided / aided)
- Etch (unaided / aided)
- Fluorescent Penetrant Inspection (FPI) and Magnetic Particle Inspection (MPI) (unaided / aided)
- Eddy Current (EC) manual, semi-automated and automated

One inspection method, which is commonly used in many industries has been intentionally left off the list of potential methods. Visible dye penetrants, such as red or black dye, must not be used to inspect Critical Rotating Parts under any circumstances. These products are considered incapable of Detecting Anomalies of the type and size of interest. In addition, use of visible dyes prior to application of the FPI process can reduce the effectiveness of FPI by preventing the penetrant materials from reaching surface connected Anomalies.

13.2.2 Pre-Inspection Processing Requirements

Pre-inspection processing requirements should be defined by NDE specifications and refer to the preparation for and application of any inspection materials to the hardware prior to examination.

For example, all hardware considered for FPI inspection should be evaluated to ensure that the part shape will allow the penetrant to be applied and emulsified/removed within specification limits. For instance, deep cavities or blind holes may limit application and removal to the point where processing for those features does not meet specification requirements. For the regions of a part that are not sufficiently covered by a proper FPI process it should be decided if a supplemental inspection method is required. The effectiveness of an etching process on the subsequent inspection can also be affected by the configuration / shape of the part.

13.2.3 Inspection Requirements

13.2.3.1 Surface Condition

Hardware Surface Condition can have a substantial impact on the effectiveness of a NDE Method. In general, the effectiveness of all the surface inspection methods decreases as the level of surface roughness increases. Etch, visual and FPI/MPI inspections typically require surfaces prepared to a 3.2 μ meter R_a (125 RMS) finish or better, while eddy current requirements range from 1.6 μ meter R_a to 3.2 μ meter R_a (63 RMS to 125 RMS) (or even smoother) depending on the inspection sensitivity requirements. Surfaces should always be clean and dry and free from potential contaminants such as oil, paint, corrosion products, scale, chemical residues, grease, etc. and have no smeared metal on the surface before commencing inspection.

13.2.3.2 Inspection Aids

Among the most used inspection aids are mirrors and borescopes designed to alleviate the line-of-sight problem. These aids are used to augment visual, etch or FPI/MPI inspections, although their application is by no means consistent throughout the aerospace industry. The use of such aids should be controlled by the NDE Method specification but in general the utilization is left to the discretion of the supervising Level III inspector.   If not controlled, then the utilization of inspection aids can vary widely from inspection to inspection.

Care should be taken when attempting to illuminate the inner diameter surface of a hole using conventional fixed or handheld lights. Conventional lighting tends to illuminate the areas immediately adjacent to the hole being inspected. In this case the inside of the hole can appear to be in a “shadow” and the capability of the inspection is diminished. An aid for etch/visual and FPI/MPI inspections that can enhance the Detection capability is a small diameter (≤ .400 inch / 10mm) light guide attached to high intensity light sources. Both UV and white light, as applicable, are used to illuminate the inner surface of a hole. By holding the light guide just inside the edge of the hole, the inner surfaces are illuminated and much more easily inspected. Holes should be inspected from both sides when possible. Clearly, the success of this method is dependent on the Human Factors as described in Section 8.2.

13.2.4 Method Descriptions

13.2.4.1 Visual Inspection

Although not considered to be a “traditional” Non-Destructive method, visual inspection methods are commonly used throughout the aerospace industry. Visual inspection provides a means of examining the surface of a part for Anomalies such as scratches, nicks, burrs, contamination, etc. and is carried out under white light. Even when common NDE Methods are employed, visual inspection can provide a useful supplement. The application of visual inspection may involve the use of a wide variety of equipment, ranging from examination with the naked eye; use of aids such as mirrors, magnifying devices, enhanced lighting, flexible / rigid borescopes; to interference microscopes for scratch depth measurement. Given proper inspection conditions (lighting, aids, etc.) visual methods can be effective as a part inspection check.

13.2.4.1.1 Advantages:

- *Can find surface Anomalies/mechanical damage* – somewhat effective for finding Geometric Anomalies such as nicks, scratches, dents, and other Surface Conditions that are too shallow to be Detected during fluorescent penetrant inspection yet are non-conforming to assigned visual standards.
- *Accessible surfaces can be inspected in a single operation.*
- *Part size is not a concern* – Processing systems can be designed for virtually any size part.
- *Inexpensive* – usually requires a minimum amount of equipment/material compared to other NDE methods and can be used to inspect a wide variety of parts. However, addition of some aids, such as borescopes, can increase inspection costs.

13.2.4.1.2 Disadvantages / Limitations:

- *Highly inspector dependent* – Visual inspection can be a monotonous and a laborious task especially when inspecting large surface areas or difficult to access features. This can lead to substantial variations in inspection results due to Human Factor issues as discussed in Section 8.2.
- *Line-of-sight limited* - Part geometry can severely limit, or negate, the effectiveness of the inspection by making certain areas difficult to view. These difficulties can be overcome to a certain degree by utilization of a visual aid.
- *Generally ineffective for Detecting cracks or Non-Geometric Anomalies* - Visual inspection is not capable of Detecting material structural changes and is not sensitive enough to Detect most cracks, especially small and/or tight cracks.
- *Inspectors typically not certified* - Inspectors are generally not controlled by certification / approval such as with other common NDE Methods. As such, interpretation of standards may not be consistent between inspectors.
- *Recording and retention of inspector observations can be poor* - Data generally consists of qualitative observations by the inspector that are not necessarily retained, except to document that a part was accepted or rejected. If observations are retained, they are usually on paper with a limited shelf life and, as a result, can be difficult to reconstruct for evaluation later. However, the increasing availability of digital camera technology can help to alleviate this difficulty.

13.2.4.2 Etch Inspection

The Etch inspection method involves the controlled, preferential chemical or electrolytic attack of the part by an appropriate agent. After etch processing the surface of the part is visually examined under white light to Detect surface Anomalies. Aids such as those described for use with visual inspection can be used. The various methods commonly used in the aerospace industry are Anodic Etch (nickel-based alloys), Blue Etch Anodize (titanium alloys) and chemical / grain size etch (all alloys).

13.2.4.2.1 Advantages:

- *Can Detect surface microstructure Anomalies* – Currently the most used and accepted method for the evaluation of grain size and Detecting Non-Geometric Anomalies such as Segregation and inclusions. Surface overheating (e.g., white layer, etc.) in titanium can also be Detected using Blue Etch Anodize.
- *Accessible surfaces can be inspected in a single operation.*
- *Part size is not a concern* – Processing systems can be designed for virtually any size part.
- *Provides an excellent surface preparation for Fluorescent Penetrant Inspection* - Has the capability to “open up” existing surface Anomalies such as cracks by removing any smeared material left by machining.

13.2.4.2.2 Disadvantages / Limitations:

- *BEA is prone to False Indications as a result of non-metallurgical discontinuities such as tool marks, scratches, etc.* This effect can be minimized by proper part handling, and when necessary, special surface preparation such as wet blasting or Sutton barrel finishing prior to the etch process.
- *Highly inspector dependent* - A high degree of concentration is required to perform etch inspection and Human Factors are a major cause of inspection variation.
- *Line-of-sight limited* - As with visual inspection, part geometry can severely limit, or negate, the effectiveness of the inspection by making certain areas difficult to view. These difficulties can be overcome to a certain degree by utilization of a visual aid.
- *Close control of processing parameters and acid solution strength is required* – Improper processing/solutions may result in excessive or inadequate material removal. It is also possible to induce unwanted Surface Conditions such as Inter-Granular Attack (IGA) through improper processing. Additionally, the electrolytic type etches have an inherent risk of arc burning if fixtures/contact points become worn or corroded.
- *Use of hazardous acid solutions can be an environment/safety concern* – Safe use of acids requires formalized training of employees and disposal of spent solutions is becoming an increasing environmental issue.
- *May require a post etch media finish such as shot-peening* – Depending on the part requirements a post etch media finish may be required to re-induce part compressive stresses relieved by the etching process.
- *Recording and retention of inspector observations can be poor* - Data generally consists of qualitative observations by the inspector that are not necessarily retained, except to document that a part was accepted or rejected. If observations are retained, they are usually on paper with a limited shelf life and, as a result, can be difficult to reconstruct for evaluation later. However, the increasing availability of digital camera technology can help to alleviate this difficulty.

13.2.4.3 Fluorescent Penetrant Inspection

A Fluorescent Penetrant Inspection (FPI) consists of the application of a fluorescent penetrant on a clean part. The penetrant seeps into an Anomaly that is open to the surface by capillary action and after removal of excess penetrant (by water washing and / or emulsifier application) a developer is applied to the surface. The developer provides a blotting action that helps to draw penetrant from the flaw to the surface, spreading the penetrant and enlarging the appearance of the flaw. The area of fluorescence created is viewed under black (UV) light.

There are, in general, four sensitivities of penetrant inspection widely used in the aerospace industry with either manual or automated processing of the part to be inspected. The levels of fluorescent penetrant inspection are classified as follows - Level 1 Low Sensitivity, Level 2 Normal Sensitivity, Level 3 High Sensitivity and Level 4 Ultra High Sensitivity. The desired degree of inspection sensitivity is the key element in the selection of the level of penetrant inspection required for a particular application.

13.2.4.3.1 Advantages:

- *Can Detect Anomalies open to the surface* - A widely used inspection method in the aerospace industry for the Detection of surface Anomalies such as cracks, porous inclusions, and other types of porosity.
- *High degree of technical training not required* - While training of the inspectors and operators is certainly required, the principles of the method are straight forward and easily understood.
- *Can be used on virtually all solid materials* – Fluorescent Penetrant Inspection may be performed on metals, plastics, and ceramics. Exceptions would be porous materials and some thermally sprayed coatings.
- *Accessible surfaces can be inspected in a single operation.*
- *Part size is not a concern* – Processing systems can be designed for virtually any size part.

13.2.4.3.2 Disadvantages / Limitations:

- *Highly inspector dependent* - Human Factor issues are the major factors causing variations that limit quantitative inspection capability (i.e., POD).
- *Line-of-sight limited* - As with visual and etch inspection, part geometry can severely limit, or negate, the effectiveness of the inspection by making certain areas difficult to view. These difficulties can be overcome to a certain degree by utilization of a visual aid.
- *Process parameters must be closely controlled* – There is a possibility of flushing penetrant completely out of a crack or other surface Anomaly if the part is over rinsed during the penetrant removal step of the process (This is especially true for water washable type penetrants). Conversely, if the rinse operation is inadequate, it is likely the parts will exhibit excess background fluorescence making inspection difficult or impossible.
- *Surface Preparation* - FPI is very sensitive to Surface Condition – the surface must be clean and dry prior to application of penetrant in order to minimize background influences and allow ingress of penetrant to the crack/Anomaly. In addition, metal smearing, which could also prevent penetrant from entering the crack/Anomaly, must be removed by a suitable process, e.g., etch.
- *Entrapment of Penetrant* – Penetrant may be difficult to remove from parts having blind holes, recessed cavities, and internal passages. Part specific design of special processing equipment is required in this case.
- *Inspection Aids required when inspecting parts having blind or deep holes, recessed cavities, and internal passages* - Borescopes, mirrors and high intensity light sources with flexible light guides are commonly used inspection aids.
- *Recording and retention of inspector observations can be poor* - Data generally consists of qualitative observations by the inspector that are not necessarily retained, except to document that a part was accepted or rejected. If observations are retained,

they are usually on paper with a limited shelf life and, as a result, can be difficult to reconstruct for evaluation later.

13.2.4.4 Magnetic Particle Inspection

Magnetic Particle Inspection (MPI) is used for the Detection of surface and subsurface Anomalies in ferromagnetic materials. When a component is magnetized, Discontinuities orientated mainly transverse to the direction of the magnetic field, will cause a leakage field to be formed at the surface of the part. The presence of this leakage field is Detected using fine ferromagnetic particles applied over the surface, with some particles being gathered and held by the leakage field. This magnetically held collection of particles forms an outline of the shape and size of the Anomaly. The magnetic particles are applied over a surface as dry particles, or as wet particles in a liquid carrier. Both direct current (DC) and alternating current (AC) are suitable for magnetizing parts for magnetic particle inspection. Depending on the magnetic particle retention capability of the part the magnetic particles can be applied to the part while the magnetizing current is flowing or after the current has ceased. The first method is known as continuous; the second, as residual.

13.2.4.4.1 Advantages:

- *Can Detect surface and slightly subsurface Anomalies* - Very sensitive method for the Detection of small, shallow cracks in ferromagnetic material. Anomalies that do not actually break through the surface can also be Detected using this method although certain limitations apply.
- *Accessible surfaces can be inspected in a single operation.*
- *Shape or size of part is not a limitation* – Techniques can be developed for nearly all part geometries.
- *UV light used for inspection* - Fluorescent particles are used with UV light to increase the contrast of Anomalies.

13.2.4.4.2 Disadvantages / Limitations:

- *Highly inspector dependent* - Human Factor issues are the major factors causing variations that limit quantitative inspection capability (i.e., POD).
- *Line-of-sight limited* - As with visual, etch and FPI inspection, part geometry can severely limit, or negate, the effectiveness of the inspection by making certain areas difficult to view. These difficulties can be overcome to a certain degree by utilization of a visual aid.
- *Not applicable to nickel and titanium alloys* – Parts inspected must be ferro-magnetic.
- *Requires magnetization in two directions (longitudinal and circular)* - For optimum Detection capability the magnetic field must be in a direction that will intercept the principal plane of the Anomaly which requires a sequence of inspections to be performed.

- *Post inspection de-magnetization and removal of particles required* – Residual magnetism and/or particles left on the surface could be dertrimental to the part performance in service and must be removed by a subsequent cleaning operation.
- *Local burning of parts possible* – Depending on part geometry some magnetizing techniques call for the passing of current directly through the part. Applying excessive current, worn copper contact pads, or otherwise improper NDE Technique parameters could cause local overheating of parts.
- *Recording and retention of inspector observations can be poor* - Data generally consists of qualitative observations by the inspector that are not necessarily retained, except to document that a part was accepted or rejected. If observations are retained, they are usually on paper with a limited shelf life and, as a result, can be difficult to reconstruct for evaluation later.

13.2.4.5 Eddy Current Inspection

Eddy Current (EC) inspection is based on the principles of Electromagnetic Induction and is used to Detect metallurgical conditions and Anomalies in electrically conductive metals. On rotor parts, a small eddy current coil system is used as a probe and scanned over the part. The probe induces a high frequency eddy current which flows in the part because of Electromagnetic Induction. If an Anomaly is present this current flow is impeded and changed in direction causing changes in the associated electromagnetic field which are registered by the EC unit. Inspection frequencies and the type/size of the probe used have an impact on the Detection sensitivity. The practicality of application is geometry dependent. In the case of circular holes, for example, there are high speed rotating probe systems which offer a reliable, cost effective inspection solution for Geometric Anomalies and Cracks.

13.2.4.5.1 Advantages:

- *Can Detect surface and near-surface Geometric Anomalies and Cracks* – Has the capability to Detect smaller surface Anomalies with higher reliability (better POD) than other inspection methods.
- *Reduced inspector dependency* – As this is an electronic based inspection, EC is much less susceptible to variations in results due to Human Factors. This is one of the major characteristics which makes it a more reliable and reproducible inspection relative to visual, etch or FPI/MPI. In addition, EC inspection is more adaptable to automation thus further reducing the effects of Human Factors (related to the level of automation adopted).
- *Good recording and retention of inspector observations* - Data recording consists of strip charts, digital images or quantitative digital data that can be retrieved and reconstructed later for re-evaluation.

13.2.4.5.2 Disadvantages / Limitations:

- *Difficult to use on certain geometries* – Sensitivity of inspection is affected when part geometry (such as an edge, complex shaped holes, very small cavities, etc.) interferes with the EC probe’s magnetic field.

- *Not yet proven as an effective method for finding Non-Geometric Anomalies in a manufacturing environment* – Laboratory development studies have shown that EC has the potential to Detect Segregation and Non-Geometric Anomalies, but quantitative data is currently limited.
- *Component surface finish may be driven to meet quality standards (i.e., accept/reject limits) required by engineering.*
- *Higher degree of training is required* – The principles of EC inspection are more complex than most other NDT methods.

13.2.4.5.3 Manual EC System Description

Manual eddy current relies on hand-controlled scanning with the probe. As with other human controlled operations, manual EC is subject to more Human Factor issues than more automated EC systems. There are a wide range of eddy current Indication Detectors and probes available on the market.

13.2.4.5.4 Semi-Automated EC System Description

Semi-automated EC refers to equipment that has some limited automated probe scanning capability but requires substantial inspector attention to initiate and complete the inspection. This configuration of hardware consists of an enhanced eddy current Indication Detector with the capability to control a simple probe location / indexing device and a rotating probe mechanism.

This configuration of hardware is portable and relatively easy to set-up in a production environment. However, it does not match the Detection capability or repeatability of a fully automated system.

13.2.4.5.5 Fully Automated EC System Description

Fully automated EC refers to equipment having extensive computer software capabilities to control key inspection functions such as scanning, data acquisition, signal analysis, graphical presentation, and storage. All aspects of the inspection are fully automated and computer controlled. The system comprises of a multi-axis mechanical probe positioner / controller, eddy current Indication Detector, computer workstation and associated data acquisition hardware / software.

13.3 Appendix E: Guidelines for the Qualification and Validation of NDE Techniques and Systems

This appendix outlines the process for qualifying NDE Methods or NDE Techniques for production inspection. An NDE engineer should review the required quality standard, Anomaly characteristics and inspection capability before recommending the appropriate NDE Method or NDE Technique to the PVF. Inspection capabilities and limitations should be specified. Final approval of the selected NDE Method should be made by the PVF.

13.3.1 Establishing Inspection Requirements

Information is required from Design, Lifing, Material and Manufacturing functions regarding possible Anomaly characteristics.

13.3.1.1 Description of the Subject/Problem

- *What type of Anomaly is encountered* – This should include relevant data on anticipated Anomaly location, size, shape, and orientation.
- *Critical size* - Determination of the Anomaly size/magnitude which can adversely impact Critical Rotating Part reliability.

13.3.1.2 Selection of Potential NDE Methods

- *What NDE Methods allow Detection of Anomalies* - Using both experience and knowledge of existing technology, define which NDE Methods are suitable for the inspection.
- *NDE Method considerations* – When assessing possible NDE Methods, consideration should be paid to geometric effects, Surface Condition, and ease of access.

13.3.2 Evaluation of Selected NDE Methods

- *Determination of process capability* – Should include test sample production containing, where possible, real Anomalies in addition to artificially created Anomalies, with known sizes.
- *Define inspection parameters* – Should include reference to calibration standards and surface preparation for inspection.
- *Comparative studies* – A comparison of NDE Techniques should be performed, including statistical analysis and verification via other measuring methods to determine false call rate and POD, if needed.

13.3.3 Selection of Preferred NDE Method

- *Comparison of NDE Method capability* – Should be drawn from recommendations of the NDE engineer and should consider the capability tables compiled by the RoMan NDE team (Tables 9.1 and 9.2 for holes).

- *Additional considerations* – Should include data acquisition and storage, Human Factors, cost/productivity considerations and reliability.

13.3.4 Transition to Production Inspection

- *Proposed integration route* – Should consider the production cycle and Process Monitoring controls to be utilized, and the design of the mechanical and electronic components of the inspection equipment. Optimization of inspection parameters should be pursued.
- *Write inspection procedure* - The procedure should include inspection sequences, calibration, pre- and post-cleaning processing parameters limits, Indication Interpretation and measurement and required inspector training.
- *Verification* - Verification of NDE results by repeated NDE inspection.

13.3.5 Implementation of Production NDE Method

The manufacturing procedures should define the following:

- *Training and certification of operators and inspectors*
- *Calibration and certification of equipment*
- *Part pre-cleaning, drying, and etching (if necessary)*
- *Selection of inspection processing parameters*
- *Identification of evaluation requirements*
- *Identification of required inspection coverage,*
- *Special inspection equipment requirements (if necessary)*
- *Selection of inspection calibration standards and re-calibration interval*
- *Inspection procedure*
- *Evaluation procedure*
- *Part post-cleaning (if necessary)*

13.4 Appendix F: General NDE Guidelines

13.4.1 Process qualification

During the development of a Manufacturing Process, the NDE Method(s) should supplement the process optimization activities by providing the PVF with technical data related to the integrity of the part being machined. It might be necessary to monitor the quality and consistency of the part with NDE Methods or with a combination of Process Monitoring and NDE (Figure 13.2). To get a good result it is necessary to have knowledge of the kind of Anomalies that potentially could occur along with a measure of the Anomaly Detection capability of the selected NDE Method.

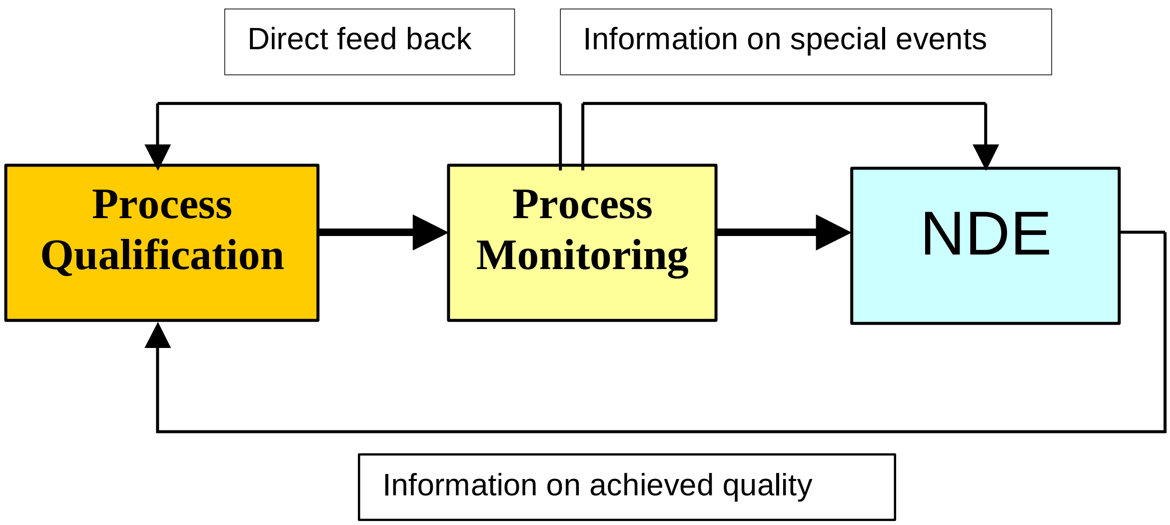


Figure 13.2: Process qualification with the aid of Process Monitoring and NDE

13.4.2 Operator and Inspector Training & Certification

All NDE operators and inspectors should receive formal technical training (classroom and practical) and certification in accordance with the relevant certifying agency requirements. Additional support and technical guidance should be provided to the operator and inspector when unique or non-routine inspections are required. NDE operators are persons that prepare the part for inspection, but do not perform the inspection.

13.4.3 Sampling

Sampling plans should only be used with NDE processes under certain limited conditions. Sampling can be used to monitor Manufacturing Processes when the inspection involves Detection of a characteristic, which is produced as a natural and expected result of the process. An example of an expected manufacturing characteristic would be surface residual stress in rotating components. Use of the NDE process to develop "trend charts" indicating the range of natural characteristics produced over a period of time is an example of where sampling plans would be appropriate. However, a suitable statistical analysis of a substantial quantity of trend data should be completed prior to specifying an appropriate sampling plan.

Sampling should not be used when the objective of the inspection is to Detect Anomalies. These relatively rare and unpredictable events are not compatible with a statistical based sampling plan. Inspections such as those applied to production parts to Detect Indications exceeding a specified size or frequency limit, or any quantitative inspection are examples of situations where sampling plans should not be used.

13.4.4 Specifications & Procedures

NDE specifications are prepared to define the basic requirements for all inspection processes. Specifications typically establish essential inspection guidelines, such as qualification of operators and inspectors, qualified processing materials (e.g., penetrants), calibration and certification of equipment, pre-cleaning and post-cleaning methods, and inspection sequence. Some specifications also include requirements for surface preparation, process control methods, processing parameter limits, and Indication Interpretation and measurement. Quality assurance provisions, which delineate controls necessary to ensure that the NDE materials and equipment provide an acceptable level of performance, are usually included. No NDE processes should be applied to production hardware without the availability of a comprehensive specification, which clearly defines the minimum requirements for conducting an acceptable inspection.

All NDE processes applied to production hardware should be performed to a written procedure, which describes how the specification requirements will be implemented. The procedure should provide the inspector with the information needed to complete the following inspection steps (at a minimum):

- Part pre-cleaning, drying, and etching (if necessary)
- Selection of inspection processing parameters
- Identification of evaluation requirements
- Identification of required inspection coverage
- Special inspection equipment requirements (if necessary)
- Selection of inspection calibration standards
- Inspection
- Evaluation
- Part post-cleaning (if necessary)

13.4.5 Equipment Calibration

As a minimum, the following NDE equipment should be certified and calibrated according to specification requirements:

- Indicators or controls used to control or verify processing parameters such as pressure, temperature, and concentration
- Meters or other electronic equipment used to measure light intensity, NDE probe output, etc.

- Measuring devices or other equipment used to determine the size of Indications, such as gages, optical measuring aids, etc.

13.4.6 Quantification of Inspection Capability & Reliability

The vast majority of inspection applications are qualitative and therefore quantification of the Detection capability of the NDE Method(s) employed is not necessary. NDE Method sensitivity is usually classified by noting magnification level (etch, visual), penetrant sensitivity level (FPI/MPI), or calibration notch sensitivity level (EC). These characteristics are generally descriptive enough to provide a reasonable idea of the expected inspection sensitivity. For example, it might be assumed that the EC response from a crack would be of the same order of magnitude, but smaller than the EC response from a notch of the same size, leading to the estimate that cracks larger than the notch would be Detectable using an accept/reject threshold equal to the notch response. Alternatively, statements about Anomaly Detection capability are sometimes based on precedent. For example, the fact that a particular type and size of Anomaly has once been Detected by a specific NDE process may lead to the assertion that the method is "capable" of Detecting Anomalies of that type and size. These statements are clearly true, but they fail to address the question of what proportion of Anomalies of that type and size might be Detected or missed.

However, there may be situations where a more precise measure of sensitivity is desired for a qualitative inspection or is required before a quantitative inspection can be applied to hardware. In these situations, a Probability of Detection (POD) evaluation must be conducted to generate a graph of probability vs. Anomaly magnitude.

POD is normally determined using a set of simulated Anomalies, which bear as close as possible resemblance to natural Anomalies. They are often more easily Detectable than natural Anomalies, although this relative Detectability is seldom quantified. Measurement of POD for surface inspection processes typically involves test blocks containing surface connected low cycle fatigue cracks. Although these cracked blocks do not always represent natural Anomalies, they are used because the fatigue crack sizes and shapes can be relatively easily manufactured and controlled (compared to Anomalies such as residual stresses, scratches, inclusions, etc.) to provide the required distribution for POD determinations and their physical characteristics are very similar to the cracks found in actual hardware. A statistically significant number of cracks whose sizes exceed the upper and lower bounds of the expected range of Detection are required to conduct a valid POD measurement. Evaluation of POD in manufacturing generally involves collection of data by several inspectors followed by a statistical evaluation of the results.

Development of POD data for Anomalies other than cracks is not possible until a valid set of test specimens becomes available. The technology needed to produce test blocks containing a controlled number and size range of other Non-Geometric Anomalies, such as severely work hardened surface layers, must be developed before valid POD data on Anomalies other than fatigue cracks can be generated.

The influence of changing some of the inspection parameters affecting Detectability may be qualitatively predictable but is rarely known quantitatively. Consequently, POD should be measured for each set of inspection parameters, inspectors, equipment, etc., and re-measured if changes are made. This requirement severely limits the applicability of individual POD curves.

All of these factors make POD determinations difficult, expensive and time consuming and explain why so few statistically valid evaluations have been conducted.

Efforts are currently underway to develop POD models for clearly defined NDE applications and Anomaly types. One example of such an effort is the FAA sponsored Engine Titanium Consortium (ETC) work to develop a methodology for calculating POD of ultrasonic inspection. This methodology involves development and validation of several models (e.g., Anomaly Detection model, transducer model, etc.) to permit prediction of the Detection capability of any given inspection system. Upon completion, this work should greatly reduce the need for (and cost of) additional full POD investigations whenever slight changes in inspection or application parameters are made.

13.5 Appendix G: Recommendations for Inspection of Holes

Selection of an inspection process for holes involves consideration of most of the factors cited previously in Appendix E. The relative capability of the candidate inspection processes to fulfill some of the key considerations for Low and High L/D Hole inspections are summarized in Tables 9.1 and 9.2 in Section 9 of this report.

The rationale for the evaluation of each of the selection factors is as follows:

13.5.1 Capability to Detect Anomalies

Cracks and Geometric Anomalies are most effectively Detected by the EC process. Aided FPI/MPI and etch have some capability but are limited by the considerations previously mentioned in Section 13.2.4. In some cases, the effectiveness of FPI/MPI and etch can be enhanced using special lighting NDE Techniques designed specifically to light the inner surfaces of the hole. Holes should be inspected from both sides when possible. Clearly, the success of this method is dependent on the Human Factors previously mentioned in Section 8.2.

Non-Geometric Anomalies are generally more difficult to Detect than Geometric Anomalies. Commercially available Eddy Current systems are not considered capable of Detecting many of these Non-Geometric Anomalies, such as near-surface inclusions, and overheated or smeared surface layers, although they can Detect embedded inclusions from broken tool tips. Microstructural variations may be Detectable by EC depending on the material and test conditions. New Eddy Current Techniques have shown promise for even more effective Detection of Non-Geometric Anomalies in titanium, but additional development is needed before they will be ready for production applications.

Aided etch inspection can Detect surface connected inclusions and surface layer Anomalies under certain conditions, especially in titanium using Blue Etch Anodize Techniques. For materials other than titanium, etch has not been demonstrated to reliably Detect Machining Induced Non-Geometric Anomalies. FPI/MPI and unaided Etch and visual inspections are considered ineffective for Detection of Non-Geometric Anomalies.

13.5.2 Method Characteristics

Several factors are included in Tables 9.1 and 9.2, which describe NDE Method characteristics important to the inspection of holes.

Inspector dependence – This is considered an important factor due to the substantial influence of Human Factors on the capability of the process to Detect Anomalies. The automated EC process has the lowest inspector dependence, followed by the semi-automated EC process. Manual EC has somewhat higher inspector dependence, but is still substantially lower that either etch, visual or FPI/MPI.

Automated process – This factor is generally inversely related to the inspector dependence factor. It refers to the degree of automation typically incorporated into the NDE process. The automated EC process has the highest degree of automation, followed by the semi-automated EC process. FPI/MPI has no automation in the evaluation portion of the process, but often the penetrant application and removal portions are automated. Manual EC, etch, and visual typically have very little automation incorporated into the process.

Cost effective/High throughput - These factors are related to some extent since labor is a substantial factor in determining the total cost of applying the NDE process. Capital equipment costs are typically highest for automated EC. FPI penetrant application and removal facilities are a substantial cost factor, with automated systems requiring a substantially higher investment than manual lines. Inspection throughput, or time to process and inspect a hole, varies somewhat with the hole size and Anomaly sensitivity. However, EC inspections utilizing a high-speed rotating probe, FPI/MPI, etch, and visual inspections are all considered relatively low-cost methods. Aided etch, visual and FPI/MPI have somewhat lower throughputs due to the additional time needed to prepare the surface and/or manipulate the visual aids.

Digital data – This factor is considered important to the data analysis and storage capabilities of the inspection. In general, only automated and some semi-automated EC processes provide digital data.

Quantifiable capability – This factor refers to the ability to establish POD curves for the NDE process. This is an established practice for both EC and FPI/MPI, although aided FPI/MPI may present a more difficult challenge due to the complexity of incorporating mirrors or borescopes into the evaluation.

14 Appendix H: Edgebreak Manufacturing Method

14.1 Edgebreak: Manufacturing Method Overview

Workpiece profiles may require an edgebreak when burrs or sharp edges are produced at the intersection of two or more surfaces. A number of Critical Rotating Part cracks and fractures have been attributed to an inadequate edgebreak, which is the combined result of the surface cutting (or feature producing) Manufacturing Method and edgebreak Manufacturing Method.

For example, Broaching of axial blade attachment slots leaves a burr on the exit side of the slot that must be removed to allow optical inspection of the slot geometry, for safe handling, and to prepare for downstream processing (e.g., shot peen). The burr removal must be included in the Process Validation of the edgebreak Manufacturing Method. Complex geometry close to the blade attachment slots that make it difficult to use chip backing rings or to automate the edgebreak operation should be reviewed during the design of the component and avoided.

In addition to burr removal, specific edgebreak geometry is generally required by the design for reasons including stress, cooling, or assembly. Such edgebreaks typically take the form of a chamfer or radius of a prescribed size, frequently with tight dimensional tolerance. The edge geometry can be very complex if the workpiece includes intersecting features or surfaces such as stepped locating diameters (i.e., rabbets, pilots, or snaps), hooks, or flowpath geometry that intersect with other geometry.

14.2 Edgebreak: Manufacturing Methods

Burrs produced on the edges or intersection of surfaces during conventional machining Manufacturing Methods can become more severe as the cutters wear, particularly in ductile and difficult-to-machine alloys. This dependency between the burr produced by the Manufacturing Method and the process capability of the following edgebreak Manufacturing Method is well established. To ensure the edges continue to meet the Design Intent, it is important to use strategies that control the range of the burr size prior to applying the edge finishing Manufacturing Method. A nominally capable edgebreak process may produce unacceptable results if the incoming burr or edge condition is outside the range assessed during the Process Validation phase.

For example, in Broaching the burr size can be controlled by using disposable back-up rings (chip rings). Chip rings are usually a few millimeters thick and sit between the exit face of the disk and the fixture. Because the exit face of the disk is completely supported by the chip ring, the burr at that interface is very slight and the larger exit burr occurs on the exit face of the chip ring, which is discarded. Although there may still be a burr on the disk, it is small and more consistent which facilitates the edgebreak operation.

For complex geometry and variability of the incoming burr, manual deburring and edge forming (aka, hand benching) has been a common strategy for deburring and edgebreak. However, hand benching, and other operator dependent edgebreak and edge inspection methods, are limited by the consistency (Process Variability) inherent in any manual method or process. The preferred strategy to produce an edgebreak is to use a fully automated Manufacturing Method such as machining of the edges followed, if necessary, by a process to smooth or round the edge geometry and remove any tiny burrs remaining from the edge Manufacturing Method.

Edgebreak machining and bulk finishing methods have become common, both to improve the consistency of the resulting edge and for ergonomic reasons. In some cases, “soft” methods like abrasive brushing or bulk media processes like tumbling can remove burrs and produce the required edge geometry. For more difficult materials with larger burrs, or applications that require a larger edgebreak, a controlled machining operation is typically required. Milling is the most common method, either using a shaped cutter or a more generic tool manipulated under 5-axis control. Small abrasive wheels may also be used. These methods are performed in a Milling machine or using a robot. Edgebreak machining itself can leave a very small burr, so after the edge geometry is produced it is common to use one or more automated brushing, polishing, or bulk finishing operations to remove the edgebreak burr and slightly round the edge.

15 Appendix I: Axial Blade Attachment Slot Manufacturing

Axial (including skewed) slots are a common feature used to attach blades to disks in the fan, compressor, and turbine stages of gas turbine engines. They are characterized by tight geometric tolerances on the blade seating surfaces (i.e., pressure or bearing faces), and may include one or several sets of pressure faces per slot. The complex geometry, difficult-to-machine materials, and tight geometric tolerances require specialized Manufacturing Methods. In addition, the operating conditions of these parts demand that the Manufacturing Methods do not degrade the properties of the workpiece material.

This section describes current and emerging Manufacturing Methods and Manufacturing Method control strategies for machining axial blade attachment slots in gas turbine engine disks.

15.1 Slot Manufacturing Method

15.1.1 Broaching: Manufacturing Method Overview

Broaching is by far the most common method used to machine linear axial blade attachment slots in all materials, including titanium, steel, cast-wrought nickel, and powder-metal nickel alloys. A Milling process, sometimes called “rotary Broaching” is employed for curved axial blade attachment slots, which are less common and not covered here.

Broaching is a single-axis machining process where the complex geometry is generated by precision-ground form cutters. Each tooth on a Broach cutter is slightly larger than the prior tooth and this size progression is equivalent to the feedrate produced by advancing a drill or Milling cutter. The increase in tooth size is small – typically ~0.0006 to 0.004 inch per tooth (~0.015 to 0.1 mm per tooth). Because of this, many teeth are required to cut even a relatively small slot, leading to long strings of cutters that require large, expensive machines.

As the Broaching process works with a fixed cutter set-up, each toolset is dedicated to a defined slot geometry. The costs and lead time for a tool set are relatively high and the set-up of a Broaching process is traditionally time-consuming. For these reasons Broaching is conducive for larger lot sizes. Once the process is set up, however, high material removal rates can be obtained, making the process productive. The stiffness of the machine and single axis tool movement can produce high geometric accuracy and fine surface finish.

High cutting forces typical of the Broaching process cause elastic deformation of the material between adjacent slots during the cutting process that can result in geometric errors. Geometric deviations of the slot feature can reduce the life capability of the part. Analytical and simulation models can be used to optimize cutting tool design to minimize geometric errors due to cutting forces.

15.1.2 Broaching: Cutter Geometry

In addition to the macro geometry that produces the cross-sectional shape of the axial blade attachment slot, the key tool characteristics are shown in Figure 15.1; rise-per-tooth, rake or hook angle, gullet shape, and clearance angle.

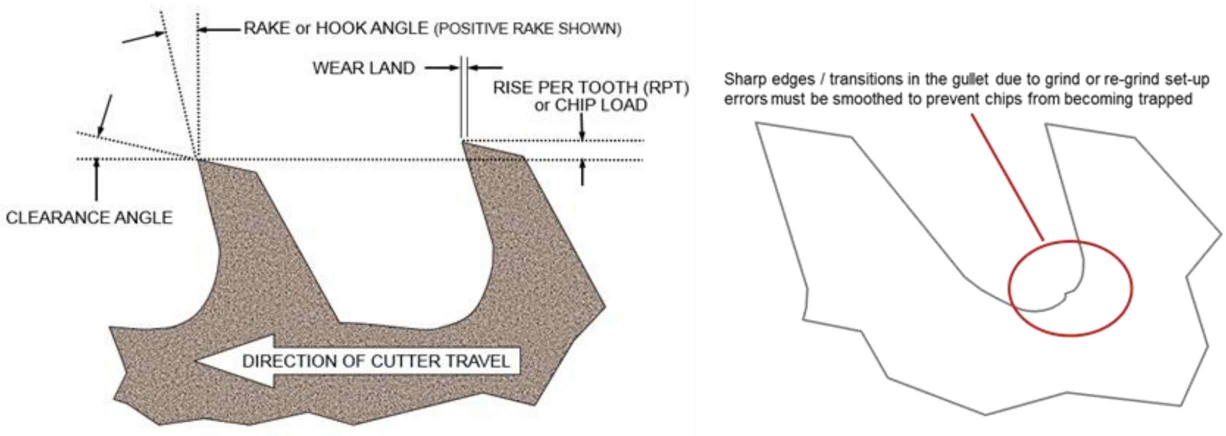


Figure 15.1: Broach Cutter Nomenclature

The rise-per-tooth (RPT) corresponds to the feedrate (chip load) in other conventional machining methods, except that unlike those methods it is fixed during the design of the cutter and cannot be changed by adjusting the machine. The RPT relates to the chip thickness, unit cutting force, and tool wear rate. Roughing cutters typically have a larger RPT (0.002 to 0.004 inch; 0.05 to 0.1 mm) than finish or form cutters (0.0004 to 0.0012 inch; 0.01 to 0.03 mm). The lower RPT of the finish cutters produces lower unit cutting forces, which can enable tighter geometric control and produce a lower cutter wear rate. However, the total cutting force is often highest for the finisher teeth. This is because although the RPT and unit force are smaller, the tooth perimeter cut by a finisher is typically much longer than a rougher leading to a higher net force.

The rake angle determines the cutting efficiency and the strength of the cutting edge. Higher (steeper) rake angles produce lower cutting forces, but also result in a weaker cutting edge that can be more prone to wear and chipping. Rake angles from about 6 to 18 degrees are common, depending on the workpiece material, but higher and lower angles have been used.

The clearance angle ensures the cutter does not rub the freshly cut surface. Values ranging from 2 degrees to 5 degrees are typical, but lower clearance angles have been used depending on the cut geometry, machine stiffness, and the workpiece material. If the clearance angle is too low, rubbed workpiece material can build up on the clearance surface of the cutter and possibly transfer to the part. This can lead to Geometric or Non-Geometric Anomalies or a poor Surface Condition and have a negative impact on part life. However, large clearance angles increase the risk of cutting edge chipping and reduce the number of times a cutter can be reground before it becomes too small to hold tolerance. Because of the nature of the tooth Grinding process, the clearance angle on finish cutters varies around the tooth perimeter (this is not an issue for the straight geometry on roughers). Thus, attention must be paid during the design and inspection of the finish cutters to ensure the intended minimum clearance angle is attained all around the tooth perimeter. Local areas with insufficient clearance angle may rub or pick up adhered workpiece material even if the nominal tooth perimeter or profile clearance angle is adequate.

The condition of a freshly ground cutting edge can have a significant impact on the initial performance of the cutter and on the tool wear. Cutter edges that are too sharp can be weak and prone to chipping. An as-ground edge can also have small burrs or tiny Grinding marks that can produce an undesirable Surface Condition in the slot and lead to accelerated edge wear of the cutting tool. Processes including abrasive finishing, glass peening, slurry honing, and brushing are used to remove the small burr left by Grinding (new and re-sharpened) and to put a very small (typically < 0.0008 inch; < 0.02 mm) radius on the sharp edge to minimize edge chipping. To some degree, the specific type and size of the edge preparation depends on the workpiece material.

Finally, the shape of the gullet (the space between the teeth) must be designed and ground to minimize the chance of chips becoming trapped, which can lead to tooth damage or surface anomalies on the part (i.e., an undesirable Surface Condition). The gullet should be smooth and free of sharp transitions and raised edges which are prone to trap chips. This may require smoothing of the gullet geometry during initial cutter machining, and smooth transitions must be maintained when cutters are re-sharpened by removing material from the rake face (Figure 15.1).

15.1.3 Broaching: Cutter Material

Most Broach cutters are made of heat-resistant grades of powder-metal high speed steel (HSS), although there are applications where cutters with carbide cutting edges are used. Carbide cutters have the potential to increase tool life or cutting speed but are currently practical mainly for roughing cuts. Tool coatings are also sometimes employed to increase tool life or cutting speed.

Use erodes the edge of a Broach cutter, leading to progressively higher forces and additional heat generation as the transition from a sharp geometry that produces a shearing action to a blunt geometry that can lead to tearing or gouging of the workpiece surface. Overly dull cutters can produce undesirable metallographic changes in the surface and near-surface regions, including excessive grain deformation, undesirable residual stress, re-bonded workpiece material, and small Geometric and Non-Geometric Anomalies. For these reasons, a strategy to replace or re-sharpen the cutters before they become overly dull is mandatory.

The maximum hot hardness of approximately 1100°F (600°C) for HSS tools limits cutting speed. Because they are harder and more heat resistant, cemented carbide tools can enable a significant increase of the cutting speed and increased tool life. Carbide tool designs include:

- Inserted tools, which use replaceable cutting edges, are predominantly used for roughing operations because of their relatively low geometric accuracy
- Tools using glued or brazed carbide cutting edges provide a higher geometric accuracy. However, this style is ground and sharpened in a manner like conventional HSS tools.
- Full carbide tools exhibit the highest possible accuracy but also the highest cost.

The application of carbide as a cutting material for finish Broaching requires a new process validation strategy regarding cutting parameters and tool geometry. Tests have shown that cutting parameters cannot be simply transferred from conventional HSS to carbide Broaching processes, as this can result in cutting edge chipping and unacceptable product surfaces.

15.1.4 Broaching: Cutter Wear and Maintenance

The tool wear is measured on the clearance face of the tool, see Figure 15.2. The characteristics used to describe tool wear are the average wear width ($VB_{average}$) and the maximum wear width (VB_{max}). The amount of wear often varies around the tooth edge perimeter. Wear is typically greater on the root and crest radii of a profile tooth or the corners of a roughing tooth where unit cutting forces and temperatures are higher. Other forms of tool wear (e.g. chipping, plastic deformation of the cutting edge, etc.) indicate issues with the tool design or process parameters, which can have a negative impact on attachment slot geometry and Surface Condition.

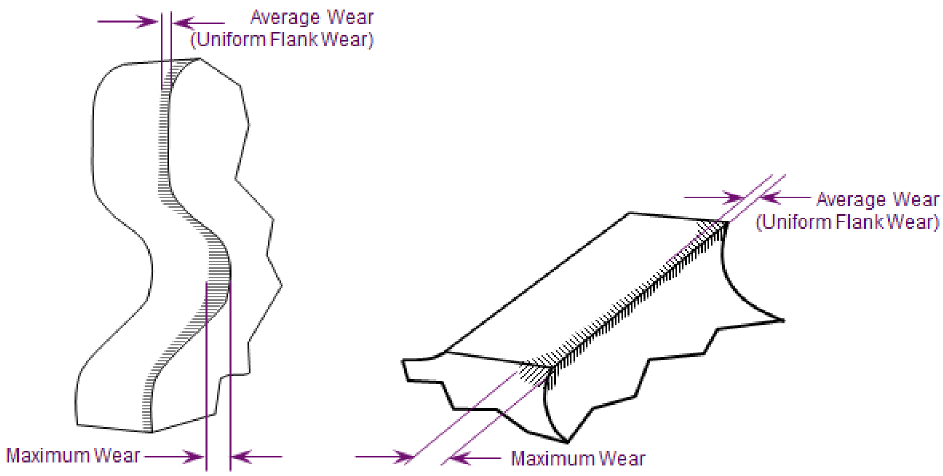


Figure 15.2: Tool Wear

As the cutters wear and their profiles become smaller the slot produced in the disk also becomes smaller. In addition, if the system (workpiece, fixtures, machine, and cutting tool) is not sufficiently stiff, the increased axial and radial cutting forces due to cutter wear can lead to a slot geometry which no longer meets the Design Intent.

The amount of acceptable tool wear is based on both the ability to maintain the intended slot geometry and to produce an acceptable Surface Condition. The maximum acceptable wear is a function of the cutter geometry and the workpiece material. As with all finish metal cutting, a Tool Change Point must be developed and validated as a portion of the Manufacturing Control Plan. Tool Change Points are determined by evaluating the number of slots that can be cut while maintaining the Design Intent. Tool wear measurements should be included in the Broaching Process Validation and should be monitored during production to ensure the specified Tool Change Point continues to meet the Design Intent.

A set of cutters can produce from one to over one hundred parts (depending on the workpiece (or part) material and slot geometry) before it must be removed to be re-sharpened or replaced. Cutters are re-sharpened by Grinding back the rake face until evidence of the wear is removed. Because of the clearance angle, Grinding back the rake face also causes the cutter profile to shrink by a small amount. This is easiest to envision on a roughing cutter which only cuts on the top end of the tooth, where each tooth also becomes slightly shorter when material is ground from the rake face. Some re-sharpened cutters may be shimmed when mounted in the machine to bring them back to the intended position, while other geometries cannot be shimmed and must be discarded when they become too small.

Small differences in the amount of cutter material ground from each tooth during re-sharpening can lead to differences in the rise-per-tooth (RPT), especially on cutters that have been re-sharpened more than once. In the extreme, uneven RPT can lead to high forces that damage individual cutter teeth. Uneven RPT can also have implications for analytical modeling of the cutting forces and potentially also for Broaching Process Monitoring, though most process monitors currently in use establish a new baseline each time a fresh set of cutters is loaded into the machine. A best-practice re-sharpening method is to determine the most worn tooth within a cutter set then Grind uniform stock from all of the teeth in the set to minimize variation in the stock removed by each subsequent tooth.

Rise-per-tooth consistency, edge preparation, surface finish, gullet geometry, and coatings (if used) must all be considered both at original Broach cutter manufacture and when re-sharpening the Broach cutters. A robust cutting tool validation and control plan is necessary to ensure a consistent Manufacturing Method. A validated cutter control plan is important to maintain cutter performance and should include conditioning of the cutting edge after initial Grinding and after re-sharpening. A strategy to avoid handling damage to the cutters must also be included within the Manufacturing Control Plan.

15.1.5 Broaching: Set-up and Process Validation

The complete set of cutters (i.e., a cutting string) may include many individual cutters, each roughly 10 to 30 inches (250 to 750 mm) in length. The cutters must be aligned in the machine such that the last tooth of each cutter is properly overlapped by the first tooth of the following cutter. This takes considerable time and, if not done accurately, can result in uneven cutting forces and unacceptable slot geometry. On large or complex slots, the final slot geometry may be produced by five or more finishing cutters precisely aligned to avoid unacceptable geometric transitions between adjacent areas cut by different finishing cutters.

Because of tight slot geometry tolerances and the complexity of aligning a set of cutters, it is standard practice to cut and inspect a test slot to validate the set-up before Broaching a production part. If the inspected geometry does not meet the Design Intent (e.g., it is oversized, undersized, contains steps or grooves in the slot perimeter profile), the cutters are adjusted, and another test slot is cut and inspected. This process is repeated until a slot meeting the Design Intent is produced. A full-size coupon (e.g., a scrap part) is recommended because it replicates all workpiece and work holding reaction forces, especially for difficult-to-machine materials where the cutting forces can be significant. In some cases, it is sufficient to cut the test slot in a small piece of the workpiece material.

A reduction of the set-up times can be achieved by integrating a part and tool probing system into the machine tool, although this is not yet a common machine arrangement.

In addition to producing the required geometry, production Broaching (and other slot Manufacturing Methods) must be validated to ensure they produce a workpiece Surface Condition consistent with the Design Intent. Tool geometry, tool cutting edge condition, cutting speed, and cutting fluid effectiveness are among the factors that can influence Surface Condition attributes such as grain deformation, Heat Affected Zone (HAZ), and residual stress.

15.1.6 Alternate Manufacturing Methods

Broaching is the most common method for producing axial blade attachment slots because it is typically the most economical. While set-up times are long and cutting speeds are very low (6.6 to 33 feet per min; 2 to 10 meters per min), the fact that a very complex, precise geometry can be produced in a single pass yields total cut times that are difficult to match with other

Manufacturing Methods. Typical process times range from under an hour to about eight hours per part, depending on the part size and material.

Cost is a function not only of cutting time, but also set-up time, tool consumption, and machine investment. For this reason, a number of alternate Manufacturing Methods are under evaluation or in limited use. The following Manufacturing Methods can be used to rough and finish axial blade attachment slots or used as roughing methods to be followed by a short set of finishing Broach cutters. Examples of alternate Manufacturing Methods include:

- Milling – Generally used for easier-to-machine alloys and simpler slot geometries like those found in fan disks and some compressor and low-pressure turbine disks. Advances in tool material are expanding the range of potential applications. Generic ball-nose Milling cutters can be used, but precision-ground form cutters are often employed to finish the slot geometry. In some cases, Milling is used to rough the slots which are then finished by a finish Broaching operation to achieve tight geometric tolerance to meet the Design Intent. Milling is also used in instances where the part geometry prevents the use of Broaching, including curved or obstructed slots, or where a small number of disks are required and the cost of Broach tooling cannot be justified.

- Grinding – Applicable to the more difficult turbine alloys, Grinding is most used as a roughing method but can be used as a finishing method as well. For most slot geometries, finish Grinding requires the use of small super-abrasive form wheels to produce the blade attachment slot geometry because some areas of the slot are not accessible to a traditional large abrasive wheel cutting in the axial slot direction.

- Electrical Discharge Machining (EDM) – Appropriate for all alloys and geometries, the challenges with EDM are slow material removal rates and the resulting re-cast layer that generally limits the process to roughing. Wire EDM can be used to finish slots if multiple passes are used to improve accuracy and cutting power is managed to minimize re-cast. This can be an economical solution where a small number of disks are to be produced, and the cost and time to procure Broach tooling would be prohibitive. With new wire EDM machines designed specifically for blade attachment slot machining, this technique is being more widely evaluated and applied. For this Manufacturing Method, detrimental Surface Conditions caused by unintended cutting artifacts such as an arc-out must be addressed within the Process Failure Mode and Effects Analysis (PFMEA) prior to implementation into production parts. Due to advancements in EDM power control technology, geometric tolerances in the range of 0.0002 to 0.0003 inches (5 to 8 µm) and good Surface Conditions can be obtained. A set of samples manufactured by a state-of-the-art EDM process showed similar LCF performance compared to a standard HSS Broaching process [Source: Wire EDM for the Manufacture of Fir Tree Slots in Nickel-Based Alloys for Jet Engine Components, ISBN 978-3-86359-361-2].

- Electrochemical Machining (ECM) – Attractive for hard-to-machine turbine alloys, ECM does not produce a re-cast layer. It has relatively low material removal rates (in the range of 2 to 3 mm/min for typical slot geometries and cross sections) and some challenges with creating acceptable radii at the edges of the blade attachment slot. ECM requires significant infrastructure to handle the electrolyte. For this Manufacturing Method, detrimental Surface Conditions caused by unintended cutting artifacts such as arc-outs, pitting and inter-granular attack must be addressed within the Process Failure Mode and Effects Analysis (PFMEA) prior to implementation into production parts.

- Abrasive Waterjet (AWJ) – Abrasive Waterjet is not yet accurate enough for finish machining of axial blade attachment slots. Challenges include variation in jet geometry due to steady nozzle wear and geometric variation at the entrance and exit of the cut. The AWJ process might be combined with other finishing processes such as Broaching or Milling.

15.2 Edgebreak Manufacturing Method

See Appendix H for a discussion of the edgebreak Manufacturing Method.

15.3 Real-Time Process Monitoring

15.3.1 Broaching Overview

Unlike critical Holemaking, Process Monitoring is not yet common for axial blade attachment slot machining. For Broaching the cost of adding a process monitor to the machine is higher than for a comparable Holemaking system, and the data analysis is more complex. However, new approaches in science and research are focusing on effective and convenient solutions using a combination of sensors and process models which enable monitoring of tool wear, tool chipping, process forces or temperatures.

While Holemaking has a relatively consistent power, torque, or force profile throughout the cut, each section of the Broach string has its own nominal or normal power or force profile. This means that rather than having one set of alarm limits (e.g., “Yellow Limit” and “Red Limit”) for the feature, each change in the cutter geometry throughout the set of cutters requires a different set of alarm limits. While the focus of machining Process Monitoring is often placed on the finish cutters that directly impact geometry and Surface Condition, issues with roughing cutters or teeth can create part conditions which cascade to affect the finish cutters, so there is value in monitoring the complete set of cutters. The fact that some types of tool damage can result in a lower cutting force presents an additional Process Monitoring challenge. Current research indicates that a combination of force sensors and additional data (e.g., temperature or vibration sensors) may be required.

15.3.2 Systems and Strategies for Broach Monitoring

There are several commercially available systems for Broaching that monitor either cutting power (ram power) or cutting force. The former is easier and cheaper to install because they monitor power inductively from the motor leads, or directly from the controller bus. While measuring the power from the machine controller bus is easy and cost efficient in terms of implementation, the correlation between the signals and the critical process characteristics is often limited for reasons which include:

- Limited sampling rates that are preset by the machine tool controller
- Power related signals that include moments of inertia coming from the machine tool power train in addition to the actual cutting forces

- Signal components caused by non-linear friction of guides and slides in the power train.

Thus, without machine tool models to separate signal components, the significance of the data correlation to the process characteristics must be treated with caution.

Force monitoring is generally considered to provide a more precise representation of the cutting process using piezoelectric force sensors installed in the cradle or fixture of the machine. External sensors can be individually set with sampling rates optimized to analyze the process in time and frequency domains. This can enable detection of vibration, chatter, and other dynamic process instabilities that can lead to an unfavorable Surface Condition. Drawbacks of piezo-electric force measurement systems are equipment cost and the expertise required to set-up, calibrate, and maintain the system.

There are commercially available Process Monitoring systems that set moving limits around a “learned” force profile, based on a first pass cut with a sharp set of cutters. These Process Monitoring systems are used to detect relatively significant cutter damage before it becomes severe enough to break a tooth or the cutter body. While unusual wear on roughing cutters may be detected, applying this strategy of moving limits in the time domain typically is not sensitive enough to detect unusual wear on finish cutters. Typically, the finish cutters will fail to hold the very tight geometric tolerances required for the blade attachment slots before unusual wear becomes significant enough to trigger an alarm. But it has been shown that high frequency acoustic emission sensors (>50 kHz) are able to detect anomalies and correlate with the tool wear in the frequency domain. Fast field programmable gate array (FPGA) systems allow for an online monitoring of the tool wear. However, these systems are not yet commercially available.

The following are examples of different measurement techniques. Figure 15.3 compares an effective power measurement (collected from the machine controller bus) with a single axis cutting piezoelectric force measurement (measured in the cutting speed direction). The top portion of the figure shows the complete Broaching stroke (entire string of cutters) where the first six roughing cutters are engaged in the time window between 5 and 45 seconds and the more complex finishing cutters are engaged in the material between 45 and 90 seconds. The bottom left measurement compares the effective power measurement (red color) and the related force measurement (blue color) when the machine tool is in idle mode. Even though the process force is zero, the power signal variation due to movement of the motor and power train can be clearly identified. The bottom right diagram shows an excerpt from the time signal when the fourth roughing cutter is engaged in the material. While the power measurement cannot resolve the single cutting teeth in engagement and only a slight offset can be recognized compared to the idle mode, the force measurement clearly shows each individual cutting edge entering and exiting the material.

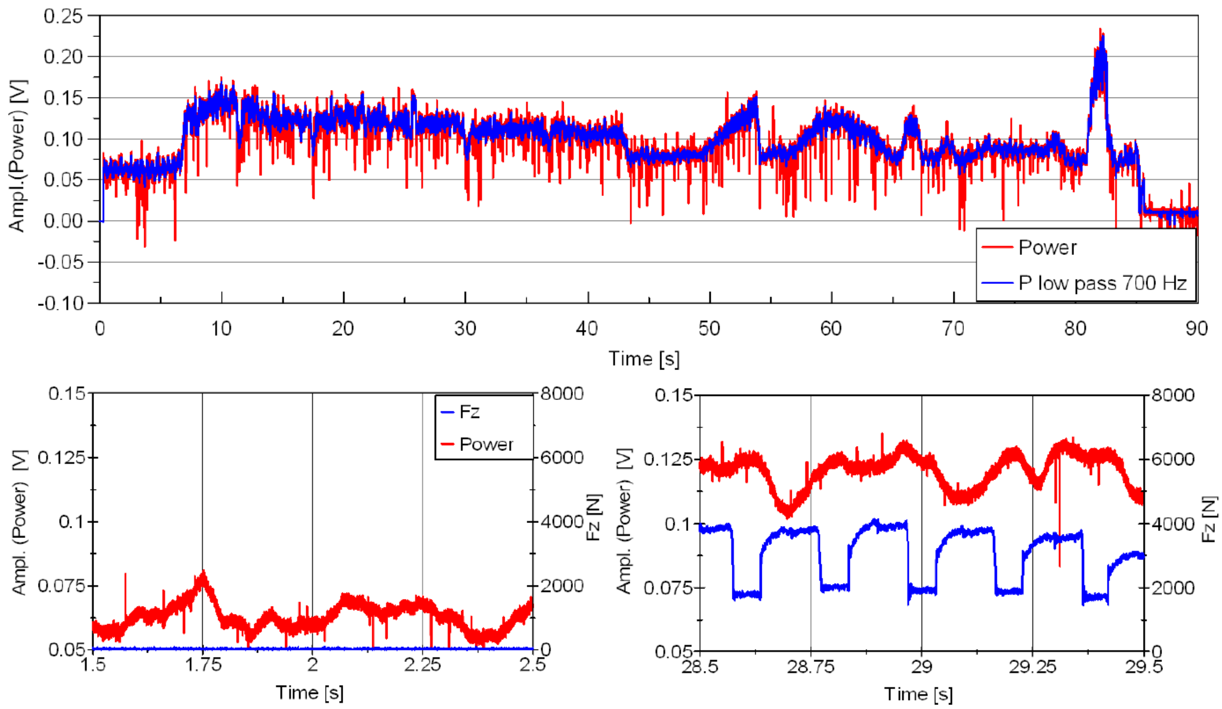


Figure 15.3: Effective Power and Force Measurement from a Broach Cut [Reference 4]

Figure 15.4 shows Process Monitoring signals from two damaged cutting teeth (severely chipped). The measurement on the left shows the power measurement (red) and the cutting force (blue) as well as the perpendicular push-off force (green) which, according to various literature sources, is more sensitive to tool wear. While the power signal (left, red curve) does not indicate the tool damage, the force measurement resolution is high enough to show an undesired vibration at about 600 Hz in the frequency domain plot (right, blue peak). The power signal, which was recorded using the same sample rate as the force measurement in this case, shows peaks in the frequency domain which have no relation to physical effects of the Broaching process.

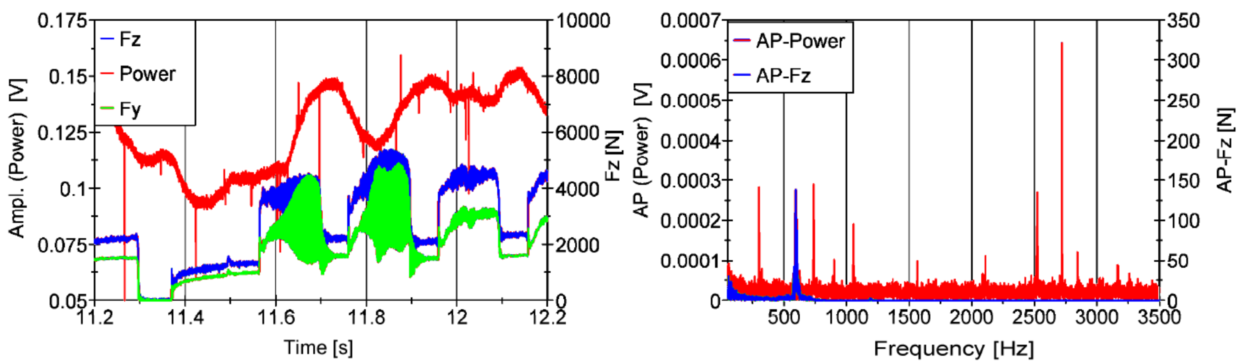


Figure 15.4: Comparison of Effective Power and Force Measurement for Defective Cutting Edges [Reference 4]

However, even if a precise force measurement system is used, cascaded static alarm limits may not be adequate since tool damage does not necessarily result in higher process power or force. Cutting edge chipping may even reduce the cutting force, as the cutting temperature can rise and soften the workpiece material. Current research is therefore developing strategies to provide more robust monitoring by combining different types of measurements as discussed in the section on Developing Technology for Broach Process Monitoring.

Research is also ongoing to correlate potential sensor signals and data analysis strategy outcomes to detrimental artifacts in the axial blade attachment slot, including

- Compromised Surface Condition due to excessive grain deformation or residual stress
- Anomalies caused by chatter/vibration due to excessive or uneven cutting forces
- Geometric Anomalies including re-bonded chips, laps, plucking
- Non-conforming slot geometry or Geometric Anomalies including mismatches, scratches, and gouges.

An approach using wavelet transformation (which combines data analysis in the time and frequency domains) to extract the stochastic portion of the power signal may be a sufficiently sensitive method to detect excessive tool wear or tool damage in real-time, but more study is needed.

Most process deviations or "Special Cause Events" in Broaching are attributable to cutter condition – either excessive wear or local damage. It is also possible for successive chips of the workpiece material to become lodged in the gullets between the cutter teeth, eventually leading to surface Geometric or Non-Geometric Anomalies if not cleared. If this leads to an increase in cutting force or power it may be detected by the systems noted above, but there is currently little research or data available verifying the detection capability for this condition.

Broach cutting fluid pressure and/or fluid flow Process Monitoring are easily done and commercially available. While these systems can detect issues including pump failures and closed valves in the delivery lines, they will not detect an adjustable nozzle which has not been properly aimed or which has been moved (for example during cutter set-up). Real-time fluid condition/health monitoring technology is still under development, but most Broaching is performed using enhanced petroleum oils which are very stable.

15.3.3 Emerging Technology for Broach Monitoring

Most of the Process Monitoring systems discussed above use methods where signal levels or features are associated with certain process conditions. In contrast, model-based approaches that include empirical data or physical relationships allow more robust and reliable identification of undesired process conditions and can be integrated with input from multiple sensors.

The major criticism of structured signal-based or classification approaches is the use of intermediate process data instead of physical values such as the process force vector and temperature field which have a direct impact on the tool or product quality. The thermo-mechanical load spectrum acting on a tool or workpiece is termed the "process signature" which describes the key physical interactions in a definite way.

For Broaching, an example of a model-based Process Monitoring approach is described in Reference 5 (see also Reference 6 for more generic information) where temperature fields are predicted by process forces using an analytical physics-based model. In this context, the relation between process temperatures and workpiece Surface Condition attributes such as tensile stress, white layer formation, and grain structure deformation are discussed against the background of forces and temperatures.

Analytical thermal models that predict temperatures based on the overall cutting energy determined using force or power measurements have existed for many years but have never been validated under real process conditions. Therefore, extensive thermal measurements of different Broaching conditions are a vital element according to Reference 5 which lead to significant adjustments to the existing temperature models.

The left graphic in Figure 15.5 presents the inputs required to model temperature fields:

- The cutting conditions input to the model include the rise per tooth or uncut chip thickness (RPT or t_c) and the cutting speed (v_c). For other machining processes (e.g., five-axis Milling) additional parameters are required to properly characterize the cutting conditions.
- The tool properties including the rake angle (α), clearance angle (Θ) and tooth pitch (p) are required to model the temperature field.
- The thermal conductivity (λ) and specific heat capacity (c_p) of the tool material are crucial model inputs. The temperature diffusivity (a) is determined by relating the thermal conductivity and specific heat capacity. Similarly, thermal properties are required for the workpiece material.
- Measured forces give essential feedback about the cutting process. Multiplied by the cutting speed, the force is a measure for the overall process power, which is broken down into the different heat sources. Force information is needed in three spatial directions to calculate the frictional forces required to distribute the thermal energy to the different heat sources at the tool, workpiece and in the shear zone. The quality of the input data is significantly reduced when using power rather than force measurements. Directional information is not available from power data.

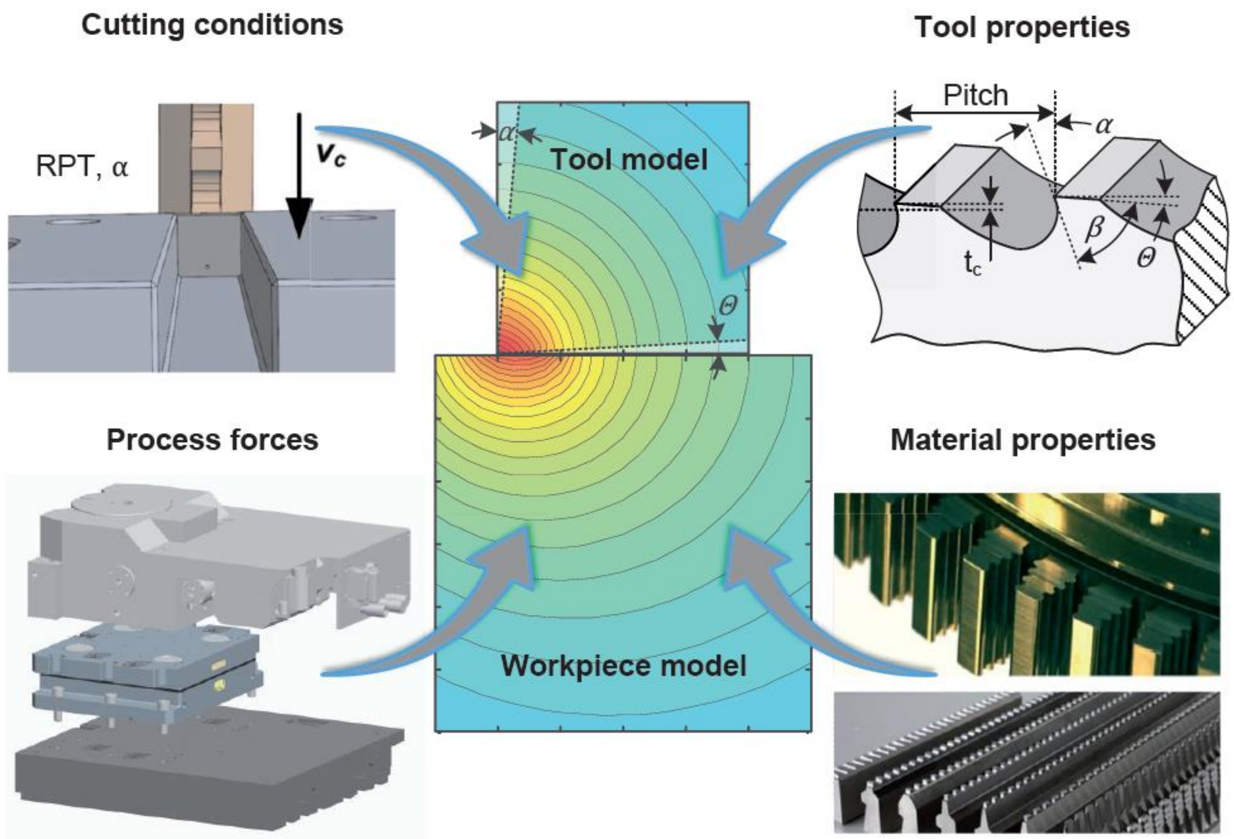


Figure 15.5: Required Inputs to the Process Monitoring System

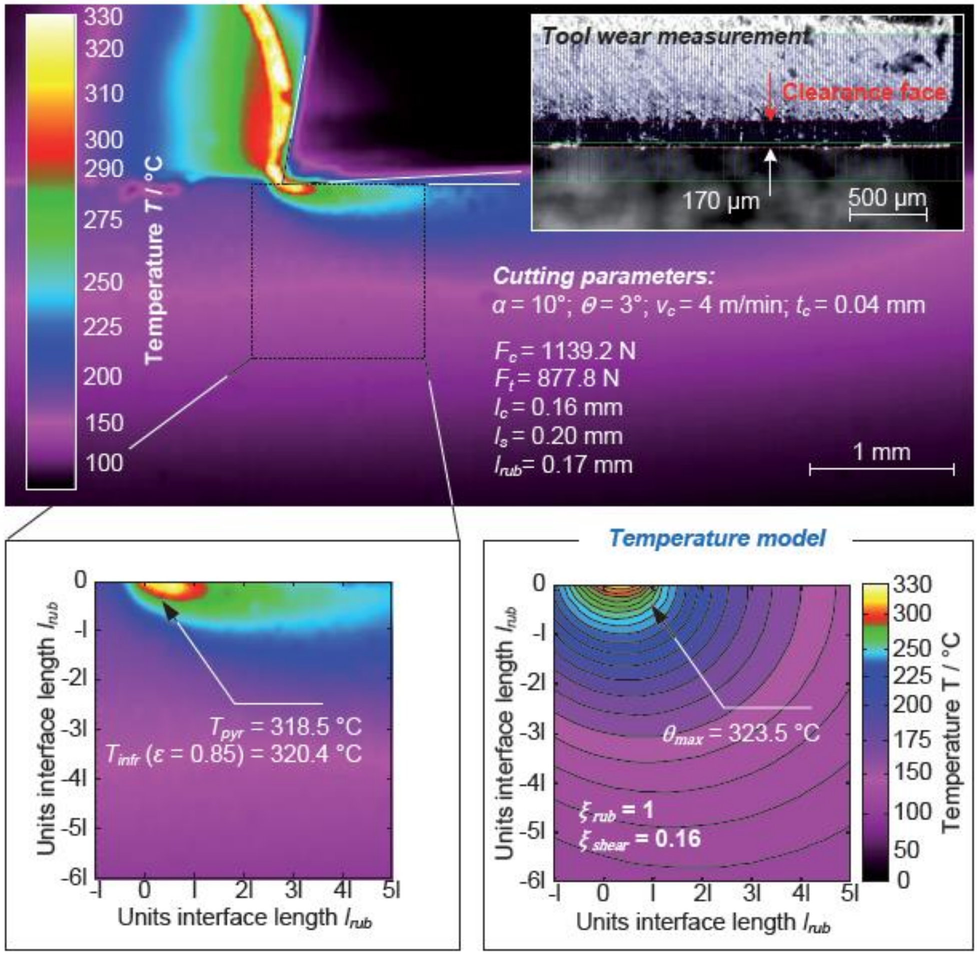


Figure 15.6: Comparison of Experimentally Determined and Modeled Temperature Fields in the Workpiece [Reference 5]

A predicted thermal image of a Broaching process cutting from right to left taking a chip from the workpiece is shown on the bottom right-hand side of Figure 15.6. The machining parameters, cutting force measurement, and the tool wear at this instant of time are listed in the top portion of the figure. An excerpt is highlighted showing the temperature field (measured by high-speed thermography calibrated using a two-color pyrometer, see Reference 7) at the lower left of Figure 15.6. The modeled temperature field is given in the bottom right which was calculated exclusively based on the inputs described in Figure 15.5. The model-based temperature Process Monitoring system from which Figure 15.6 is derived shows good correlation for a broad range of Broaching conditions with orthogonal cutting profiles including roughing and finishing parameters at different cutting speeds and tool wear states. Expansion of the model to incorporate complex finishing geometries such as dovetail or firtree slots may be an extension of this approach. An overview for implementing this type of system in an industrial environment is described in Reference 5.

In addition to the improved prediction quality of model-based approaches over signal-based or classification Process Monitoring strategies, physics-based approaches also help provide process knowledge, i.e., how tooling and process parameters impact the thermo-mechanical load spectrum acting on the product. Using signal-based strategies, the question is often how to assign alarm thresholds for “yellow” or “red” limits. The model-based approach, in contrast, is a method to translate process input parameters into thermo-mechanical loads in a deterministic way, which the statistics of the material (metallurgical differences within the boundaries of a specified material) predict a resultant probability that certain Surface Condition defects may occur.

Other in-process sensors, including temperature, vibration and acoustic emission are being evaluated for tool condition and machine health monitoring, but are not in significant commercial use at this time. Integrating thermal sensors (such as pyrometers or infrared cameras) is complicated because the emissivity of the material is unknown and hence an accurate temperature measurement is not yet practical. However, it may be possible to estimate temperature by correlating data from force sensors or calibrated power sensors.

15.3.4 Process Monitoring for Alternate Axial Blade Slot Manufacturing Methods

While Broaching and Milling are the most common methods used for manufacturing axial blade attachment slots, other processes such as EDM, ECM and AWJ can be used as noted previously. Process Monitoring for these processes is commercially available, albeit often focused on a stable process rather than the potential to introduce detrimental artifacts into the product.

- EDM: The main parameters for Process Monitoring are current and voltage. The Process Monitoring data can be used to calculate electrode wear and chances of faulty discharges to optimize rough or finish processing. Modern Process Monitoring systems can use fuzzy logic to determine and ensure surface roughness and geometric properties by controlling the relevant process parameters.
- ECM: As ECM is a forceless process at ambient to moderate temperatures, the only relevant characteristic in terms of safety aspects is geometry. Within the PEC-Machining (Precise Electro Chemical Machining), the circulation time can be used to both measure the gap as well as the position. This allows for very precise manufacturing with tolerances of 10 µm. Electrolyte flow is a critical parameter which should be monitored.
- AWC: Abrasive water jet cutting has recently been used for slot roughing and it is free of any thermal effects. However, fluid beam expansion can lead to geometric deviations. Therefore, the wear of the nozzle aperture is a common subject of Process Monitoring systems. Furthermore, the expansion of the water beam is a function of the water pressure, so water pressure is commonly monitored as well.

15.3.5 Process Monitoring for Axial Blade Attachment Slot Edgebreak Methods

Process Monitoring of edgebreak Manufacturing Methods used on the entrance and exit faces of the slot perimeter profile is not yet commonly performed. Even when Milling processes are used to cut the initial edgebreak, the light cuts and very low material removal rates make conventional power or torque monitoring difficult. Nevertheless, while using power or torque may not be feasible, using the frequency domain of high-frequency acoustic emission sensors have proven to be capable of Process Monitoring edge breaks using a Milling tool. Because Milling tools are generally made of hard metals (e.g., carbide) Milling tool breakage may be detected by sensing a characteristic pattern in the frequency domain output of an acoustic emission sensor.

The bulk processes frequently used for edge finishing (e.g., tumbling, abrasive flow, brushing, buffing, etc.) have few Process Monitoring options, but are also less prone to undetectable Special Cause Events. Rigorous Process Control and periodic inspection is usually sufficient to ensure consistent performance of bulk finishing Manufacturing Methods for axial blade attachment slot edgebreak features.

15.4 Process Modeling for Enhanced Process Validation

Computer modeling of Manufacturing Methods as referenced above is a rapidly advancing field. A number of finite-element and mechanistic models have been developed which attempt to predict the effect of Manufacturing Method inputs such as tool geometry, tool coatings, parameters, and Cutting Fluid application on outputs including cutting force, tool wear, workpiece thermal damage, and residual stress.

While Axial Blade Slot Manufacturing Methods are not yet commonly modeled, the use of modeling to predict cutting forces has seen some application. These predictions can be used to optimize Manufacturing Methods, for example by improving cutter designs, eliminating transient peak forces (aka, force spikes) that can damage the cutters, or to accommodate stiffness limitations of the machine, workpiece, or fixture.

15.5 Geometric Characteristic Verification

15.5.1 Verification of Geometric Characteristics

The loads/stresses on the rotor axial blade attachment slot and mating blades are influenced by the contact zones between them, as well as stress concentrations that can occur due to Geometric Anomalies. Because the rotor components generally operate at high stress and/or temperature, many geometric characteristics have very tight tolerances. Critical axial blade attachment slot geometric characteristics can include:

- Slot perimeter profile
- Pressure face flatness and parallelism to the rotor component centerline
- Slot position (centerline, radial distance, spacing variation)
- Profile discontinuities, blends, reversals, gouges, ridges, etc.
- Edgebreak size, consistency, transitions, absence of burrs
- Slot and edgebreak surface finish
- Radial pressure face to pressure face spacing (see Figure 15.7 dimension P) in a multi-lobe axial blade attachment slot

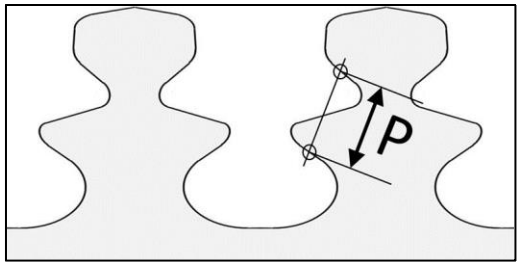


Figure 15.7: Pressure Face Spacing (P) in a Multi-Lobed Axial Blade Attachment Slot

15.5.2 Slot Inspection Techniques

The most common NDE Technique to evaluate whether the profile of a slot is within tolerance is the use of an optical comparator (shadowgraph). Light projected through the slot creates a magnified shadow on a glass screen. The screen supports a transparent mylar master on which is inscribed the minimum and maximum tolerance bands. Twenty times (20x) magnification inspection is common, but other magnifications are used, depending on the size of the slot and the comparator. Angular, X, Y, and focus adjustments are required to determine a best fit of the shadow within the profile, so skilled inspectors are required.

Production rotor parts (or a statistical sample of production rotor parts) are usually measured directly on a comparator. It is common to measure multiple slots on each disk because factors during machining of the slots including pre-slotting, cutter wear, workpiece and machine stiffness, cutting forces, and whether there is an adjacent slot installed relative to a slot currently being cut can affect slot geometry to a measurable fraction of the tolerance. However, in some instances a slot cut into a metallic or graphite coupon is evaluated instead, particularly for large disks that are not practical to mount on a comparator. In some instances, rotor part coupons of a more readily obtainable material than the production part forging are used. Since factors including the coupon material, coupon thickness, and fixtures can cause subtle differences between the slot cut in the coupon and the slot cut in a production rotor part, when coupon inspections are used to establish the geometry of production hardware the inspection strategy must be validated to ensure the production part meets the Design Intent.

In other instances, instead of mounting the complete rotor part on the shadowgraph, a casting of the slot is made using a material similar to that used for dental impressions. A slice of the solidified material is then assessed for profile conformance only. Slot geometric size and positional data are still assessed using the production rotor part.

High quality castings of detected Geometric Anomalies can also be assessed on specialized optical scanners that are capable of micron measurement resolution detection levels.

Inspecting the profile on the comparator can also identify unacceptable Geometric Anomalies that fall within the tolerance bands (e.g., blends, mismatches, and reversals). However, Geometric Anomalies that do not occur over the entire length of the slot will typically not be visible in a shadowgraph inspection because the shadow represents the maximum material condition. Comparator images can also be influenced by exit burrs, dirt, or oil, so it is important that the slot be free of burrs and carefully cleaned prior to comparator inspection.

While most NDE Methods rely on the inspector to visually evaluate the conformance of the slot perimeter profile, comparators are now available with cameras that can capture a digital profile of the slot for automated analysis. Use of these automated systems is not yet widespread. With the increasing resolution of digital cameras, stand-alone optical systems (not integrated with a comparator) and other optical NDE Techniques are also being proposed for axial blade attachment slot inspection.

There are a variety of NDE Techniques used to verify slot characteristics beyond the slot perimeter profile. In some cases, comparators have been adapted to measure pressure face radial distance and slot centrality, but these and other measurements are also made with a variety of gages or on full contact scanning coordinate measuring machines (CMMs). When using CMMs, the effect of probe size must be considered, as larger probes can mask small non-conformances. Some slot characteristics are commonly measured by clamping a calibrated artifact ("flag") in the slot to mimic a blade, then taking measurements from the flag.

In addition to the various NDE Techniques and equipment, a visual inspection is often specified. Anomalies that are discontinuous, within the tolerance band, or very small can in some cases be detected visually, and then be investigated further with targeted NDE Technique(s).

A NDE Technique measurement system assessment should be performed to ensure the NDE Technique has the measurement resolution to measure the target slot characteristic. For this reason, multiple NDE Techniques are often required to validate the slot characteristics and meet the Design Intent.

Due to the complexity of verifying axial blade attachment slot characteristics, it is especially important that the design responsible company and manufacturing source are in concurrence with respect to the slot characteristics, measurement techniques, and acceptance criteria.

16 Appendix J: Guidelines for Mechanical Finishing of Titanium to Prevent Surface Damage and Spark Impingement

16.1 Purpose

The information in this appendix is a compilation of best practices to increase safety of high energy rotating aircraft engine parts. The industry has many documented instances where damage inflicted on titanium rotating parts from hand work and re-bonded sparks has led to a detrimental Surface Condition.

16.2 General Information

This appendix is to be a guideline for mechanical finishing of titanium major rotating or other Critical Rotating Parts to prevent surface damage that could result in surface initiated cracks.

This does not include strategies for processes that generate high energy conditions such as welding, water jet machining, flame cutting, high temperature coatings, Electrical and Chemical Discharge Machining, etc. which can also produce sparks and overheating conditions that require process validation and special controls.

Nor does this appendix provide the information about how sparks are created, what they are or how re-bonded sparks ultimately damage the finished part surface material.

Mechanical finishing is defined as power-assisted machine or hand polishing, blending and/or edge breaking, not under a flood Cutting Fluid, which includes the use of air guns, hand-held electric Grinders, abraders, belt sanders, polishing lathes, and rotary tables, etc., or a combination of these tools.

Refinement of the Manufacturing Process to achieve required surface finish and edge geometry is preferred over the use of hand finishing. These guidelines apply to power-assisted hand, machine and/or automated finishing when post-process anomaly removal is required. All manufacturing, automation and hand finishing operations require Process Validation and Process Control. The proper combination of finishing controls and protection of surfaces is necessary to prevent finished part surface damage.

Detailed process steps are the responsibility of the manufacturer and should be documented in the process work instructions, Manufacturing Control Plan and/or determined by the Manufacturing Methods.

16.3 Spark Prevention Strategy

There are many companies that offer low speed electric and air Grinding tools marketed as “Low or No Spark” tools and often referred to as “Safety Tools”. These tools are sold in the oil industry as safe methods of Grinding to prevent fires. The key to these tools not producing sparks is the combination of cutting tool material, rotating wheel size and slow operating speed (revolutions per minute). “No Spark” tools that limit tool speed to 1,000 revolutions per minute are one example.

Application of “Safety Tools” is another strategy that can be applied to Critical Rotating Parts to prevent part damage. The key learning from the use of “Safety Tools” is to control the speed of the cutting material at the point of cut to less than 25.4 m/sec (5000 surface feet per minute).

There are many electric and air-operated hand Grinding devices to choose from when designing a power-assisted finishing process. The manufacturer should select a good combination of a low speed Grinding device and moderate sized cutting wheel. The manufacturer should evaluate various combinations of power tools and cutting materials to find the best fit for the process.

Example Combination:

Surface speed = RPM * diameter * π

For a 2400 RPM air gun and a 0.150 meter diameter wheel,
2400 * 0.150 * π / 60 = 18.9 meters per second

For a 2400 RPM air gun and a 6 inch diameter wheel,
2400 * 6 * π / 12 = 3772 feet per minute

16.4 Spark Impingement Prevention

For the purpose of this appendix, spark impingement is defined as an Anomaly caused during operations such as machining, Grinding or hand benching (i.e., hand finishing). It occurs when a hot chip or particle lands on a finished part and re-melts to its surface. Spark impingements are known to be created from finishing techniques on the subject part or adjacent processing from other parts. Spark impingement prevention methods include:

- Apply a processing technique that does not produce sparks
- Apply surface speeds under 25.4 m/sec (5,000 sfpm)
- Apply grit sizes under 150 ANSI (89 microns average / 0.0035 inches average)
- Protect the finished surfaces from the sparks

16.5 Best Practices

- When applying a process that can create a spark (for example, burr removal, polishing, edge breaking, etc.), the surface(s) processed and adjacent surface(s) should be masked or covered to protect the finished part. One best practice is to cover exposed part surfaces with Cutting Fluid or oil to act as a mask. The Cutting Fluid or oil should be in the concentrated state, not mixed with water, so as to provide a film on the surface of the part that will act as a barrier to cool the hot spark before the spark reaches the part surface. This film should be replenished often to ensure the protective film is available throughout the application of the spark producing process.
- Separate the processing of titanium parts from the processing of other materials to reduce the use of wrong tools and contamination.
- Use dedicated work stations, barriers or screens to prevent sparks migrating from other parts and processes (including processes which may be associated with facility maintenance or construction).

- Beneficial compressive surface residual stresses, such as those created by peening to a minimum intensity of 4A, should be introduced to ensure any residual embedded grit from the polishing or blending does not adversely affect the part fatigue life. This is of particular concern for part features which are not required to be peened or only peened to complete coverage and when the feature stress level is moderately high to high and the life limiting stress is perpendicular to the lay of the polishing or blending scratches.

16.6 Compatible Materials

The Cutting Fluid or oil used to protect finished surfaces during mechanical finishing should be controlled or restricted to those materials that have been tested to be compatible with titanium and not subject to chemical attack or reaction. The oil should have a high flash point and have low volatility and should never be atomized as oils will have a reduced flash point in a vapor state. For example, oils such as Mobile/Exxon DTE 25, Castrol Hyspin AWS 46 and Altra AW46 have been proven to be effective and free of chemical reaction on titanium.

16.7 Polishing or Blending Pressure

Overheating should be avoided while polishing or blending. A light, even pressure on the abrasive by the operator or machine will give the best results, as it allows the abrasive to cut freely without loading. Loading occurs when the part material being removed accumulates in the spaces between the abrasive grit, reducing cutting effectiveness, increasing polishing forces and temperature, and creating a condition where the accumulated material is rubbed back against the part being finished.

Heavy or extreme pressure exerted on the abrasive by the operator or machine will cause it to load and result in "orange peel" or burning of the metal. The use of a coarse stone dressing stick can be used to clean the abrasive and will provide better results without being aggressive on the part surface.

16.8 Polishing and Blending

Polishing and blending are the Manufacturing Methods most associated with spark creation.

Polishing, unlike deburring, is typically performed on large surfaces of the part where significant work is required to accomplish the desired finish.

Blending is intended when there is a surface discontinuity such as a dimple or transition between two surfaces and the requirement is to blend the higher surfaces down to the lowest surface. Typically blending is required to reduce the stress field at a transition or to remove a tool mark.

Silicon carbide abrasive should always be used for polishing and blending the surface of titanium parts. Silicon carbide is more friable than aluminum oxide. Silicon carbide is thus able to refresh its sharp cutting edges, delay loading of the tool and reduce cutting temperature.

To remove heavy lines, or for stock removal on titanium parts, coarse abrasive (typically 120 to 150 ANSI grit size) should be used. To refine the surface to the Product Definition requirements, use progressively finer abrasive until the requirement is met. The operator should ensure that each preceding tool or Grinding line is removed before the next finer abrasive is used, and should replenish the protection Cutting Fluid / oil frequently. If necessary, final passes could employ the use of non-abrasive cloth buffing wheels and very fine, over 400 ANSI grit size, polishing compounds.

Polishing can generate hot sparks unless the process is controlled. Limiting the air gun or grinder speed and the wheel size will significantly reduce the risk of burning the part or making sparks.

Best practices include:

- Use power tools with rotation speed limited to under 3,400 RPM
- Use cutting abrasives with the cutting wheel / abrader tip wheel under 150 mm (about 6 inches)
- Limit abrasive size to 150 ANSI grit size or finer
- Use physical barriers / masking and oil / Cutting Fluid barriers

The slow surface speed will minimize part burning and the use of light oil on the part surfaces will protect from spark impingement. When polishing disk web areas, power rotation of the part will increase efficiency and reduce variation.

The manufacturer should apply fixed RPM tools or tools where the maximum RPM achieves the required process controls, as the application of variable speed tools adjusted to meet process conditions is not mistake-proof and people may re-adjust the speed upwards to increase cutting action.

No speed restrictions are necessary when applying cloth wheels with liquid abrasive for fine finish polishing.

16.9 Deburring / Edge Breaking

Deburring is intended to remove small volumes of material to break or profile part edges, typically using small carbide cutting tools or small abrasive tools. The same surface speed rules, as previously discussed, apply to prevent spark creation.

Small diameter cutting tools work well and will stay within the surface speed limits. Cutting tools made of tool steel, carbide, silicon carbide and aluminum oxide can all work well for deburring.

Cutting tools with very fine abrasive, such as found in impregnated nylon and fiber unified wheels, work well with surface feet above the 25.4 m/sec (5,000 surface feet per minute) restriction, but process validation should include an evaluation for the transfer of wheel material to the finished part. A best practice is to apply cloth wheels with liquid abrasive to remove the film left by impregnated nylon and fiber wheels.

Often deburring an edge with a hard tool is followed by blending or polishing to remove tool marks on the edge and the surfaces adjacent to the edge. The Manufacturing Method should follow the rules in this appendix for blending and polishing these transition areas.

16.10 Final Notes

The methods to prevent spark impingement provided in this appendix have been proven in production environments for more than 40 years. Process Validation and implementation of an appropriate Manufacturing Control Plan are key to achieve success. It is also very important to scrutinize manual Manufacturing Methods and seek automation, as Human Factors make it very difficult to ensure true Process Control. Follow the same tool control rules in this appendix when applying automation to prevent the creation of sparks. Apply Cutting Fluid, oil and polishing compounds during finishing to prevent detrimential Surface Conditions arising from spark impingement.

Once a metal spark has attached to the finished part surface, just removing the attached nodule does not remove the surface damage created. Evaluation of the Surface Condition requires destructive testing and life impact evaluation to develop a repair for future instances. These are costly alternatives to applying a Manufacturing Process using proven Process Control methods.

16.11 Related Technical Papers / Information

1. Hazard and Health Considerations (Reference 8, page 29) includes the following guideline from Reference 9:

   "Occasionally, titanium turnings may ignite when the metal is cut at high speeds without the adequate use of a proper Cutting Fluid. The situation is similar when titanium is ground dry because of the intense spark stream."

2. Setup Conditions (Reference 8, page 91)

   "A grinding fluid should be used when taking continuous cuts over fairly large areas. It reduces grinding temperatures and quenches the intense sparking that occurs when titanium is ground. Because of the extremely hot sparks formed by titanium, only sulfochlorinated grinding oils possessing high flash points (above 325^{o}F) should be used. They should be applied close to the grinding point for rapid spark quenching."

17 Appendix K: The Turning Manufacturing Method

Turning is used to machine axisymmetric features in all materials, including titanium, steel, cast-wrought nickel, and powder-metal nickel alloys. Because most Critical Rotating Parts have primarily axisymmetric geometry, Turning is the most common Manufacturing Method for these types of components. Turning is typically not only capable of the highest specific material removal rates in^3/min (mm^3/min) of the conventional machining methods, but it can also produce tight tolerances and fine surface finishes.

Turning is best suited to producing rotationally continuous (i.e., circular, full hoop or axisymmetric) “smooth” surfaces. Turning cannot be used where the circular surface is interrupted by positive-material features such as bosses. In such instances Turning can be used to machine the outer diameter surfaces and the material between the protruding features is typically Milled. Conversely, it is possible to Turn surfaces that include negative-material interruptions such as holes and slots. However, this is a less robust method that results in accelerated tool wear. It can create localized Surface Condition non-conformances and must be evaluated against the Surface Condition requirements of the part.

17.1 Turning: General Information

17.1.1 Manufacturing Method Overview

Turning is a two-axis machining method where the cutting tool moves in the radial (towards or away from the axis centerline) and axial (parallel to the axis centerline) directions while the material rotates about its axial centerline. Turning is typically performed on a lathe, although modern multi-function machine tools make it possible to Turn features on other types of machines and to perform machining operations like Milling on lathes.

Typical Critical Rotating Part features produced by Turning include inner and outer diameters, bores (small bores may be produced by Holemaking methods), hubs, webs, hooks, flanges, seal teeth and other axisymmetric features. Most Turned surfaces have a constant radius about the part centerline, but it is possible to produce somewhat non-round cross-sections by precisely varying the radial position of the tool within each rotation of the part.

The method parameters in Turning are cutting speed (feet/min or m/min), depth-of-cut (inches or mm), and feedrate (inches/workpiece revolution or mm/workpiece revolution). See Figure 17.1. These three parameters determine the material removal rate (in^3/sec or mm^3/min).

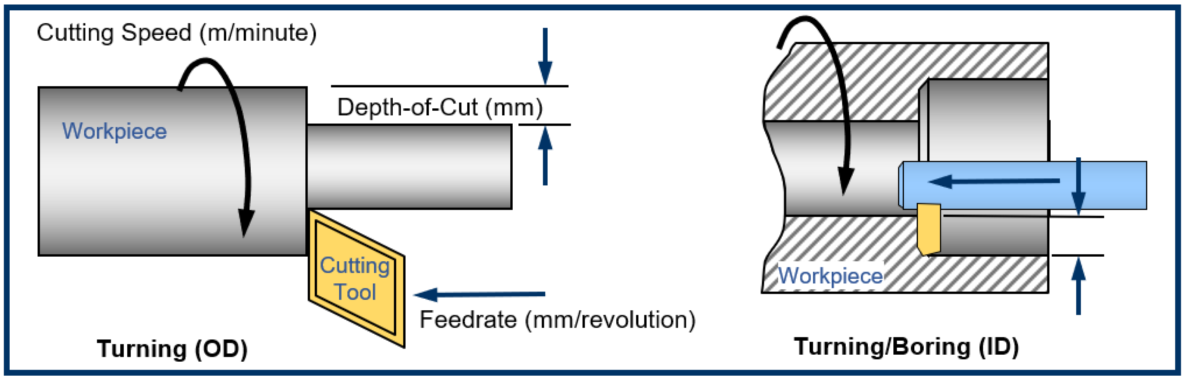


Figure 17.1: Turning Process Parameters

As with other conventional machining methods, cutting speed is related to heat generation (higher cutting speed produces more heat) and strongly influences tool life (higher cutting speed typically decreases tool life). The depth-of-cut and feedrate are primarily related to cutting force. Increasing either parameter will increase the cutting force, which can have implications for tool life as well as workpiece or tool deflection that reduces geometric accuracy. Finally, the feedrate, in conjunction with the tool geometry, defines the surface finish. Higher feedrate will produce rougher surface finishes.

17.1.2 Cutter Geometry

Almost all modern Turning operations use replaceable cutting edges, commonly referred to as "inserts". This allows the bulk of the tool (i.e., the "toolholder") to be made of a cheaper material like steel, while the cutting edge is made of more durable material. Inserts are typically affixed to the toolholder with a screw clamp and can be replaced quickly. Also, because the toolholder does not have to be moved to replace an insert, tool realignment is typically not required when an insert is replaced. This reduces set-up time and improves precision.

Inserts are available in a wide variety of shapes and sizes, including round, diamonds of various aspect ratios, and custom shapes designed to produce a particular geometry on the workpiece. Many of the generic shapes can be rotated or flipped such that a single insert offers multiple cutting edges.

Some inserts have complex topography (chip breakers) pressed into the rake face to break the nominally continuous chip produced in most aerospace alloys into smaller, more manageable pieces which can result in a more stable process.

The cutter "nose" radius determines the smallest workpiece feature that the insert can cut and, along with the feedrate, defines the surface finish. Most of the rest of the cutting geometry, including the rake and clearance angles is controlled by the orientation of the toolholder. A representative cutter/insert geometry is presented in Figure 17.2. As with other machining methods, the rake angle influences the cutting force, chip formation, and cutter edge strength. The clearance angle prevents rubbing of the insert on the freshly cut surface immediately behind the cutting edge. For OD Turning this is a minor concern because the workpiece geometry naturally fades away behind the cutting edge, but for ID Turning, a generous clearance is required to prevent rubbing. Clearance for the tool holder must also be considered to ensure that it doesn't rub against the workpiece away from the cutting zone. This is particularly true where the cutter must be manoeuvred into a confined space under manual control, such as when an operator is required to make an offset adjustment. Tool holders are typically made of steel, which may be softer than the work material. An inadvertent rub can transfer material from the toolholder to the workpiece surface, which is difficult to detect but can have a negative impact on the Surface Condition.

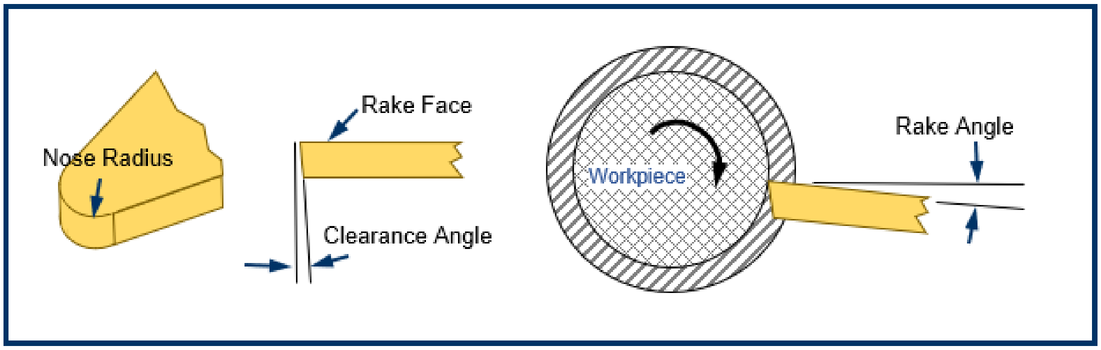


Figure 17.2: Cutter/Insert Geometry

The geometry of the cutting edge itself can have a significant impact on cutter performance and on tool wear. Edges that are too sharp can be weak and prone to chipping. A chamfered or rounded edge is stronger but will result in increased cutting forces. Most standard carbide inserts are pressed and sintered, which naturally produces a very slight rounding of the edge. Some insert coatings have a similar effect. However, custom carbide inserts, and other insert materials are typically ground, which produces a sharp edge. These inserts may be post-processed (conditioned) to produce a slight edge chamfer or rounding – typically 0.001 inch (0.025 mm) or less. This edge conditioning is particularly necessary when cutting nickel alloys, which require good edge strength to avoid edge chipping.

17.1.3 Cutter Material

Tool materials including tungsten carbide ("carbide"), ceramic, cubic boron nitride (CBN), and diamond are commonly used to Turn aerospace alloys. Each is available in various grades. Characteristics including grain size, binder percentage, fibre reinforcement, and coatings are tailored to optimize performance for a specific alloy or application to provide an insert with appropriate hardness, toughness, or temperature resistance.

Carbide is the most common tool material and is useful for all aerospace alloys. It is economical, has a good combination of toughness and hot hardness, and provides a wide range of performance across the range of available grades and coatings.

Ceramics have significantly better hot hardness, allowing them to be run at higher cutting speeds/temperatures than carbide. However, they are not as tough as carbide, and whisker-reinforced grades are typically required to machine aerospace alloys. They are not suitable for use on titanium alloys.

Superabrasive tool materials (CBN and diamond) provide superior hot hardness and thermal conductivity resulting in potentially long tool lives at high cutting speeds. Diamond is suitable for machining carbide and non-ferrous alloys, while CBN is used for ferrous and nickel-based alloys. Most grades lack the toughness required for interrupted cuts in aerospace alloys.

Somewhat counterintuitively, ceramic and superabrasive cutting tools can perform poorly when run at cutting speeds which are too low. The localized heat produced by higher cutting speeds reduces chipping of the cutting edge and improves tool life. There are additional best practices unique to these cutting tool materials (e.g., programming techniques to reduce the propensity for a depth-of-cut notch to form in ceramic tools) that are critical to their successful application. Cutting tool manufacturers have resources available to optimize the performance of their products.

Coatings can be applied to many of the basic tool materials to improve the performance of the tool in a specific application. For example, a coating with good thermal resistance might be applied to a tough carbide grade to allow higher cutting speeds or longer tool life. Coatings are often developed specifically for a particular tool material grade, with the combination targeting a narrow range of process and workpiece material applications (e.g., Turning of nickel alloys).

Ultimately, the choice of cutting tool material is an economic decision, weighing the benefits of achievable cutting parameters against tool life and tool purchase cost.

17.1.4 Cutter Wear and Maintenance

Tool wear is measured on the clearance face of the tool, see Figure 17.3. The amount of wear often varies along the arc of contact with the workpiece. This is particularly true for ceramic inserts, which are prone to significantly higher wear at the maximum depth of contact (“depth-of-cut notch”). Other forms of tool wear, such as edge chipping, indicate issues with the tool material, tool geometry, or method parameters.

As cutters wear, the edge recedes, resulting in a slightly reduced depth-of-cut (stock-on condition). This is exacerbated by increasing cutting forces which can lead to deflection. While the combined effect is usually small (<0.002 inch (<0.05 mm)), compensation may be required when cutting dimensions with tight tolerances.

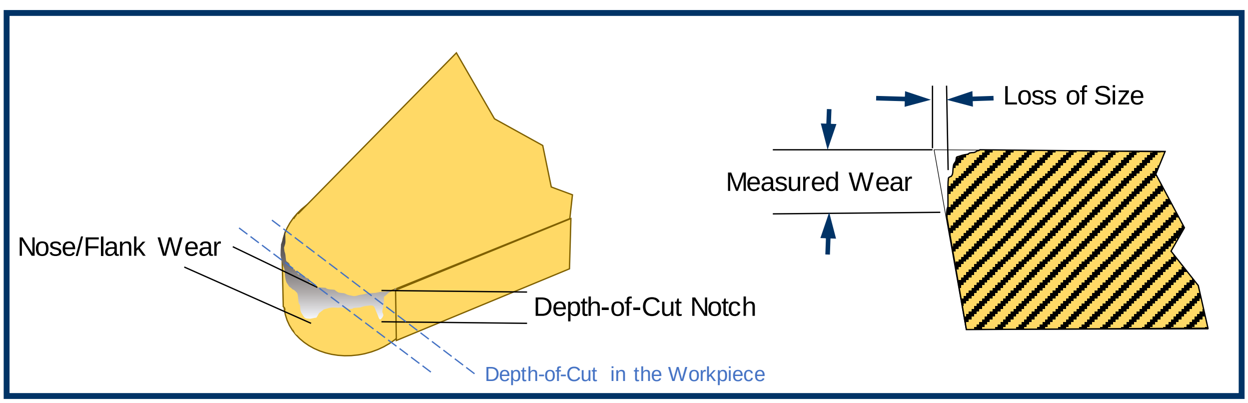


Figure 17.3: Tool Wear

Cutting forces and heat generation both increase as the cutter wears. Overly worn cutters can produce undesirable Surface Condition changes, including excessive grain deformation, undesirable residual stress, re-bonded workpiece material, and Geometric and Non-Geometric Anomalies. The higher forces also increase the risk of cutter failure. For these reasons, a strategy to replace or re-sharpen the cutters before they become overly worn is mandatory, especially for tools that are used on the final passes which produce finished surfaces.

Most Turning operations use inserted cutters, and the vast majority of inserts are discarded/recycled after each available cutting edge has been used. Inserts made of more expensive materials or those produced in custom shapes may justify the cost of re-sharpening, assuming the insert does not include a chip-breaker geometry. Re-sharpening typically involves Grinding back the clearance face of the cutter until the worn edge is removed. Another approach is to Grind the rake/top face, which will change the profile of the cutter very little but reduces the height and thus typically requires a program offset (geometry adjustment). In either case, the edge must be returned to the original geometry and quality by the re-Grind process. Cutters may also be re-purposed as the size is reduced by Grinding. For example, a 0.4 inch (10mm) round cutter could be sharpened to a 0.36 inch (9mm) diameter. If coated inserts are re-ground, they must be re-coated to ensure that performance is consistent with new inserts. For this reason, most coated inserts are discarded when worn.

The consistency of cutting tool material properties and geometry is generally excellent, however many users can cite cases where a batch of tools failed to perform as expected due to a manufacturing issue at the tool supplier. This is a particular risk where the tool is being used near the edge of its capabilities or where dimensional tolerances are extremely tight. Off-specification tools can also pose a risk to the Surface Condition of the workpiece. Where tool performance issues can affect product quality, a risk abatement strategy is necessary. Examples include incoming inspection, third-party sampling, real-time Process Monitoring, periodic auditing of tool condition (wear), and statistical process control (SPC) trending of workpiece dimensions. The risk of geometry variation and edge condition tends to be greater for re-ground tools, so risk abatements are also necessary when tools are re-ground.

Changing cutting tool suppliers/sources requires thorough Process Validation. Contractual language should also be in place to ensure users of cutting tools are informed when changes to the tool material or tool processing are made by the cutting tool supplier. The cutting tool supply chain should be managed as a fixed/frozen process.

Toolholders also require a strategy for condition monitoring and maintenance. Both the mounting surface for the cutting insert and the surfaces that mate to the machine tool are subject to wear. Worn toolholders can result in tool breaks due to inadequate insert support/clamping (e.g., under-clamped or over-clamped), cutting edge chipping or fracture due to vibration, and geometry variation due to clearance at mating surfaces. Each of these conditions increases process variability.

17.1.5 Set-up and Process Validation

As with all finish machining, the Turning method must be developed and validated as a portion of the Manufacturing Control Plan. Controlled parameters include:

- Cutting Speed (feet/minute or m/minute): The cutting speed influences heat generation. For most tool materials and applications this correlates to tool wear, so increasing the cutting speed results in accelerated tool wear and decreased tool life. However, for heat-resistant tool materials like ceramics and superabrasives, running hot enough to soften the material in the chip may be necessary to improve cutting efficiency and achieve acceptable tool life. Finally, in some materials (e.g., stainless steels), cutting too slowly can result in a poor surface finish due to phenomenon known as built-up-edge, where some of the work material bonds to the cutting edge rather than flowing smoothly up the rake face with the chip.

- Feedrate (inches/revolution or mm/revolution): The feedrate influences cutting force. More aggressive feedrates produce higher forces, which can result in deflection of the tool or workpiece and difficulty in holding tight tolerances. The feedrate also directly impacts surface finish, with higher feedrates producing a rougher finish (assuming consistent tool geometry). While feedrate does not typically have a strong influence on the tool wear rate, excessive forces can lead to edge chipping or tool fracture.
- Depth-of-Cut (inches or mm): Like feedrate, the depth-of-cut influences cutting forces, but unlike the feedrate it does not impact surface finish. To reduce the deflection/inaccuracy that can result from high cutting forces, the depth-of-cut on finishing passes is typically very light.
- Cutting Tool: The selection of tool material and geometry influences the achievable material removal rate and the tool wear rate. Changing the insert grade or geometry used on a validated process may result in an increased tool wear rate, therefore changes to the cutting tool require the process to be re-validated.
- Tool Change Point: Influences cutting forces/tolerance, Heat-Affected Zone, and Surface Condition. Tool Change Points or criteria are determined by evaluating the length that can be cut while maintaining the Design Intent. Tool wear measurements should be included in the Turning Process Validation and tool wear consistency should be monitored during production to ensure the specified Tool Change Point continues to meet the Design Intent.
- Cutting Fluid: The cutting fluid type (water soluble, synthetic, oil) and method of application (pressure, direction, flow rate, and temperature) influence the tool wear rate, heat-affected zone, surface Anomalies (e.g., re-bonded material) and surface finish. The primary benefit of the cutting fluid in Turning is to reduce the friction between the chip and the rake face of the cutting tool. The fluid also removes heat and helps to transport chips/swarf away from the cutting zone. Improved chip flow over the rake face and good flushing of the swarf can reduce the risk of surface Anomalies such as micro-burrs, re-bonded chips, and smearing.

  Low pressure “flood” Cutting Fluid application is adequate in many cases, but modern machines are frequently capable of delivering fluid at pressures of 1160 psi (80 bar) or higher. This can improve tool life and allow higher cutting speeds. High pressure Cutting Fluid can also assist in breaking long stringy chips typical of ductile materials, especially when applied using nozzles directed at the zone where the chip forms against the rake face of the tool. A number of cutting tool companies offer high pressure nozzle systems incorporated into the tool holder to optimize chip control and improve tool life. Systems that deliver pressures significantly above 1160 psi (80 bar) are also available but are in limited use. They can provide chip breaking for very tough alloys, but under some circumstances can promote the bonding of chips to the surface of the workpiece, which is undesirable. Pulsed delivery of high-pressure Cutting Fluid can present a risk to the Surface Condition in some situations.

There are several other cooling/lubrication technologies that serve niche applications, but they are not widely used for Turning of aerospace alloys. These include micro-lubrication (small amounts of oil delivered by pressurized air) and various cryogenic strategies (e.g., liquid CO_2 or N_2, sometimes combined with a lubricating fluid).

Fluid condition must be maintained to ensure consistent process performance. The required maintenance depends on the fluid type. For example, concentration, pH, cleanliness, and tramp oil are some of the characteristics that must be managed for water-based fluids. Straight oils have different maintenance requirements. Temperature should also be controlled for all types of fluids.

Some process parameters have a greater impact on the Surface Condition than others, and in some cases a parameter may be validated across a range. Also, because Turning is so ubiquitous, some cuts may not pose a risk to the durability of a part (e.g., roughing operations that leave sufficient stock, finish Turning of low-stress locations). The Design Authority must have a strategy to identify which Turning operations require Process Validation, the Process Validation requirements, and the necessary degree of process parameter control including which process parameter changes require re-validation.

17.1.6 Process Control

The ideal Turning method does not require any operator intervention, other than to monitor the method for Special Cause Events. As with any Manufacturing Method, human intervention introduces Process Variability, even when the operators are highly skilled.

Most Turning operations performed on Critical Rotating Parts utilize computer-numerically-controlled (CNC) machine tools. The geometry and process parameters are pre-programmed and generally not adjusted by the operator. In some instances, the operator may be required to adjust the geometry of the final cutting path to compensate for tool wear and other process variation. In such instances, the operator will perform a measurement after the prior cut and manually input an “offset” into the program without adjusting the other process parameters.

Machines may also be equipped with contact or non-contact probes that allow the measurement to be made automatically after which the machine calculates and applies the required offset. This approach is preferred, as it minimizes the opportunity for measurement error and eliminates the possibility of the operator inadvertently typing an incorrect offset. The probe may also be used at the beginning of the program to check the location of reference features on the workpiece to verify it has been loaded in the correct position and the run-out is within requirements.

The cutting tools/inserts should be pre-selected, qualified, and managed such that the same geometry, grade, and coating are used each time a cut is performed. When the operator is allowed to select between alternate tools, each tool should be pre-qualified. A disciplined strategy is required because cutting inserts of different materials, coatings, and detailed features may be physically interchangeable but perform differently.

Tool Change Points should also be pre-determined, with the machine programmed to pause the operation for the insert to be changed. Many machines include a tool magazine which allows for the machine to replace the worn tool with a fresh tool without operator intervention. Either during a manual in-process tool change, or when inserts are replaced after an operation is complete, the operator should note any unusual condition of the worn cutters (e.g., Tool Breakage or excessive wear) for investigation by a process engineer.

17.2 Turning: Process Monitoring

17.2.1 Process Monitoring Overview

A number of Process Monitoring strategies are available for Turning, but with the exception of probing and Cutting Fluid monitoring, most are not yet in widespread use. This is mainly due to the complexity of analyzing the sensor signals to provide information to benefit the process. Process Monitoring strategies fall into several broad categories:

- Error Proofing: This category includes the use of workpiece probing to verify set-up accuracy and check in-process dimensions and cutting tool probing to verify the insert has been correctly loaded.
- Machine Health: This category includes vibration, acoustic emission, and a number of off-line strategies to predict and address machine issues prior to failure.
- Process Stability: This category includes Cutting Fluid pressure or flow monitoring, power/torque/force to monitor tool condition, and acoustic/vibration monitoring to detect vibration and chatter.

Some of the same sensors and analysis techniques applied in Process Monitoring are also used for adaptive machining. In adaptive machining, the signals are used to adjust parameters to optimize the material removal rate or respond to tool wear or undesirable conditions (e.g., chatter). When adaptive machining is employed the automated parameter adjustments must remain within the validated process envelope.

17.2.2 Error Proofing

Probes integrated into the machine can be used prior to machining to verify the workpiece is correctly loaded (e.g., fully seated in the chuck) and to ensure that run-out meets the requirement. Probes are also used during the machining process to verify dimensions. This is done between cuts with the spindle stopped.

Turning machines may also be equipped with cutting tool probe systems. These include contact or optical/laser non-contact probes. Tool probes are primarily used to avoid gross errors, including loading of the wrong tool, improperly clamped inserts, and damaged tools. They can be used to measure the tool length for the purpose of performing program offsets, but tool measurements are more commonly performed off-machine and the offset data is transferred to the program manually, electronically, or through a radio frequency identification (RFID) tag system. Tool probes may also be used to check the insert after the cut to verify the insert did not break during the operation. When a tool measured after the operation is outside of the expected range, the system notifies the operator to inspect the workpiece for evidence of damage or non-conforming geometry.

17.2.3 Machine Health Monitoring

Machine health monitoring is an active field of university research and commercial machine system development. Application of machine health monitoring is growing, but not currently widespread. Machine health monitoring equipment and techniques for Turning are the same as those used for other machine tools. Most techniques involve monitoring signals related to the performance of spindle and feed axis drive systems for changes that indicate degradation of the mechanical components. One example is the use of acoustic emission or accelerometers to measure the vibrations produced by spindle bearings. Another is monitoring of the power consumed by spindle or feed axis drives for trends over time. In either instance, signal thresholds are set to detect a deviation from the nominal operating condition so proactive maintenance can be scheduled to prevent machine damage or part non-conformance caused by machine degradation. Note that a key enabler for an equipment health monitoring strategy is the information infrastructure to collect, analyse, and respond to the data.

17.2.4 Process Monitoring

Process Monitoring of Turning operations is typically intended to identify an unusual tool wear rate or incipient tool failure.

Power/torque is the most easily acquired Process Monitoring signal, but unlike some other machining operations the nominal power/torque can change significantly throughout the cut. This makes signal analysis and interpretation (such as to set a threshold) more complex.

- Turning is generally performed using a constant cutting speed, which requires the machine to continuously adjust the spindle speed (RPM) as the cutting tool radial position changes. Because the spindle power curve is not linear, this complicates the use of spindle power as a corollary of the cut energy.
- The depth-of-cut and feedrate typically vary throughout the cut (especially for rough and semi-finish passes), resulting in varying material removal rates and therefore varying nominal cutting forces.

These power variations require the monitored signal to be compared to a continuously variable nominal tare power/torque (a “learned” variable nominal signal). This is more complex than the constant threshold alarm limits that can be used with other machining processes, but there are commercially available systems which can perform this function.

Force monitoring provides the most direct measurement of the condition of the cut. However, it requires installation of force sensors in the tool holder system and most machines have multiple tool positions which requires multiple sensors. Adding sensors may also change the cutting tool position (e.g., by raising the toolholder which reduces the operating envelope) or change the static or dynamic stiffness of the toolholder system. While force monitoring eliminates the complexity introduced by spindle power variation, the cutting forces vary as a function of the depth-of-cut and tool engagement so the data analysis must account for the variation in the nominal force profile.

Vibration and acoustic emission sensors are reasonably inexpensive, robust, and can be positioned remotely from the cutting tool. These sensors are easily capable of detecting Tool Breakage, but substantial data analysis is required to account for different cutting conditions, cutting tool behaviour, machine characteristics, etc. (see also Section 15.3.2). Using these types of sensors to detect tool or workpiece vibration (chatter) is more straight-forward. There are commercially available systems that use vibration or acoustic emission signals to automatically initiate process adjustments (typically cutting speed) to address vibration/chatter in real-time, but they are not widely used for Turning because workpiece vibration is not a common issue.

Cutting Fluid monitoring is easily performed and in wide use on modern CNC equipment. Both pressure and flow monitoring are available, with pressure monitoring being more common. When the Cutting Fluid pressure/flow falls below a pre-determined alarm limit the cutting process is stopped. In most instances a Turning operation is sufficiently insensitive to Cutting Fluid delivery such that the monitoring system can stop the operation before damage to the tool or workpiece occurs.

In addition to the noted complexities associated with instituting real-time Process Monitoring, the pace of Process Monitoring implementation for Turning is limited to some degree by the variety of machines and Turning applications, and by the fact that Turning is a relatively stable process.

17.2.5 Adaptive Machining

Adaptive machining uses sensors and analysis techniques to vary machining conditions in real-time. The most common goal is to optimize process time, but the same techniques can be used to increase tool life and reduce the risk of Tool Breakage.

Adaptive machining of Critical Rotating Parts complicates the Process Validation and Process Control strategies of the Process Validation Function. The fixed or frozen Process Validation Function documents the critical process parameters, but adaptive machining intentionally varies the process parameters in response to monitored signals. As such, an appropriate Process Validation Function strategy is required to ensure the full range of allowable process parameter adjustments are validated and controlled.

Commercial systems are available that adjust the Turning parameters to consume consistent energy based on up-front process modelling or real-time measurements of power, torque, or cutting force. Typical adaptive machining strategies include maximizing feedrates when the cutting force is low or non-existent (non-cut time), increasing process parameters when the measured process energy is low (sharp tool), and reducing the process parameters as the tool wears (becomes less efficient) or localized cutting conditions cause a spike in energy consumption. Because the depth-of-cut affects workpiece geometry and the cutting speed directly influences the tool wear rate, the most common adaptive adjustment is made to the feedrate.

17.3 Turning: Surface Finish and Surface Condition

17.3.1 Surface Finish

The surface texture of a Turned surface is primarily a function of the nose radius of the tool and the feedrate (distance between successive feed lines) which, in cross-section, form a series of scallops. The surface texture can be made smoother by selecting a tool with a larger nose radius (decreases the height of the scallops) or by decreasing the feedrate (decreases the distance between feed lines). Adding “wiper” geometry to the insert can improve the finish by reducing the height of the cusp produced during the prior revolution of the workpiece, but this can lead to unacceptable Surface Condition ("white layer") and is not recommended for aerospace applications. In addition to the macro-geometry, micro-burrs, re-bonded chips, and other surface Anomalies can increase the roughness of the surface. However, a smooth surface texture does not guarantee an acceptable part Surface Condition.

17.3.2 Surface Condition and Anomalies

Turning is among the most efficient and robust of machining operations. Most Turning operations feature good access for Cutting Fluid application and sufficient space for chip formation and evacuation. Despite high material removal rates, the heat generation is relatively low and heat transfer away from the cut is good. However, Turning operations can present the same Surface Condition risks, including Non-Geometric and Geometric Anomalies, similar to other conventional machining operations:

- Heat Affected Zone (HAZ) – typically due to a Cutting Fluid application failure or an excessively worn cutting tool. Because of the favourable cutting conditions, this is generally a lower risk than with other Manufacturing Methods.
- Residual tensile stress – typically due to a worn cutting tool. Turning cuts can produce either residual compressive or tensile stresses in the near-surface layer of the workpiece. The effective depth of these stresses is generally shallow (<0.004 inch (<0.1 mm)), although low magnitude stresses may be deeper. As tool wear progresses the residual stress is more likely to be tensile and becomes deeper. Titanium alloys are less prone to residual tensile stress from machining than nickel.
- Near-surface grain deformation – becomes more pronounced and deeper as the tool wears. All conventional machining Manufacturing Methods cause some degree of mechanical grain deformation (dragging) at the surface. The degree and depth vary from ~0 to ~0.002 inch (~0 to ~0.05 mm) depending on the workpiece material, material grain size, and the machining operation. Some degree of grain deformation may be considered benign, depending on the part design stress level and whether the surface is subjected to additional processing which removes material or imparts a beneficial Surface Condition.
- Surface Anomalies (including re-bonded work material, tearing, plucking, laps, and burrs) – typically due to poor tool geometry/condition or inadequate Cutting Fluid application. These surface Anomalies can result in a significant low cycle fatigue life debit, particularly if the surface is not subsequently peened. Many Anomalies can be identified non-destructively, but magnification is generally required. Other Anomalies including laps and excessive surface material distortion require destructive evaluation. Anomalies can occur within validated Manufacturing Methods due to unusual process conditions, so disciplined long-term Process Control is necessary.
- Embedded tool material – due to Tool Breakage. Tool material can become embedded in the workpiece material when an insert fracture occurs. If the fracture occurs on an internal surface, it can be difficult to determine whether embedded tool material is present.
- Geometric Anomalies (including chatter, "orange peel", surface finish variation) – due to ineffective Process Validation or Process Variation. Because Turning often produces large smooth surfaces, the opportunity exists for unusual visual conditions that may or

may not be detrimental to the performance of the part. The risk of these conditions is greater in instances of low stiffness, inadequate damping, thin workpiece sections, and poor fixturing. Inconsistent Cutting Fluid delivery or tool performance can be contributing factors.

17.3.3 Examples of Turned Surfaces with Manufacturing induced Anomalies

Although Turning is an efficient and robust machining method, Turning operations have been identified as a likely contributor in Critical Rotating Part Anomalies, cracks, and fractures. Recent examples include:

- Embedded Cutting Tool Material:

  Description: When a cutting edge (insert) fractures, it is possible for pieces of the insert material to become embedded in the surface of the workpiece. When an insert breaks while machining inside a cavity (e.g., between the webs of a drum) it can be difficult to identify both the radial and circumferential location of the event. It is also difficult to verify that all remnants of the insert have been removed. Small pieces of undetected tool material have led to cracks in, and fractures of, Critical Rotating Parts.

  Lessons Learned: The most effective abatement for embedded tool material is to employ Process Validation and implement Process Control strategies that minimize conditions which might lead to tool fracture. These include a quality control strategy for tools, parameters verified to be well within the strength and wear capabilities of the tool and ensuring consistent stock envelopes for finish cuts. This could include an analysis of the strength and stiffness of the cutting tool and holder relative to the cutting forces and vibration modes. Process Monitoring or post-operation inspection of cutting tools should be considered within the Manufacturing Control Plan.

  Inspection techniques vary depending on the part geometry, workpiece material, and tool material. Visual or FPI inspections may be adequate where line-of-site is possible. Aided-visual (e.g., borescope) or Eddy Current may be required for features with poor line-of-sight. In some instances, a chemical etch may be used to make the embedded tool material more visible or to remove workpiece material that may be smeared over small pieces of embedded tool material. Due to the nature of the Turning operation, the exact circumferential location of the event is unknown and a 360^{o} band around the surface must be inspected.

- Impact Damage:

  Description: Like embedded tool material, impact damage (e.g., dents) can be difficult to detect on surfaces which do not allow line-of-sight. FPI, the most common NDE method, will not detect this type of damage unless there is also an associated lap or burr. Impact damage can be caused by tool breaks (with or without embedded tool material) and inadvertent non-cutting/positioning movements of the tool. The latter are a particular risk where tools are manually loaded in close proximity to the workpiece, or where position offsets and adjustments of the tool are performed manually. However, the most common cause is “handling damage” which takes place off-machine during transportation or storage of the part.

Lessons Learned: Manual intervention during workpiece load/unload, tool offsets, and measurements must be minimized to eliminate on-machine impact damage. This includes the use of fixturing strategies that do not require manual adjustment of the workpiece, automated tool offsets and inspections, and optimized ergonomics if manual tasks cannot be eliminated. Regular preventive maintenance of machines and toolholders is also important. The most common practice to minimize off-machine handling damage is the use of protective containers or dunnage. Lean manufacturing principles should also be employed to minimize the distance parts travel and the time they are exposed to potential damage.

Inspection for impact damage is typically visual, as most commonly used NDE methods will not detect it.

- Rubbing from Non-Cutting Locations on the Tool:

  Description: The tool holder is typically made of steel, and to provide the necessary reach and stiffness it is significantly larger than the cutting tip. Contact between the tool holder and the workpiece may produce a Geometric Anomaly (groove, cusp, rub, etc.) which acts as a stress concentration and can be difficult to detect. Heavy contact can result in transfer of tool material to the surface of the workpiece causing a combination of Geometric and Non-Geometric Anomalies and a non-conforming Surface Condition.

  Lessons Learned: It is necessary to design and model the tooling and cutting path to prevent contact between the tool holder and the workpiece, including accounting for workpiece and tooling tolerance stack-up. There are commercially available software packages that allow the user to model and run the machining process virtually to detect and eliminate potential points of interference between the workpiece and the machine and toolholder assembly prior to cutting the first part. Geometry variation between tool holders and variation inherent in manual set-ups must be accounted for when establishing clearances. Ongoing verification of tool geometry and preventative maintenance for machine and toolholders should be employed to ensure process drift does not exceed the calculated clearances.

- Re-bond:

  Description: Re-bond (re-bonded workpiece material) is a condition where small pieces or chips of workpiece material pass under the cutting edge and re-adhere to the surface of the workpiece. This adverse Surface Condition can have a significant negative effect on low cycle fatigue (LCF) life properties. Large (~0.002 in^2 or ~1 mm^2 and greater) re-bond can be detected visually and may also be found with a tactile inspection or FPI. However, detection can be difficult when patches of re-bond are small or there is no line-of-sight. Undetected re-bond has resulted in cracks and fractures of Critical Rotating Parts.

  Lessons Learned: Causes of re-bond include inappropriate tool geometry, overly worn tools, inappropriate cutting parameters, and ineffective Cutting Fluid delivery. Strategies must be in place to control those factors through Process Validation, Process Control, and appropriate NDE Technique to maintain re-bond below the level required for the Critical Rotating Part design.

- Surface Roughness:

Description: While not unique to Turning, a number of issues on Critical Rotating Parts have been attributed to excessively rough surfaces, and particularly to localized deep feed lines, "grooves", or "tool marks". These features are typically confined to a limited area and not attributed to inappropriate parameter selection. Rather they are due to Process Variations including unusual cutting tool breakdown, inconsistent Cutting Fluid delivery or other Special Cause Events.

Lessons Learned: Because surface finish anomalies are generally associated with Special Cause Events, the most effective approach is to ensure the process is stable through rigorous Process Validation and Process Control. Surface Finish anomalies can generally be detected by visual inspection, but this may be difficult for small features and those without line-of-sight.

- Geometric Variation:

  Description: Failure to account for small inconsistencies in tool geometry or workpiece fixturing can lead to geometric issues at mismatches where separate tool paths overlap. Poor path programming can also create geometric issues.

  Lessons Learned: CAD/CAM software and toolpath verification programs can improve process robustness as a portion of a Process Validation strategy. Process Control is also critical to address normal variation in tool geometry, workpiece characteristics, and machine performance. Geometric Anomalies including geometry and roughness excursions can be detected non-destructively by various metrology methods. Inspections should be developed to interrogate areas of the part where Anomalies are likely to occur, however, if Anomalies happen intermittently or at varied locations, there is a risk Anomalies may be undetected.

17.4 Turning: Alternate Manufacturing Methods

Turning is a highly efficient, cost-effective process and usually has the highest material removal rate on features for which it is geometrically suitable. Therefore, alternate machining methods are typically only employed when there is a part characteristic that makes Turning impractical or where resource constraints dictate the use of an otherwise less favourable process.

Multi-axis Milling can be used to produce axisymmetric features, but in most cases the material removal rates are significantly lower.

Cylindrical Grinding has traditionally been used instead of Turning for high hardness workpiece materials. However, in some instances hard materials that would traditionally have been ground can now be Turned using superabrasive cutting tools ("hard Turning"). Grinding is still typically the most effective process where the requirements include very tight tolerances or fine surface texture. While Grinding is less prone to produce Surface Conditions such as rough surface texture, re-bond, and near-surface grain deformation, it is an energy inefficient process and the risk of thermal damage (Heat Affected Zone) and residual tensile stress are greater than for Turning.

Finally, if the required feature is such that a sufficiently strong Turning insert geometry cannot be realized, non-conventional machining methods may be utilized. However, non-conventional machining material removal rates are low, and secondary processing may be required to remove surface Anomalies such as recast.

18 Appendix L: Marking of Critical Rotating Parts

18.1 Purpose

The information in this section is a compilation of lessons learned and best practices when applying the processes associated with identification and other Markings applied to Critical Rotating Parts. This document only applies to Markings required to be applied directly to finished part surfaces and does not apply to Markings applied to labels, containers or packaging. Critical Rotating Parts typically require part number and serial number, but may also require material heat identification, quality level, special process, assembly and other Markings for the purpose of traceability, assembly and serviceability.

All permanent Marking Methods applied directly to part surfaces result in local altered Surface Condition that must be considered in the design, life assessment, and control of the part and the Marking process.

Restrictions, guidelines, controls, and other practices described within this section are intended to provide best practices based upon industry lessons learned to prevent part damage and part failure.

18.2 Marking: General Information

Within this appendix the words should and shall have the following meanings:

- Use of the word "should" indicates a lesson learned.
- Use of the word "shall" indicates a best practice.

18.3 Marking: Standard Practices

Standard practices, such as those described within this section, should be applied by all part manufacturers.

18.3.1 Lifing Debit

All Marking Methods have the potential to reduce part life. A life impact assessment should be completed when defining the Marking requirements to ensure meeting the part Design Intent. Each Marking Method could be evaluated to determine an explicit life debit, or an appropriate worst case debit could be applied when the design requirements allow multiple Marking Methods.

18.3.2 Restrictions

The Surface Condition impact of the Marking Method on the part life capability shall be assessed to ensure the Design Intent is met.

Explicit specification driven process controls should be developed to ensure the Surface Condition impact is well understood and restricted as required. Marking Methods with known severe consequences, such as deep laser Marking, shall be explicitly disallowed or the product definition shall identify the allowed Marking Methods and the Marking location(s) on the part. The Marking location(s) and Marking Method shall be validated to prevent a Surface Condition which may compromise a fatigue critical location.

18.3.3 Application Controls

Engineering Requirements that specify allowable Marking Methods and Marking location on the part shall be applied.

18.3.4 Intended Electrical Contact

Marking Methods requiring electrical contact have a part life debit associated with both the Marking location and the grounding electrical contact location. The life debit could be different between the grounding and application locations, and each shall be evaluated. Each of the Marking and grounding contact locations shall be explicitly defined in the product definition. Process Controls should be applied using a process specification.

18.3.5 Unintended Electrical Contact Controls

Part protection to prevent unintended contact should be specified by process specification or Process Control requirements.

Process Controls are important because unintended electrical contact, which may cause arcing or sparking, may not be discovered by traditional inspection methods. In instances when wires associated with electrical devices, systems, or processes may contact Critical Rotating Parts, double insulation shall be applied to the wires. Megger® wire insulation resistance testing, or similar wire inspection methods, shall be performed routinely to ensure the wire insulation is still effective. Rules shall be established to replace the wires if there is evidence the outer or redundant insulation has been damaged, exposing the inner insulation to potential damage.

Another effective method is to mask the part, only exposing the Marking areas to contact.

Considerations such as masking, part protection and extra wire insulation should be applied to any process where electricity is applied to Critical Rotating Parts.

18.3.6 Testing

To determine the life impact debit to be applied, evaluation of all Marking Methods applied to Critical Rotating Parts should include adverse condition testing to determine the worst case impact to the material characteristics. Surface Condition testing of the affected Marking locations shall include evaluation of the Marked surfaces, as well as adjacent surfaces. Controls shall be established within the product definition or by process specification for the chemicals, part protection, application, and post-Marking treatments such as neutralization and cleaning.

Example: Etch Marking requires the use of chemicals which may have an adverse effect on the part Surface Condition both at the intended contact surface where the flow of electrical current is applied and on adjacent surfaces exposed to the chemicals.

18.3.7 General Application of Chemicals

Chemicals used in Marking, or any other process, should be tested under adverse conditions to establish the necessary controls and restrictions. Process specification(s) or other Process Control documentation shall ensure chemicals do not have an adverse affect on the Surface Condition.

Chemicals that are acidic or basic shall be neutralized or removed immediately after use. Chemicals that could react with the material at elevated temperature shall be removed prior to high temperature exposure. Evaluations should be applied to all chemicals used in fabrication, Non Destructive Testing, cleaning, etc. All chemicals used in the factory such as for eye glasses, floors, windows, bench cleaners, etc. should be evaluated if any have the potential for part contact. Process Controls shall be applied to ensure Critical Rotating Part life capability is not adversely affected.

Example: Some inks have chemicals that will etch metals during application or damage the material at elevated temperature. All inks should be evaluated under adverse conditions for stress corrosion or other effects.

18.3.8 Unfinished Material, Temporary or In-Process Marking

Otherwise restricted or more aggressive Marking Methods may be allowed on part surfaces subsequently machined as long as the minimum stock removed is specified and is sufficient to remove all traces of the Marking and associated adverse Surface Condition. A best practice is to use an unfinished material surface as a grounding location for electrical contact to ensure any potential damage at the grounding site is removed. Temporary Marking Methods used to ensure tracibility during fabrication and handling should have the same Process Controls as the permanent Marking Method(s) specified.

18.4 Marking: Quality Requirements

18.4.1 Mark Depth

Engineering Requirements should specify the depth of material affected by the Marking Method. This should include both non-destructive (physical dimensions and visual conformance) and destructive testing allowances (material characterization) used for Process Validation. For example, engraving is a Marking Method that applies a hardened conical tapered tool with a small spherical point to the part with enough force to penetrate the part surface. Letters, symbols or Marks are scribed into the part surface by controlled movement of the engraver point. This leaves a groove in the Marked surface with raised material at the edges of the groove. Engineering Requirements should include groove depth, height of raised material, geometry at the bottom of the groove and visual allowances such as lay, lap, chatter, distance from edges, etc. These should be measured by a destructive method or NDE during Process Validation with ongoing verification as deemed necessary. Other methods such as laser Marking introduce surface and sub-surface damage which must be assessed using destructive evaluation during Process Validation.

18.4.2 Measurement Requirements

Measurement methods and acceptance criteria should be defined by specification, drawing note or other quality requirements.

18.4.3 Mark Material Characterization

Engineering Requirements should specify allowable sub-surface characteristics of the material affected by the Marking Method. In the engraving example, this includes sub-surface characterization of the grooved material by means such as destructive testing or inspection technology applied at Process Validation.

18.4.4 Readability / Legibility

Quality requirements for Legibility (character recognition) and Readability (the ability to understand the information) should be defined in the Engineering Requirements or quality requirements. Readability is an industry requirement for 2D matrix and other machine-verified Marking symbols, but is also expected for human-readable information.

18.5 Final Notes on Marking

Application of Marking to Critical Rotating Parts shall include Process Validation, verification, planning, analysis, and design consideration. Part Marking has a localized effect on the part Surface Condition which can mimic the effects of sharp object surface damage from handling or process Anomalies. Therefore, special attention to the part design and Marking application method is required.

18.6 Considerations for Electrical Contact Application

Processes that require the application of electricity with the intention to flow current through the part require special design and Process Controls to prevent part damage from the electrical current flow.

Damage to the part can occur when there is a breakdown in the electrical contact application. The wrong tooling, poorly designed tooling, or tool component wear can allow electric current to escape the system and contact the part at locations other than at the specified contact surfaces. Such unintended contact typically results in damage such as arc burns and over-heating.

- Arc burns occur when there is a breakdown in the current carrying apparatus such as breaks or leaks in the insulation of the wire or other system components, or when there is insufficient contact area (e.g., inadequate clamping or point of contact) such as gaps between the clamp and the workpiece. Arc burns typically result in phase changes in the workpiece Surface Condition resulting from recast material and other contamination.
- Overheating can occur when there is a high resistance in the circuit, such as when a wire is broken or frayed so that the wire is not sufficient to carry the current load efficiently. Even with low current, very high resistance can create temperatures sufficient to melt insulation and the wire. Overheating can create local phase changes or contamination of the workpiece Surface Condition. Surface contamination from overheating can also result from the wires or wire insulation.

18.6.1 Safe Contact Surface

An electrical circuit requires a closed loop from the source through the circuit returning to the source. There will be a contact location on the workpiece where work is to be performed, such as the Marking location and a non-working contact area(s) where the electricity is desired to safely return to the source without damaging the part. A small area of contact will lead to increased electrical resistance that may result in local workpiece overheating. For the purposes of this section, the non-working location will be called the "Safe Contact Surface".

To eliminate arcing or overheating at the Safe Contact Surface, the following should be applied:

- The area of the apparatus or tool contacting the Safe Contact Surface should be greater than twice the effective area of the wire used to transmit the electrical current in the working portion of the circuit.
- Serrated clamps which result in point contact(s) may not guarantee the minimum necessary contact area is achieved.
- In all conditions, the electrical contact shall be designed to remain in contact with the workpiece during the entire time that electrical current is applied.
- It is a best practice to design the contact to be secured to the workpiece using non-serrated clamps, fixtures, or spring-loaded devices that ensure a Safe Contact Surface area is maintained. Examples include the use of a swivel between the clamp load and the workpiece contact device to ensure the Safe Contact Surface area is not reduced to a line or edge, but that the entire minimum contact area is maintained.
- The reliance upon gravity, such as hanging workpieces on hooks or fixtures, without securely fastening the electrical contact does not guarantee adequate contact area is maintained. Hook or fixture contact surfaces that rely upon the weight of the workpiece to make electrical contact are subject to movement between the contacting tool and workpiece that may result in intermittent or lower than the minimum prescribed contact area. This often occurs when submerging the workpiece in fluid as buoyancy will lift the workpiece from the tool creating intermittent contact. Intermittent contact, movement between the tool and the workpiece, contact on an edge or gaps between the contact and the workpiece will all result in less than the designed or intended contact area. These gaps or other situations that reduce the contact area, even momentarily, will increase electrical resistance and can result in arcing across a gap or increased temperature across the contact area. If a hook or fixture is only intended to carry or move the workpiece and electrical contact is intended to be applied elsewhere, then the hook or fixture shall be electrically isolated or insulated to prevent an unintended electrical path.

18.6.2 A Correctly Grounded System

The electrical system applied shall have proper system grounding with a dedicated grounding conductor connected to earth. Proper grounding is essential for the operation of electrical circuits. Current flow through circuits will seek the path of least resistance. A well-grounded system will ensure that all the current in the system, including current bled off to balance the load, only flows from the intended source, through the intended path(s) and to earth. A badly grounded electrical system may develop current spikes or current leaks within the circuit or at contact locations. Current leaks result in arcing that can damage sensitive circuits or leak out of the system to the operator or the workpiece. Correct grounding is designed to shunt or drain all current to earth when the system is turned off. This protects the circuit, the workpiece, and the operator from electrical energy that could otherwise remain after the circuit is shut down.

Correctly designed circuits shall also contain a circuit breaker or "over current" device. Circuit breakers protect systems from short circuits or over-current conditions. The grounding wire connected to the circuit breaker shall be sized to handle these conditions.

18.6.3 Final Notes on Electrical Contact:

When applying the flow of electricity through a workpiece, the entire application shall be evaluated for potential failures. Safeguards shall be applied.

- Correct sizing of circuits, wires, connectors, and ground are all required to protect the operator and the application.
- The Safe Contact Surface area between the circuit and the workpiece shall be correctly designed to be much larger than the internal circuit carrying capacity, so the workpiece does not become the failure site in the circuit during an overload condition.
- Wires that may contact the workpiece or tooling shall be double insulated.
- Periodic maintenance and frequent inspections shall be applied.

18.7 Marking: Related Industry Part Failures and Lessons Learned

The lessons provided are intended to prevent new incidents of Critical Rotating Part damage due to part Marking processes. It is important to provide the context of these failures to aid understanding of the information provided.

18.7.1 Marking Failures Related to Arc Burns

- <u>Electrolytic Etch Marking</u>

  Description: Cracks and fractures have initiated at arc burn melted material on the surface of Critical Rotating Parts. The arc burns resulted from failed Marking equipment that induced an electrical discharge not at the Marking location.

  Lessons Learned: Avoid Etch Marking or apply special controls, masking, insulation, or workpiece protection to prevent inadvertant arcing. Control grounding & Marking contact.

- <u>Laser Marking</u>

  Description: Cracks and fractures have initiated at arc burn melted material on the surface of Critical Rotating Parts processed by laser Marking. The arc burns resulted from melted material at the Marking location, but the Marking location was unable to absorb the fatigue life impact and maintain the full Critical Rotating Part life.

  Lessons Learned: Avoid laser Marking and do not Mark in critical part locations.

18.7.2 Arc Burns Not Related to Marking

- <u>Plating</u>

  Description: Cracks and fractures have initiated at arc burn melted material where fixturing was not isolated from electrical current flow or not designed with the correct Safe Contact Surface area during plating or other electro-chemical processing.

  Lessons Learned: Error proof masking or fixture design to isolate current flow or improve required electrical contact.

19 Appendix M: The Milling Manufacturing Method

19.1 Features Produced by Milling

Milling is a Manufacturing Method that uses defined cutting edges.

It is a conventional machining operation where material is removed by a rotating cutting tool, typically cutting on the periphery of the tool. The tool, workpiece, or both, are moved along additional axes to provide feedrate and depth-of-cut. A Milling cutter may also be used in a single axis plunge motion to produce holes.

Typical Critical Rotating Part features produced by Milling include blades of integrally bladed rotors (IBRs), scallops, holes, and edge rounding. Less often, the Milling Manufacturing Method is used to produce other features like splines or axial blade slots.

19.2 Overview of the Milling Manufacturing Method

19.2.1 Machine Types

Depending on the task or workpiece feature different kinds of machines are used: starting with three axis machines (e.g., for balance feature Milling) up to five axis machines used to Mill complete IBRs.

The machine type itself can also be a combined Milling/drilling center or a combined Turning/Milling center.

19.2.2 Workpiece Fixtures

The workpiece fixtures used should rigidly support the workpiece and should not cause damage to finish-machined surfaces. Furthermore, the fixtures should be optimized to provide sufficient clearance to prevent damage to the part arising from detrimental machining conditions such as chip congestion. Part-specific fixturing is preferred.

19.2.3 Tool Holders

Tool holding systems serve as connecting elements between the tool and the machine spindle. They are a portion of the overall process and have a significant influence on the machining result.

Within this system, the tool stand-out length (i.e., the distance from the end of the tool holder to the end of the tool) is of particular importance and, based upon the stand-out length, specific conditions such as deflection, vibration, or runout may need to be addressed. Runout and vibration issues increase as the tool length-to-diameter ratio (L/D) increases.

Tool holding systems have different characteristics due to their design and physical properties. For example, heat shrink chucks are very stiff with good runout and hydraulic chucks have a vibration dampening effect with good runout. Tool holder proximity to the workpiece may cause chip congestion and should also be addressed to ensure good chip evacuation.

Due to these different characteristics, machining trials should be performed to make sure that the requirements regarding the component Surface Condition, tool wear and tool life are satisfied. The type and extent of the investigations and documentation required should be defined by the designated Milling process specialist or expert.

19.2.4 Milling Tool Characteristics

The aim of this section is the definition of Milling tool geometric characteristics. The first portion of this section focuses on tool shape and geometry (macroscopic characteristics) and the second portion links those with cutting edge characteristics (such as cutting angle and clearance angle).

19.2.4.1 Macroscopic Tool Characteristics

Milling tools are composed of several cutting edges separated by flutes (see Figure 19.1). The active cutting edge could be a portion of the cutting edge or the whole cutting edge depending on the application. Also, depending on the machined feature, the Milling cutters come in different sizes and shapes such as blade / airfoil Milling ball-nose cutters or barrel-shaped cutters. For scallops, cylindrical end mills are used, whereas for edge rounding on scallops, holes, and axial blade slots, radius cutters might be used.

The number of cutting edges depends on the diameter of the tool and the Milling application. The number of teeth on the Milling cutter is important. Tool stability improves and machining time at equivalent feedrate decreases with an increasing number of teeth. A drawback to increasing the number of teeth is the Milling tool forces also increase resulting in higher deflections. The cutting edges are straight or twist around the tool surface. This twist angle is commonly denoted as helix angle. This helix enables a progressive and smooth tooth entrance into the workpiece material and, in comparison to straight edges, reduces cutting edge forces, improves chip evacuation along the flute, and increases tool life.

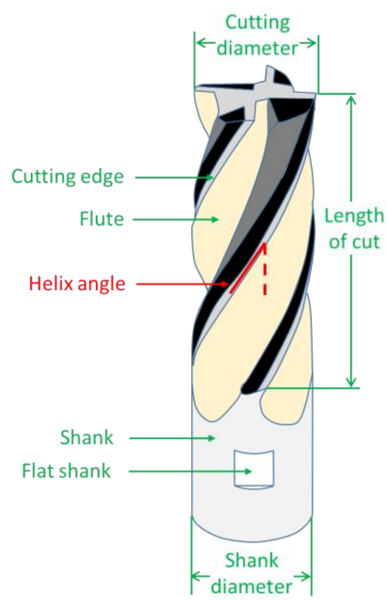


Figure 19.1: Milling Tool Characteristics

The angular distance between each tooth in a plane perpendicular to the tool axis is the pitch (see Figure 19.2). The pitch is equal between teeth (regular pitch) or it is different (variable pitch). During Milling operations, internal waves (vibration) are generated by the cutting tool contacting the workpiece which can adversely impact the Surface Condition. Should regular pitch tools induce vibration, variable pitch may be useful to avoid/minimize the vibration.

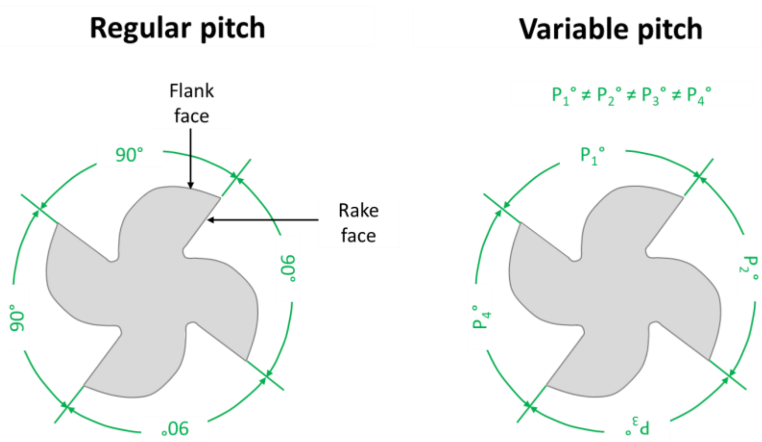


Figure 19.2: Regular and Variable Pitch

The tool profile is the projection of the cutting edge onto the plane containing the tool axis (see also Section 19.2.4.3). Milling tool profiles must be very accurate if the workpiece feature form is the same as the Milling tool profile itself. The non-fluted end of the tool is the shank, which enables the tool to be held by the tool holder. There may be flats on the shank depending on the type of tool holder.

Runout is a term which recognizes no tools are perfectly concentric with the tool holder. As such, the tool cutting edges do not trace a perfect circle in exact alignment with the spindle axis. The tool typically removes more workpiece material than desired due to teeth eccentricity, which also increases mechanical load on the tool and reduces the tool life. The total runout is the sum of cutting zone runout, shank runout and tool holder runout (see Figure 19.3).

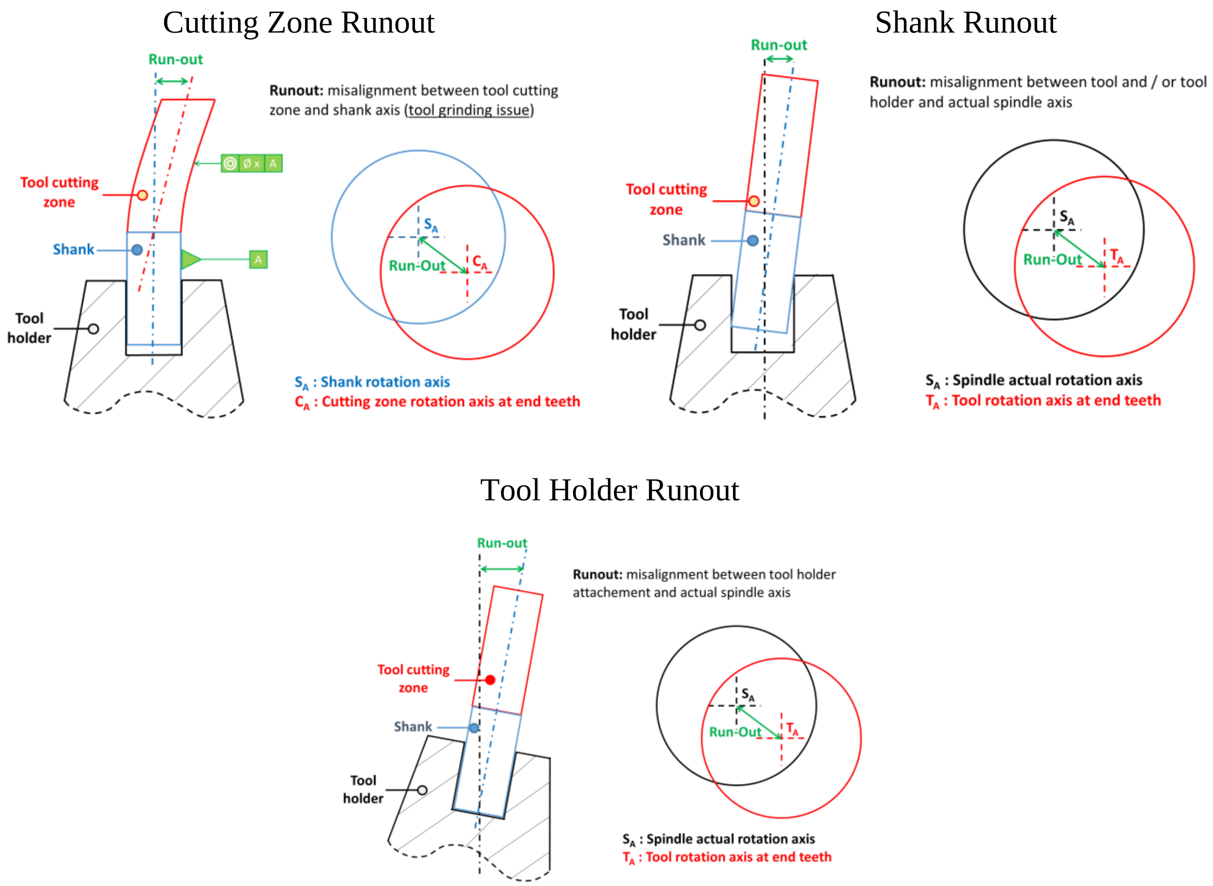


Figure 19.3: Sources of Runout

19.2.4.2 Cutting Edge Characteristics

A definition of the cutter surface and tool dimension reference plane is required to determine the cutting edge angles (see Section 19.2.4.3). Control of the Milling tool geometry can be impacted by the choice of the reference plane. Characteristics such as cutting angle or clearance angle (see Section 19.2.4.3) can be measured in different ways and different values can be obtained depending on the chosen reference plane. In general, the Milling tool reference plane should be defined first and the main cutting edge characteristics are then defined relative to the reference plane.

Cutting edge geometry requirements depend on the application and workpiece material. Each of roughing, finishing, and rework operations may require different cutting edge geometries based on the cutting depth.

Titanium Alloys:

> Milling cutters used for machining titanium alloys usually have a helix angle of 30°, with a clearance angle of 8° to 12°. The rake angle can vary between 6° and 10°. Barrel-shaped Milling cutters for blade Milling usually have a higher helix angle of 45° to achieve less variation in the cut and minimize vibrations through process damping. A

small cutting edge preparation might be applied to Milling cutters for use in roughing operations to avoid chipping along the cutting edge.

Nickel Alloys:

Milling cutter geometry used for machining nickel alloys does not differ much from the titanium cutter geometry. However, the rake angle is typically lower (e.g., 6°) and a cutting edge preparation is usually applied to stabilize the cutting edge for both roughing and finishing operations.

For rework, tools with sharp edges and without edge preparation should be used due to the small depth-of-cut and chip load.

To avoid any undesired Surface Condition (like severe grain deformation), edge rounding tools have no edge treatment and are used in the sharp condition because the material thickness removed is very small. Radius tools for edge rounding also require a higher relief angle than "regular" Milling cutters. High relief angle tools are used for edge rounding of axial blade attachment slots with small radii and for smaller holes to avoid contact between workpiece and the non-cutting surfaces of the tool.

19.2.4.3 Tool Surface and Reference Definition

Milling Tool Reference Planes (See Figure 19.4)

This section presents the most important reference planes of a tool. The knowledge of these planes is essential to control Milling tool cutting edge characteristics. The definitions of these planes are given as follows:

- The tool reference plane $\mathbf{P_r}$ is a plane perpendicular to the intended cutting direction containing the Milling tool axis at a defined location of the tool cutting edge.
- The conventional working plane $\mathbf{P_f}$ is a plane perpendicular to the $\mathbf{P_r}$ plane and parallel to the intended feed direction at a defined location of the tool cutting edge. The $\mathbf{P_r}$ plane is perpendicular to the Milling tool axis.
- The back tool plane $\mathbf{P_p}$ is a plane perpendicular to the $\mathbf{P_r}$ and $\mathbf{P_f}$ planes at a defined location of the tool cutting edge.
- The tool edge plane $\mathbf{P_s}$ is a plane tangential to the edge at a defined location of the tool cutting edge and perpendicular to $\mathbf{P_r}$ plane.
- The orthogonal edge plane $\mathbf{P_n}$ is a plane perpendicular to the edge at a defined location of the tool cutting edge.
- The orthogonal tool plane $\mathbf{P_o}$ is a plane perpendicular to the $\mathbf{P_r}$ and $\mathbf{P_s}$ planes at a defined location of the tool cutting edge.

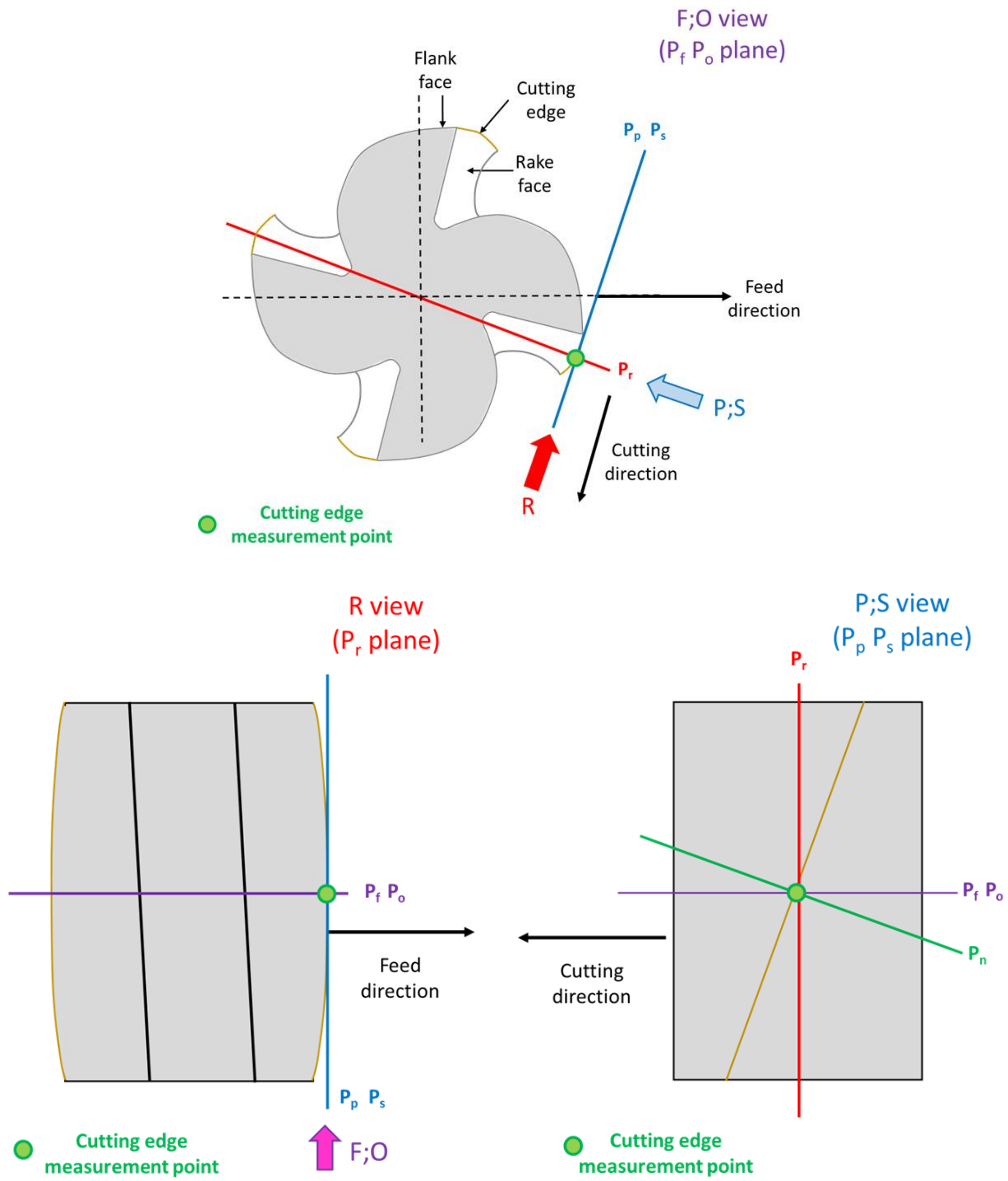


Figure 19.4: Reference Planes

Rake (cutting) Face and Flank Faces

The rake (cutting) face is denoted as A_γ (see Figure 19.5) and corresponds to the entire face(s) of contact between the tool and the chip. On this surface the generated chips slide. If the surface is composed of several adjacent surfaces with different angular inclination, all these surfaces are considered a portion of the rake face. These surfaces are numbered as a function of their distance from the edge as follows: first or main rake face, second rake face, third rake face, etc.

The flank face is denoted as A_α (see Figure 19.5) and corresponds to the entire surface(s) beneath which freshly machined material moves. If the whole surface is composed of several adjacent surfaces with different angular inclination, all of these are a portion of the flank face. These surfaces are also numbered as a function of their distance from the edge as follows: first or main flank face, second flank face, third flank face, etc. The use of multiple clearance angles avoids contact between tool and the freshly machined material. The various surfaces that make up the flank face have different sizes to ensure clearance to the finished workpiece surface.

The intersection between rake and flank faces defines the cutting edge. The orthogonal projection of this edge onto a plane is called the tool profile. In general, on tool drawings, the plane used to do this projection is the $\mathbf{P_r}$ plane unless another plane is mentioned.

Milling Tool Angles (see Figures 19.4 and 19.5)

This section presents the most common angles used to characterize a Milling tool edge. Many other characteristics exist and can be controlled but are not commonly used on Milling tool drawings. The definitions of these angles are given below:

- The edge inclination angle or helix angle $\boldsymbol{\lambda_s}$ (see Figure 19.1) is the angle between the cutting edge and the $\mathbf{P_f}$ plane measured in the $\mathbf{P_s}$ plane.
- The orthogonal cutting angle $\boldsymbol{\gamma_n}$ is the angle between the cutting face $\mathbf{A_\gamma}$ and the $\mathbf{P_r}$ plane measured in the $\mathbf{P_n}$ plane
- The side cutting angle $\boldsymbol{\gamma_f}$ is the angle between the cutting face $\mathbf{A_\gamma}$ and the $\mathbf{P_r}$ plane measured in the $\mathbf{P_f}$ plane
- The orthogonal cutting angle $\boldsymbol{\gamma_o}$ is the angle between the cutting face $\mathbf{A_\gamma}$ and the $\mathbf{P_r}$ plane measured in the $\mathbf{P_o}$ plane
- The orthogonal clearance angle $\boldsymbol{\alpha_n}$ is the angle between the flank face $\mathbf{A_\alpha}$ and the $\mathbf{P_s}$ plane measured in the $\mathbf{P_n}$ plane
- The side clearance angle $\boldsymbol{\alpha_f}$ is the angle between the flank face $\mathbf{A_\alpha}$ and the $\mathbf{P_s}$ plane measured in the $\mathbf{P_f}$ plane
- The side clearance angle $\boldsymbol{\alpha_o}$ is the angle between the flank face $\mathbf{A_\alpha}$ and the $\mathbf{P_s}$ plane measured in the $\mathbf{P_o}$ plane

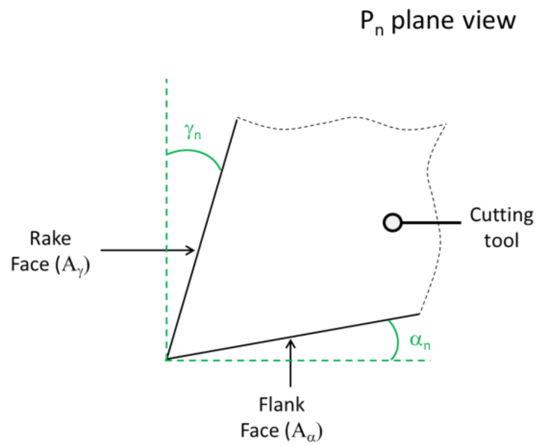


Figure 19.5: Milling Tool Angles

The clear definition of these angles on a Milling tool drawing is crucial to enable control of these characteristics. As described above, the cutting angle and clearance angle can be measured with regards to different references by inspection equipment. Therefore, it is required to know the type of reference plane used to determine the values of the angles specified on the Milling tool drawing. The measurement procedure is directly linked to the defined Milling tool reference plane and is required to ensure the Milling tool design intent is achieved. If no information about the reference plane is given on the drawing, measurement procedures should be shared between the tool supplier and the machining source to control the Milling tool in the same manner.

The defined angles work in combination to deliver good performance of the Milling tool cutting edge during machining. The choice of these angles depends on the operation, Milling strategy, tool material, and the workpiece material. Depending on the cutting angle and the clearance angles, the robustness of the tool changes (e.g., plastic deformation and chipping) and the risk of introducing adverse damage into the workpiece can be increased or decreased. At the same time, high forces at the cutting edge or chatter generation can be avoided through an appropriate choice of angles (e.g., cutting angle, clearance angle, and helix angle) in combination with an appropriate choice of the number of teeth.

19.2.4.4 Edge Preparation

Edge preparation produces the surface finish of the cutting edge after the Milling tool sharpening operation. The goal of edge preparation is to prevent significant tool damage such as rapid chipping or Tool Breakage by strengthening the cutting edge to improve the tool life and surface finish. In general, the importance of the edge preparation type and amount increases with the brittleness of the tool material. However, excessive edge preparation can also have a negative impact on the workpiece Surface Condition (e.g., burnishing, re-bonded chips, smearing, etc.).

Edge preparation can result different shapes, see Figure 19.6. The most common shapes are full radii and chamfers. The choice of the shape depends on the workpiece material, the tool material and the type of Milling strategy / operation performed.

Edge preparation can be realized by several types of operations such as brushing, mass finishing, wet blasting, or fine sandblasting.

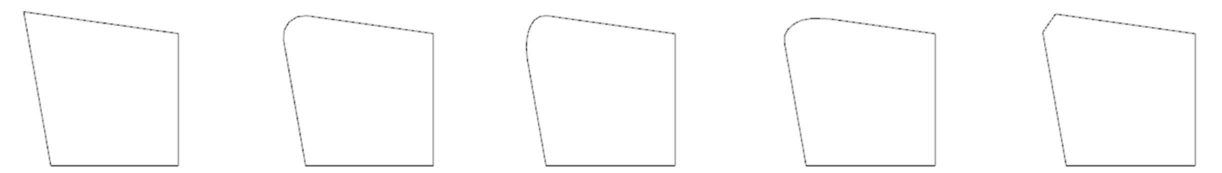


Figure 19.6: Types of Edge Preparation

19.2.4.5 Cutter Material and Coatings

In general, refer to Section 17.1.3 in the Turning appendix for a description of available cutter materials and coatings.

Because Milling is effectively an interrupted cut, the edge strength of the cutter is more important than in other Manufacturing Methods such as Turning. Conversely, heat resistance is not quite as important in Milling than in certain other Manufacturing Methods because the cutter is not in continuous contact with the workpiece.

Carbide is the most commonly used material for Milling tools. High Speed Steel (HSS) is less common due to a lower tool life. However, large diameter HSS tools (>0.8 in (>20 mm)) may be useful for roughing processes. In contrast to Turning tools, ceramic material for Milling cutters is rarely used due to its low toughness. Brazed diamond or diamond coated cutters are not commonly used in Milling.

Coatings are usually not required for titanium alloy Milling since the tool life is already high for uncoated tools. Coatings might be used to reduce friction and / or reduce adhesion between the workpiece and cutter material. Use of coated tools for nickel-based alloys may provide reduced tool wear. If coated tools are used, then recoating (and process validation) must be done after regrinding or resharpening the tools.

19.2.5 Cooling and Lubrication

Provision of an external Cutting Fluid supply to the cutting edge (flood cooling) is used with all types of Cutting Fluids for Milling operations. The Cutting Fluid is used to reduce friction and evacuate the chips from the cutting zone. The fixture needs to be designed such that it allows for chip evacuation and prevents entrapment of the chips.

In general, so long as the Cutting Fluid supply ensures adequate Cutting Fluid is always supplied to the Milling tool cutting position, an external Cutting Fluid supply / flood delivery is sufficient for most Milling operations since Milling is an "open" process so that the Cutting Fluid is reaching the cutting zone easily and evacuates the chips without any problems. In the case of machining deep cavities, fluid delivery through the cutting tool might be useful.

Because the Milling process is an “interrupted” cutting process, using high pressure Cutting Fluid for chip breaking, as with the Turning process, is typically not required. Care needs to be taken when applying high pressure Cutting Fluid to prevent tool vibration. High pressure Cutting Fluid may be required in situations where evacuation of the chips is difficult (e.g., deep holes or slots). In such situations the Cutting Fluid pressure should be high enough to evacuate the chips but not to break them.

19.2.6 Process Parameters

19.2.6.1 Type of Cut

There are two types of Milling: climb (down-) Milling and conventional (up-) Milling which are differentiated by the rotation direction of the cutter relative to the feed direction, see Figure 19.7. Down-Milling is associated with a decreasing chip thickness as the cutter moves through the workpiece while up-Milling is associated with an increasing chip thickness.

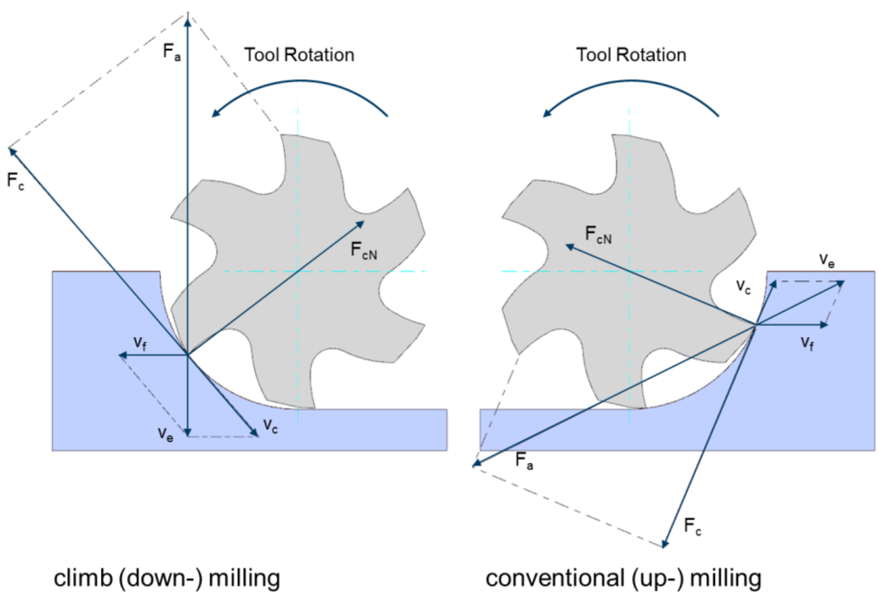


Figure 19.7: Climb (Down-) Milling and Conventional (Up-) Milling

The preferred technique is climb Milling. Climb Milling is advantageous because the chip width starts from a maximum size and decreases to zero. Also, chips are removed behind the cutter which reduces the chance of chip re-cutting.

During climb Milling the force vectors are also directed into the workpiece helping to hold it in place. But this can also be a disadvantage if any of the machining elements, Milling machine, cutter, or the workpiece, are not sufficiently stiff such as manual machines or workpieces with poor stiffness. When the stiffness is not sufficient, the cutting forces might cause chatter which can lead to a non-conforming Surface Condition. In this case conventional Milling is an option.

Conventional Milling causes the tool to rub more at the beginning of the cut causing faster tool wear and decreased tool life. Chips are carried upward by the tooth and can fall in front of cutter creating a marred finish and chip re-cutting.

Figure 19.8 shows the difference between "flank Milling" and "point Milling" by indicating the cutting edge used for each process. Flank Milling is often used to remove large amounts of material such as during the roughing process between the blades on integrally bladed rotors. The material can be quickly removed in one pass by aligning the side of a cutting tool to the blade. The alternative is to make many passes with the tool tip, a process known as point Milling. For applications where the geometry allows it, flank Milling is often favored for shorter cutting times and better surface finish.

However, most compressor blades have some "twist" angle between the tip and root blade contours. Simply aligning the tool vector with the blade gives a deviation that increases with the twist. Therefore, positioning a tool to cut with just the ball tip (point Milling) is necessary to create the desired surface contour. With point Milling the tool can be freely oriented but requires more passes to achieve the desired machined surface.

By using flank Milling, the surface created by the Milling process is usually within the finished part roughness requirements whereas with point Milling the surface roughness is determined by the depth-of-cut and number of passes per unit area.

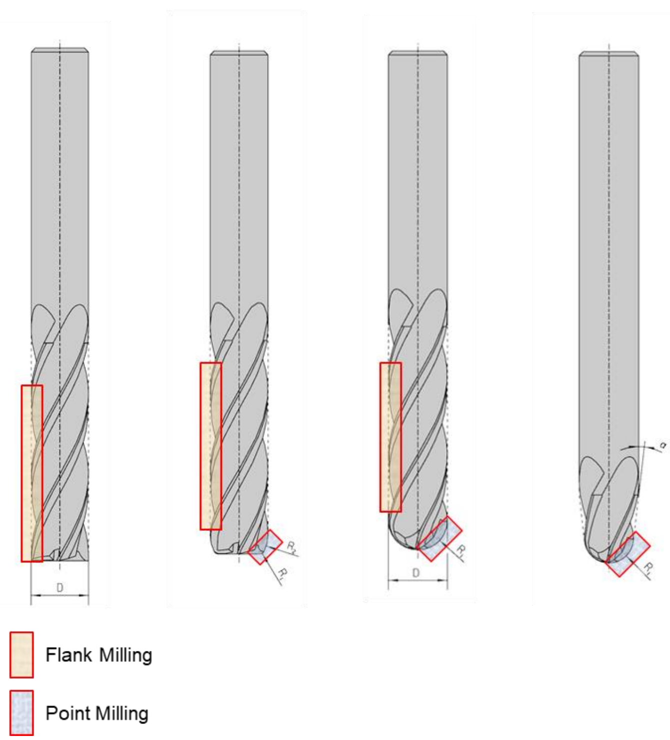


Figure 19.8: Flank Milling and Point Milling

19.2.6.2 Cutting Time / Tool Life

For any given workpiece material, the cutting time / tool life is usually limited by a predetermined maximum allowed tool wear. In most cases friction wear is the only acceptable form of tool wear. Other kinds of wear usually lead to a change in the tool cutting edge geometry by changing the rake angle. Chipping particularly creates an undefined tool cutting edge geometry.

The amount of tool wear influences the deformation and stresses induced into the surface zone of the workpiece and can have a negative impact on the finished part (i.e., workpiece) fatigue life. The tool wear and the tool life are influenced by attributes such as the workpiece material, cutting parameters, fluid application, and machine condition.

19.2.6.3 Cutting Speed / Revolutions

The selected cutting speed depends on the workpiece and tool material. For example, Milling of titanium alloys with carbide tool material may be performed at ~400 ft/min (120 m/min) whereas the cutting speed for Ni-based alloys is much lower, ~100 ft/min (30 m/min).

As a result of the tooth-passing frequency, the combination of cutting speed and workpiece configuration is one of the major factors in controlling vibration in the Milling Manufacturing Method. When Milling thin parts or features, the dynamic behavior of both the workpiece and of the tool should be addressed to avoid chatter.

The cutting speed definition might be different from tool to tool depending on the tool shape. For an end mill, and usually for ball-nose milling cutters, the maximum diameter is used to calculate the cutting speed. For form milling cutters, like edge rounding cutters, the calculation of the cutting speed is more complicated. In general, the cutting speed is determined at the main cutting diameter of the tool where most of the cutting action occurs.

19.2.6.4 Feedrate

Tool feedrate (see Figure 19.9) is the speed at which the cutter is fed, that is, advanced relative to the surface of the workpiece. It is also possible to move the workpiece relative to a fixed tool position. Feedrate is expressed in units of distance per revolution for Turning and boring (typically inches or millimeters per revolution). It can be expressed similarly for Milling, but it is often expressed in units of distance per time for Milling (typically inches or millimeters per minute). The chip load on each tooth can be determined by knowing the number of teeth (or flutes) present on the Milling cutter.

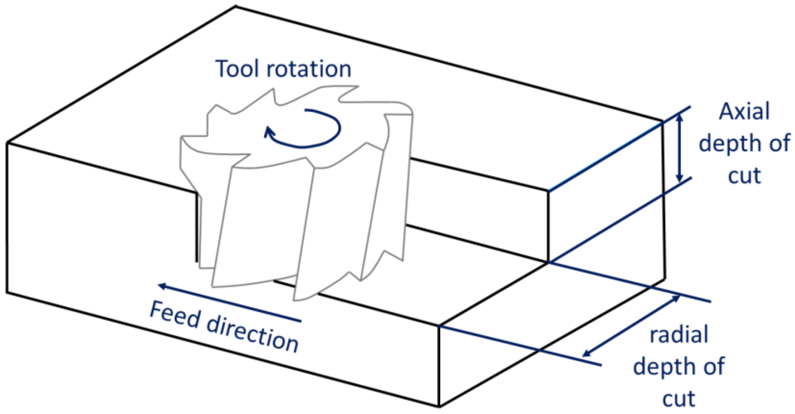


Figure 19.9: Tool Feedrate and Depth-of-Cut

$$Feed\ Rate\ \left[\frac{in\ or\ mm}{minute}\right] = RPM\ \left[\frac{rev}{min}\right] \times Cutting\ Edges\left[\frac{teeth}{rev}\right] \times Chip\ Load\ \left[\frac{in\ or\ mm}{tooth}\right]$$

The typical feed per tooth used is similar for both Ni-based and titanium alloys. Together with the chip load, the feedrate defines the forces on the cutting edge. If the forces are too high, the cutting edge of the tool may break.

The feedrate impacts tool wear and hence the tool life. Higher feedrate reduces in-process time and reduces the contact time between the tool and the workpiece. This can result in lower tool wear. Conversely, high cutting speed and low feedrate can increase the tool wear.

The feedrate can also depend on the machine and CNC control: For older machines the dynamics and the calculation of the movement of 3 to 4 axes may restrict the feedrate.

19.2.6.5 Chip Load

Chip load (chip thickness) or feed per tooth (flute) is the thickness of material that is fed into each tool cutting edge as it moves through the workpiece (see Figure 19.10). Chip thickness is different at each angular position of the cutting edge as it rotates through the workpiece material but is typically listed as the maximum value.

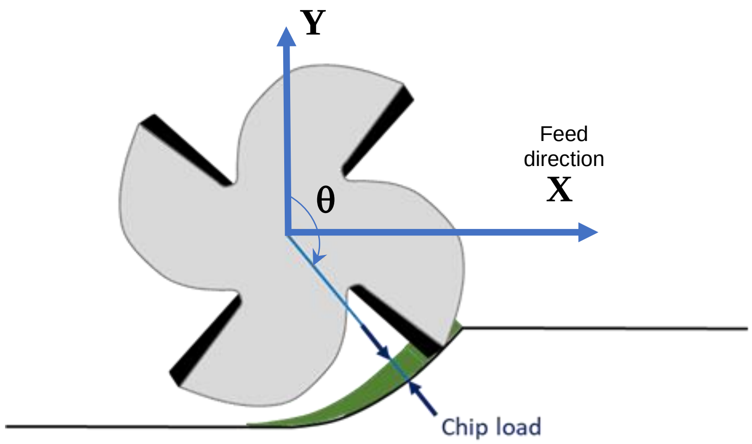


Figure 19.10: Chip Load

Chip load (thickness) in feed direction (X):

$$Chip\ Load\ (Thickness)\left[\frac{in\ or\ mm}{tooth}\right] = \frac{Feed\ Rate\ [\frac{in\ or\ mm}{min}]}{RPM\ \left[\frac{rev}{min}\right] \times Number\ of\ Cutting\ Edges[\frac{tooth}{rev}]}$$

Instantaneous chip load (thickness) at the cutting-edge location θ:

$$Chip\ Load\ at\ location\ \theta \left[\frac{in\ or\ mm}{tooth}\right] = \text{Sin}\ \theta\ \times Chip\ Load\ (Thickness)\ \left[\frac{in\ or\ mm}{tooth}\right]$$

The chip load relates to the chip thickness, unit cutting force, and tool wear rate. The chip load for a roughing pass is typically higher than that of a finishing pass. For the roughing process, cutting tool material limitations, workpiece material characteristics, and workpiece clamping are usually the limiting factors due to the higher cutting forces.

For finish operations, the workpiece Surface Condition requirements limit the chip load. Chipping of the cutting edge is generally not allowed. To maintain the necessary workpiece Surface Condition, the finishing pass chip load is significantly reduced to limit the amount of energy generated at the workpiece surface. Therefore, the chip load for the final cut is usually around 0.0006-0.002 inches (0.015-0.05mm) for general Milling operations.

For Ni-based alloy Milling, where the tools may have an edge preparation / edge rounding, the chip load should be larger than the edge preparation to ensure the cutter is “cutting” and not pushing or burnishing the workpiece surface under the clearance face.

19.2.7 Flank Wear

Tool flank wear happens on the flank face (see Figure 19.11). This type of wear occurs for all combinations of the tool / workpiece material. During chip formation, the tool edge induces local material compression and elastoplastic strain. With subsequent relative motion between the tool and the workpiece, the freshly machined material is no longer compressed. This leads to elastic recovery in the freshly machined material which then rubs on the tool flank face and generates tool wear. Generally, the value of flank wear is measured as the distance between the cutting edge and the farthest flank wear position normal to cutting edge.

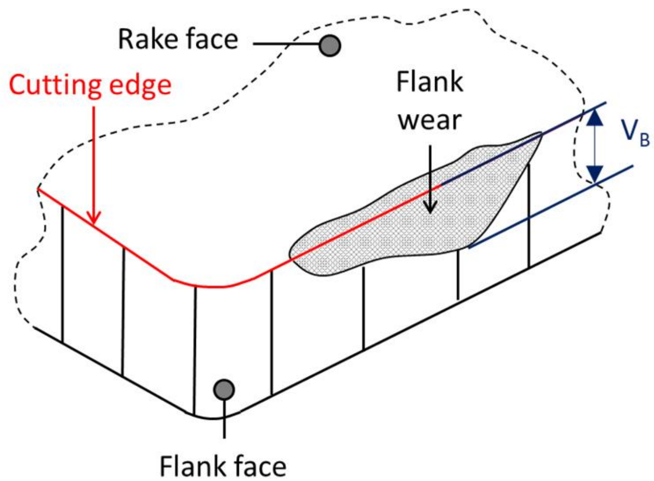


Figure 19.11: Flank Wear

The successive rubbing of freshly machined material increases the flank wear progressively. This flank wear evolution has three stages (see Figure 19.12). The first one corresponds to wear initiation with a rapid increase in wear. The second stage corresponds to a linear increase in tool flank wear which generates a uniform (predictable) increase in cutting force. The third stage consists of an exponential and uncontrolled increase of tool wear. To ensure a robust machining operation, tool flank wear should not exceed stage two.

As tool wear progresses, cutting forces and heat generation increase along with an increased risk of an unacceptable workpiece Surface Condition. Therefore, tools should be replaced before transitioning into stage three and before compromising the workpiece Surface Condition.

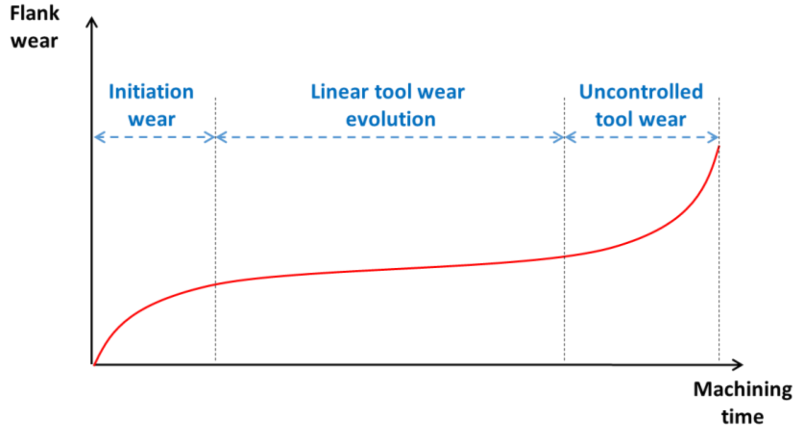


Figure 19.12: Flank Wear Evolution

Flank wear also has an impact on tool geometry. Flank wear modifies the position of the cutting edge compared to the unworn geometry or condition resulting in a reduction of the depth-of-cut. For surfaces with tight dimensional or geometrical tolerance, the depth-of-cut change can be important and tool flank wear should be addressed accordingly. Generally, the tool flank wear maximum value is between 0.004 in and 0.012 in (0.1 mm and 0.3 mm) for finishing cuts, but it depends on the tool size and application.

19.2.8 Crater Wear (Rake Face Wear)

Crater wear is generated on the rake face of the tool. The name of this type of wear is representative of a crater shape generated by chip rubbing on the rake face. This rubbing occurs at a specific zone along the tool length depending on the tool (e.g., material, angle, and coating) and the workpiece material. This zone is close to the cutting edge where compressive stresses generated by the chips are high. The relative motion between chips and the tool induces rubbing and leads to the loss of tool material. The successive passage of chips generates a crater (see Figure 19.13).

Crater wear does not occur directly adjacent to the cutting edge but at a distance from it. It is characterized by the maximum crater depth and the distance between the cutting edge and the location of maximum crater depth. Crater wear is linked to the temperature generated by the rubbing action of the chip against the tool. The size of the crater correlates with the rub length of the chip on the rake face. If the rub length is small, the crater wear is close to the edge and if it is high, the crater wear is far from the edge. The location of crater wear depends mainly on the workpiece material and the geometry of the active cutting edge. For example, in Milling of titanium alloys, tool crater wear occurs closer to the cutting edge than tool crater wear from Milling of steel alloys.

Crater wear results in local tool rake face geometrical variations and in rake angle variation. As the size of the crater increases, the forces generated by the Milling operation increase, the tool cutting edge is weakened, and, as with all wear conditions, the workpiece Surface Condition (especially the surface finish) can become non-conforming.

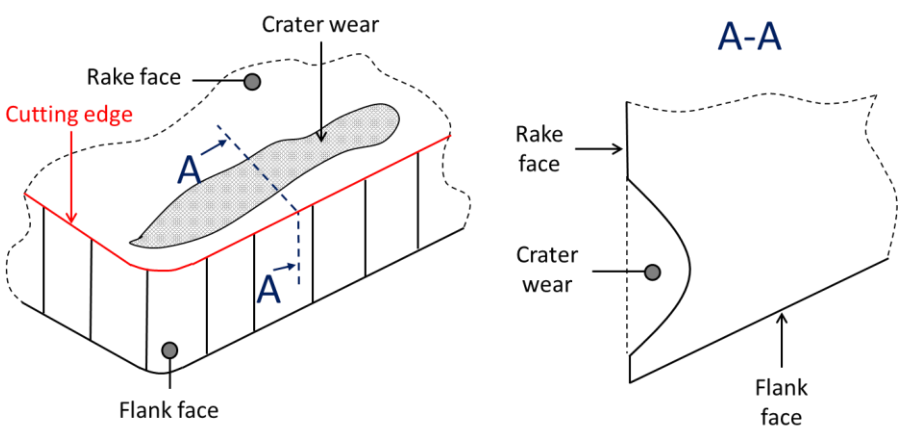


Figure 19.13: Crater Wear

19.2.9 Chipping or Notch Wear

Generally, chipping occurs on the cutting edge where a notch is generated between the flank and the rake face perpendicular to cutting edge (see Figure 19.14). Chipping is generally observed as a lost piece of the cutting edge due to cyclic mechanical or thermal loads upon entrance and exit from the workpiece material.

In the worst case, the tool material chips adhere to the machined surface and creates a negative impact on workpiece material fatigue life. To avoid the risk of low fatigue life, it is important to prohibit tool chipping or notch wear.

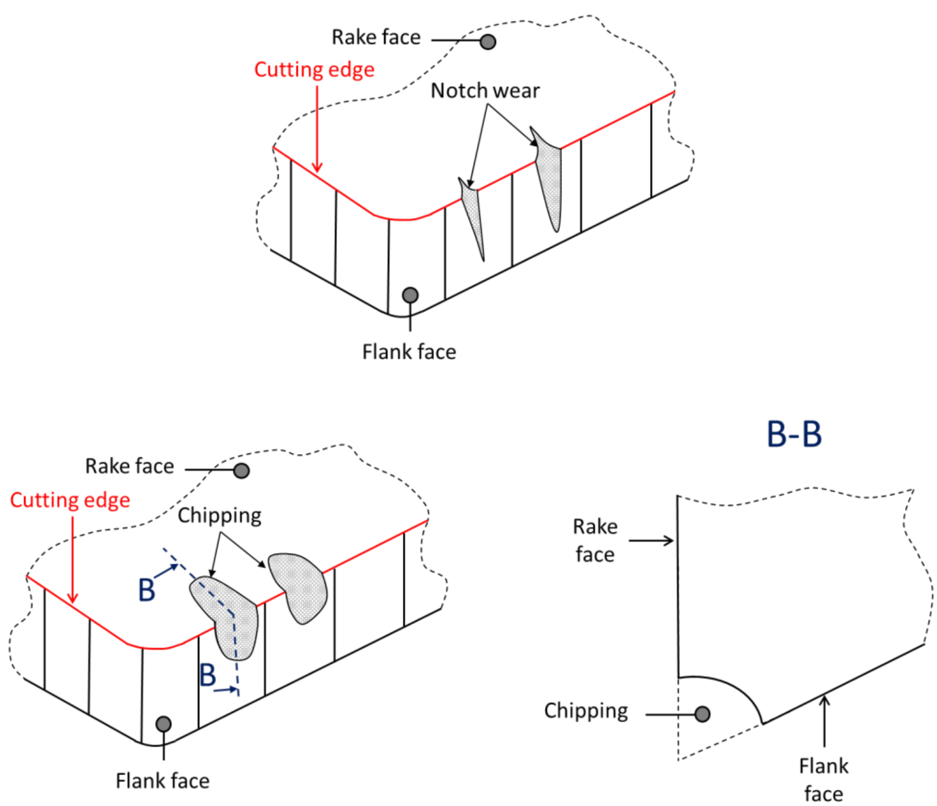


Figure 19.14: Chipping and Notch Wear

19.2.10 Plastic Deformation

Plastic deformation of the tool is generated when the tool is exposed to high thermomechanical loads. It generates a local variation in the tool shape close to the cutting edge. These geometric variations between the start and the end of the machining process change the behavior of the tool, which can result in poor workpiece Surface Condition including Non-Geometric and Geometric Anomalies. Excessive plastic deformation leads to cracking and breakage of the tool edge.

In general, plastic deformation occurs when the tool material or edge characteristics are not appropriate for the machine, the workpiece material, or the cutting parameters. It may also be the result of a lack of lubrication. For carbide cutter materials, this type of wear occurs mainly due to excessive temperatures at the cutting edge. For High-Speed Steel (HSS), it can be induced by various mechanical loading conditions.

Plastic deformation reduces the tool clearance and increases the tool flank wear and rubbing on the freshly machined workpiece material. It also can cause a degradation of the Surface Condition. In the worst case, pieces of the cutting edge are embedded into the workpiece surface. The embedded tool material has a negative impact on the workpiece fatigue life.

Conditions that cause plastic deformation should be minimized. Key strategies include selecting an appropriate tool material compatible with the workpiece material and by controlling the temperature of the tool.

19.3 Milling Tool Control

19.3.1 Verification of Milling Tool Characteristics

A CNC tool measuring machine is the most relevant device to verify all tool features such as angles, dimensions, profile, or runout. The accuracy of this type of machine is close to several micrometers. Contactless measurement by high-resolution camera or contact measurement with a probe are two ways to perform tool measurement. In theory, the profile and all tool dimensions are measurable except when probe or camera accessibility issues arise. Once the measurements are obtained, they need to be translated such that the measurements are relatable to the tool drawing to verify the tool characteristics.

For rake and clearance angles, it is crucial to know in which plane the angles need be measured. If is the appropriate reference plane is not clear or the measurement procedure is not shared between the tool supplier and the customer, a non-conforming tool could be used to machine the workpiece and a non-conforming Surface Condition may arise. Moreover, the location of the measurements should be defined clearly, especially for complex tool shapes with varying rake and clearance angles along the cutting edge.

The zone inside which the measurement of angles is performed on the rake face and flank face must be clearly defined in a procedure or on the tool drawing. For complex tool flute shapes and profiles, differences between the measurement results obtained using different measurement zones can be significant.

Concerning runout measurement on a CNC measuring machine, two strategies are typically applied. The first one is to measure the runout of the tool. To do this runout measurement, a reference position should be established on the tool shank. The tool runout is then measured for the most relevant zone(s), for instance, the tool cutting edge zone used to finish machine complex surfaces of the workpiece (e.g., scallops and slots). The second way is to control the runout with the tool mounted in the tool holder used for machining. This method accounts for the runout of both the tool and the tool holder but does not provide direct measurement of the actual tool runout conformity. Runout can also be measured on a calibrated tool pre-setter, however using a pre-setter for runout measurements is less accurate.

19.3.2 Measurement of Edge Preparation

The current generation of CNC tool measuring machine is also able to verify the edge preparation (e.g., a cutting edge hone) if they are equipped with a high-resolution camera and dedicated software. This allows for rapid measurements and integration with the other geometric tool characteristics. Other contactless measurement devices exist which have measurement accuracies of a few micrometers. Some confocal microscopes perform edge preparation measurement and analysis using dedicated software. Such confocal microscopes are generally a laboratory device and have the best measurement accuracy.

19.3.3 Tool Wear Measurement

Tool wear is typically measured with a microscope or a binocular. Magnification should be adapted to the dimension of the tool wear. Generally, magnifications between 10x and 60x are used. The microscope or binocular accuracy needs to be at least 0.0004 in (0.01 mm).

Flank wear is the most common measurement to assess tool condition. As described before, the flank wear must be evaluated to assess the machining operation robustness. To obtain accurate flank wear measurements, the flank faces should be positioned perpendicular to the axis of the lens of the measuring device.

19.4 Process Monitoring

19.4.1 Introduction

Natural process variation or Special Cause Events that result in an undesirable workpiece Surface Condition can occur even when frozen parameters and tools are used. If relevant changes in the machining characteristics are not corrected by the machine itself (e.g., closed loop control of spindle speed variation), the initiation of corrective actions relies on the operator who may not be able to detect these deviations or may detect them too late.

The goal of process monitoring systems is to ensure the machining process runs as planned by monitoring key characteristics with the help of sensors. Computer algorithms interpreting the sensor signals drive machine responses intended to avoid, reduce, or stop undesired behaviour.

Process monitoring systems are divided into two families: machine condition monitoring and cut monitoring.

The machine condition monitoring scope includes systems ensuring proper behaviour of the machine. For Milling operations, the main elements being monitored are the spindle, axes, and the cutting fluid.

Cut monitoring focuses on the interaction between the cutting tool and the workpiece. This monitoring targets the desired dimensional and Surface Condition characteristics of the workpiece while preventing detrimental machining effects (e.g., unusual tool condition, Tool Breakage, or vibration/chatter).

19.4.2 Process Monitoring to Detect Abnormal Conditions

In CNC machines the most basic and important sensors are force and torque sensors. During the machining process, abnormal force or torque can occur due to unexpected machining conditions (i.e., high depth-of-cut due to extra stock, low machinability material, or usage of a non-conforming cutting tool). This can lead to premature abnormal wear, damage, or failure of machine components such as the axis and spindle. To preserve these components, force sensors and power sensors are mounted directly in the machine and managed by the CNC. If an excessive mechanical load on an axis or the spindle is detected, the CNC stops the operation before damage of these components can occur.

During multi-axis Milling operations, the risk of collision between the tool or spindle and other elements within the machine (e.g., workpiece or fixture) are more likely than with other machining processes. The consequences of collision include loss of machine axis geometry / accuracy and spindle or axis damage. Accelerometers can be used to reduce or avoid the dynamic collision and resulting damage. Compared to force sensors fitted to machine axes, accelerometers respond more rapidly to allow the CNC to prevent severe consequences due to collision.

Another cause of spindle collision is incorrect tool length. Tool diameter and length are measured by the operator before loading the tool or set on dedicated presetting machines. Even when the measurement is automatic, the value is often keyed manually into the CNC. More recent systems allow the presetting machine to communicate directly with the CNC, eliminating the error-prone manual step. Alternately, a touch probe or laser measurement system can be integrated directly into the CNC machine to check for tool presence and verify tool characteristics such as diameter, length, or runout. Moreover, at the end of the machining operation, the monitoring system can detect whether tool or teeth breakage has occurred. This is beneficial to machining accuracy and protection of the machine (e.g., tooling or spindle) and the workpiece.

Sensors can also be used to detect degradation of machine components due to normal wear. Accelerometers fitted near the spindle detect low intensity vibrations when the spindle is running without machining. Causes include misalignment of the spindle or significant bearing wear. If a pre-set vibration threshold is exceeded, the CNC can react before any issue occurs.

19.4.3 Cutting Fluid Monitoring

Cutting Fluid quality and delivery consistency must be controlled to minimize process variation and avoid inappropriate machining behavior or abnormal tool wear. Separate sensors are used to monitor the Cutting Fluid flow and pressure. Flow sensors detect when the Cutting Fluid flow falls below a pre-set threshold. Pressure sensors ensure a certain Cutting Fluid pressure is maintained.

Monitoring the Cutting Fluid pump alone is not sufficient. Sensors should be near the spindle since an increase / decrease in the Cutting Fluid delivery system capacity leads to a change of pressure and flow. Also, since most modern machines have by-pass flows extracted between the pump and spindle, monitoring flow and pressure close to the pump may miss detection of insufficient Cutting Fluid delivery at the spindle / cutting edge. Flow rate is the more effective sensor since a flow blockage leads to an increase in pressure that would not trigger a pressure sensor.

To ensure Cutting Fluid consistency, especially for water-based Cutting Fluids, special monitoring systems can be used to control cutting fluid properties in real time. These systems monitor temperature, conductivity, pH, concentration, or contamination. Some systems can automatically react to out-of-range characteristics, for instance automatically adding water to reduce the Cutting Fluid concentration or adding concentrate to increase it.

The Cutting Fluid properties can also be checked manually. For example, the machine operator might check the pH-value and concentration daily, while sending a sample weekly to a chemical laboratory to check for bacteria or fungi.

Cutting Fluid oils used for machining operation require much less maintenance than water-based fluids.

19.4.4 Cut Monitoring

The most widely used sensor type for cut monitoring is the spindle power signal. The monitoring of power consumption of a specific tool can detect unexpected workpiece conditions, cutting Tool Breakage, inappropriate tool behavior, and abnormal tool wear.

In practice, the cut power is monitored in real time. The cut power is the difference between the power consumed by the spindle without machining and the power consumed by the spindle during the machining operation. Minimum and maximum thresholds frame the normal cut power for a particular Milling operation and are established during process development or using a learning method. The learning method consists of reevaluation of signals each time the operation is performed. For either approach, if the limit threshold is underrun or exceeded, a pre-determined action is taken by the CNC control (e.g., interrupting the operation). Thresholds should be defined to detect unusual conditions/events but should not trigger an untimely alarm because the threshold level is too close to the normal machining signal level.

The spindle power consumption signal can be measured directly or determined indirectly. The direct way is to use power sensors as close as possible to the spindle drive outputs. It implies that sensors are physically implanted in the machine. The indirect way is to calculate the machining power by using, for example, the spindle current.

In cases where the power consumed by the spindle during machining is low or much less than the power consumed without machining (e.g., a small cutter used in a high-power spindle), the cut power can be difficult to distinguish from the much larger spindle power signal. For small cutters, other types of sensors may be used, like acoustic emission sensors which are very sensitive. These sensors can detect high energy events or hazards such as tool or tooth breakage. Due to their more difficult implementation, these sensors are used only for certain specific applications.

Machine feed axes can also be monitored, typically with force sensors. The force signal processing is the same as the spindle power signal, using limit thresholds. This type of monitoring system is in less widespread use than spindle power for Milling operations.

In addition to detecting and interrupting processes that stray outside of a validated range, monitoring systems can be used to proactively adjust process parameters to maintain a sensor signal within a desired range. A common example is manipulating feedrate to maintain a desired spindle power, for example decreasing the feedrate as the power increases due to tool wear. These strategies are typically targeted to increase productivity and, if employed, careful consideration must be given to the potential impact on Surface Condition throughout the range of the automatically-adjusted parameters.

19.4.5 Vibration Monitoring

During machining, chatter phenomena may appear. The root causes of these vibrations are diverse. These phenomena are more common in Milling than in other machining operations due to the discontinuity of the cut and due to non-constant forces as the cutter teeth engage and disengage. Accelerometers can be positioned at specific locations in the machine to detect these vibrations. If a critical vibration intensity threshold is exceeded, actions can be taken automatically to reduce these vibrations and thereby minimize the impact on the tool and the workpiece. The automatic actions may include changing the cutting parameters such as the cutting speed, feed, etc. However, all permitted cutting parameter changes shall remain within the established Process Validation.

19.5 Process Validation

19.5.1 Surface Integrity / Material Distortion

Process Validation is essential when qualifying Manufacturing Methods. Some effects can only be quantified by destructive means such as metallographic inspections. Other surface Anomalies such as surface roughness, smeared material, cracking, and embedded material can be detected non-destructively.

To ensure that any Manufacturing Induced Anomalies do not remain on finished workpiece surfaces, the Milling strategy (e.g., stock left after rough machining for finish passes, finish machining process parameters, tool wear) must be properly developed and validated. It is especially important that tool wear limits be maintained during the finish machining processes to ensure no additional Manufacturing Induced Anomalies are generated.

19.5.2 Deburring

Another important aspect of machining Process Validation is burr removal. Insufficient burr removal can create lap-like features such as pits or distorted microstructure on the surface which may not be detected by visual inspection. Once these lap-like features are peened over, they can create Manufacturing Induced Anomalies which cannot typically be detected non-destructively and can be a source of fatigue cracking. The deburring process must ensure complete burr removal without generating a Manufacturing Induced Anomaly.

Similarly, any changes to edgebreak machining and subsequent burr removal processes should be carefully assessed and validated. Changes in either the Milling or the edgebreak process may create a different kind of burr either in direction or shape.

19.5.3 Cutting Fluid / Overheating

Surface microstructure and Surface Condition can also be influenced by insufficient Cutting Fluid delivery to the cutting edge. The effect of insufficient Cutting Fluid supply can be overheating or ineffective chip evacuation. Overheating might not be visible on the part surface and may only occasionally be detected by inspecting the cutting edge of the tool. Excessive heat generation can change the workpiece material microstructure and reduce fatigue life. Poor chip evacuation can lead to Tool Breakage or surface Anomalies due to chips deposited on or into the part surface, The latter can result in crack initiation and reduced fatigue life.

Cutting Fluid deficiency can have different root causes. Changes in Cutting Fluid flow due to system issues (e.g., pump degradation, flow blockage) can be readily monitored as discussed earlier. Cutting Fluid flow and pressure monitoring should be utilized to ensure sufficient Cutting Fluid supply to the cutting edge. Changes to tools, fixtures, or cut paths can also reduce the effectiveness of Cutting Fluid nozzle delivery. Therefore, after any changes to the Manufacturing Process the Cutting Fluid nozzles placement/orientation should be verified.

19.5.4 Similarity

When qualifying or validating a machining operation by similarity to another part or machining operation, all parameters should be carefully checked. Machine tool kinematics and dynamics, CNC control, material removal, and machine operating conditions all influence the cutting forces, tool wear rate, and the resulting Surface Condition. Even machines of the same type can perform differently due to how the servos are tuned, and differences in age, prior use, and component wear.

When qualifying a machining operation or step by similarity, certain factors should be assessed including any differences in the cutting tools, cutting parameters, Cutting Fluid, workpiece material and geometry, fixturing, tool wear rate, and the static and dynamic conditions of the cut. For example, using more machining passes in the new operation or step than in the originally validated process may lead to higher tool wear.

If in doubt when assessing similarity, an additional test piece cutup should be processed and evaluated for Surface Condition.

19.5.5 Interaction between Design and Manufacturing

Design requirements/constraints may result in difficult-to-automate feature and edge break geometries, e.g., features with poor tool access or interrupted cuts. Such features may require small Milling tools, complex toolpaths, special Cutting Fluid delivery strategies, or manual operations.

For example, when using a line-by-line toolpath to mill an edge break in multiple passes, a sharp cusp can be generated which is susceptible to creation of a lap-like Anomaly during shot peening. These cusps should be removed prior to peening but if the feature cannot be finished using an automated process due to complex geometry, a manual cusp removal operation may be required. An effective inspection with sufficient cusp detection capability should be performed after the manual operation. Manual operations may introduce other Anomalies like scratches and collateral damage to adjacent areas.

Therefore, during the design phase the engineer should assess the producibility of all features and especially the possibility to use an automated process. It is recommended the design engineer collaborate with the manufacturing engineer to avoid features that will require manual operations.

19.5.6 Inspection of Cutting Tools After Machining

Depending on the machining process and feature, Tool Breakage can result in adverse Surface Conditions and undetected embedded tool fragments.

To reduce the risk of Tool Breakage, robust processes should be defined. But even then, Tool Breakage can occur, and additional measures should be taken to detect Tool Breakage events. In modern CNC machines, Process Monitoring and Tool Breakage control (e.g., post-cut tool inspection) can be implemented. In less sophisticated machines visual tool control by the operator is necessary.

Once Tool Breakage is detected special care should be taken. Embedded tool material is not always visible by a visual inspection. Gouges and smeared material can cover remaining tool material embedded into the surface. As such, the affected area / feature should be noted and, in addition to a specific visual inspection, an inspection method such as eddy current should be considered.

19.6 General Lessons Learned / Best Practices

This section details lessons learned and best practices derived from specific cases that have been observed in the aerospace industry where Manufacturing Induced Anomalies have been attributed to Milling processes. It is not an exhaustive list of Milling best practices.

19.6.1 Reduction of Vibration

The Milling operation is sensitive to vibrations. Mechanical stress variation is inherent to the Milling Manufacturing Method as the forces continuously change during the successive entrance and exit of cutting edges to and from the workpiece. Vibration results when these force variations excite resonant frequencies of the workpiece, fixture, Cutting Tool, toolholder, or machine. Vibration can cause a poor Surface Condition, including chatter marks.

Two types of vibration exist: regenerative vibration and forced vibration. The root cause of the vibrations can be difficult to find and eliminate. In the following, some recommendations are given to reduce vibration.

19.6.1.1 Elimination of Regenerative Vibration

Regenerative vibration is due to dynamic instability during the machining operation. It is linked to force variation at the cutting tool / chip interface due to friction variability at the interface between the tool flank face and the workpiece, as well as the variation of the chip thickness.

Chip thickness variation is often due to surface undulations generated by the prior machining operation. Improvement of surface quality from the prior machining operation can reduce this type of vibration. Increasing the depth-of-cut or chip load are other possibilities to dampen vibration by increasing the contact length between the workpiece and the tool cutting edge.

19.6.1.2 Reduction of Forced Vibration

Forced vibration is due to the eccentricity of tool, tool holder or spindle, poor stiffness of the machining system, or variation of mechanical stress (force) during the Milling operation.

To reduce the eccentricity, the tool runout and the runout of the tool assembled with the tool holder should be minimized. The length of the tool holder and the tool protrusion from the tool holder should be optimized for the Milling operation. Reducing the length and the protrusion increases the stiffness of the system and reduces vibrations. Shrink-fit tool holders provide more stiffness compared to traditional tool holders and can help minimize vibrations.

Appropriate Cutting Tool designs can also reduce vibration. The goal is to have progressive entrance and exit to and from the workpiece and continuity of the cutting operation. Increasing the helix and the cutting angles or increasing the number of cutting teeth promotes cutting stability and reduced vibrations. Variable pitch (uneven circumferential spacing between the cutting edges) can also help reduce vibration.

19.6.2 Surface Condition Assessment

Visual inspection is usually the first NDE Technique applied on the entire part surface. Visual inspection is done directly by naked eye or using low magnification if surface Anomalies are suspected. Other NDE Techniques such as FPI (Fluorescent Penetrant Inspection), MPI (Magnetic Particle Inspection), Eddy Current, macroscopic chemical etching also be applied, as necessary.

When potential Anomalies are detected, surface roughness measurement or microscopic / macroscopic local chemical etch may be performed to characterize the indications and determined whether the Surface Condition is acceptable.

Surface Condition assessment by test sample or workpiece cutup and micrographic evaluation is a useful method when developing a Manufacturing Process. Periodic cutup evaluation may also be used to monitor the stability of a Manufacturing Method.

19.6.3 Fixturing Best Practices

Fixtures should be designed to ensure easy assembly and clamping of the workpiece. Care should be taken to avoid marking, scratching, or denting of the workpiece surface.

Workpiece clamping should be tight enough during the Milling operation to resist the cutting forces. This is especially important for machining of thin-walled structures where the fixture is required to provide additional stiffness to the workpiece to minimize vibrations which can cause surface Anomalies. The fixtures should also be designed to allow free flow of the Cutting Fluid into cutting zone as well as chip evacuation.

Clamping pressure should be applied to the workpiece in a controlled manner to avoid deformation (e.g., clamping on a flange or using an expanding mandrel on a bore). Excessive pressure can distort the workpiece prior to machining during the clamping process. Even if the toolpath is correct and the geometry of the workpiece is conforming when it is clamped, it may not be conforming when the workpiece is unclamped. Use of a torque wrench is recommended to ensure consistency if manual tightening of fixture bolts is required.

19.6.4 Tool Clamping

Loss of the tool length control or tool fracture can result if the tool holders are not properly sized or properly maintained. These tooling shortfalls can cause undetected geometric variations in the workpiece and/or embedded tool material from Tool Breakage. Similarly, the interface between the tool holder and the machine spindle should be maintained to ensure adequate clamping force, stiffness, and runout.

19.6.5 Tool Control

Tool control is one of the main factors necessary to maintain an acceptable Surface Condition.

19.6.5.1 Validation of Tool Geometry and Cutter Material

The choice of the tool characteristics depends on the workpiece material, the machining strategy, and the workpiece geometry. Tool characteristics include tool shape, tool material, edge geometry, and tool coating as described in Section 19.2.4. A poor combination of tool characteristics can result in excessive tool wear, Tool Breakage, vibration, and other process variability leading to the risk of an unacceptable Surface Condition.

Tool material characteristics are a compromise between hardness and toughness: the harder the tool the less rapid the tool wears but the cutting edge is more brittle. A low toughness (more brittle) tool material can be prone to edge chipping or Tool Breakage, possibly resulting in embedded cutting tool material in the workpiece surface. In contrast, low tool hardness can result in an increased tool wear rate and result in a compromised Surface Condition or Tool Breakage. Appropriate selection of tool material and tool grade requires Manufacturing Method development. Some recommendations are given in Section 19.2.4.

Tool geometry (e.g., ballnose or cylindrical), clearance angles, cutting edge characteristics (including edge angles and edge preparation), and the machining strategy all impact the workpiece Surface Condition. For instance, Milling cutters with an inadequate clearance angle or an excessive cylindrical land may cause rubbing of the tool flank face on the workpiece surface. This situation mainly occurs when complex shapes are machined or when continuous 5-axis machining is used with varying tool orientations. In another example, tool geometry that results in a weak cutting edge may lead to excessive tool wear. A poor choice of tool geometry can result in poor Surface Condition including deep distorted grain layers or unfavorable residual stress. To prevent these situations, tool and edge geometries should be chosen considering the workpiece material, machining strategy, the type of operation (such as flank Milling or slotting), and the shape and volume of material to be removed (e.g., roughing vs. finishing). The tool and edge geometry should be verified before machining to ensure compliance with the cutter drawing. For Milling cutters, it is recommended to have the following information on the tool drawing as a minimum: rake angle, primary and secondary clearance angles, helix angle, and the pitch value (especially if the pitch is variable). Mismatches resulting from tool geometry variation can create undesirable stress concentrations in the workpiece, therefore tool tolerances should be included on the tool drawing and controlled as described in Section 19.2.4. These Milling cutter characteristics should be controlled as described in Section 19.2.4.

Complex shapes such as slots and scallops may be machined using a form Milling cutter matched to the target workpiece geometry, or by using profile Milling to generate the workpiece geometry using a generic cutter shape.

19.6.5.2 Tool Wear and Chipping

Crater wear and flank wear are normal wear modes for Milling cutters. Tool wear limits should be established in conjunction with the cutting parameters during Process Validation to prevent excessive tool wear.

Severe tool wear such as plastic deformation, breakage, notching, or chipping can occur if the Manufacturing Method is unstable or if the cutting tool quality is inconsistent. These tool wear types can also appear during Special Cause Events such as Cutting Fluid interruptions or machine failures. Unusual tool wear can have a negative impact on the workpiece Surface Condition.

Milling tools are sensitive to notching, chipping, and cutting edge distress due to repetitive entering and exiting of the cutting edges from the workpiece material. Cutter material grades and edge geometry selection can reduce the risk of tool failure from these damage modes. There are also toolpath programming techniques that can minimize the effect of entry and exit. As notching and chipping are typically intermittent, a best practice is to inspect the Milling cutter for damage after the tool life is consumed and before the tool is discarded or resharpened. This inspection is performed visually or using low magnification. If notching, chipping, or edge distress is observed, additional NDE should be considered to ensure the workpiece Surface Condition conforms to requirements.

19.6.6 Process Control

Process Control includes control of the cutting parameters, Cutting Fluid delivery, and the toolpath. Control of these factors ensures the Surface Condition is consistent with the Process Validation.

19.6.6.1 Cutting Parameters

After initial qualification of the Milling process, the cutting parameters are frozen to ensure stable process performance. In addition to the cutter selection, the critical cutting parameters include cutting speed (or spindle speed), feed (or feedrate), radial or axial depth-of-cut, and cutter orientation/toolpath. These parameters should be fixed/frozen through the CNC program and/or through the operator work instructions.

Aggressive cutting parameters can cause Surface Condition degradation, inconsistent tool wear and low Milling process robustness. The cutting parameters should be chosen considering the workpiece material and limitations with respect to the maximum tool wear established during Process Validation.

Some cutting parameters, such as cutting speed and feed, are controlled directly by the machine. The initial machine qualification validates that the actual values match the programmed values within the Process Validation tolerance requirements. This difference is monitored periodically or continuously to confirm no deviation to the Process Validation defined Manufacturing Method has occurred.

19.6.6.2 Cutting Fluid Control

Cutting Fluid control includes two main aspects: Cutting Fluid consistency and Cutting Fluid delivery.

For consistency of water-based fluids, the main parameters to monitor are concentration and the pH-value. The frequency of this control depends on the specific fluid, the volume of the machine tank or system, and other factors, but is generally between daily and weekly for water-based fluids. It is also important to periodically check the degree of contamination (e.g., tramp oil from the machine). Monitoring and regulating Cutting Fluid temperature is also beneficial, both to reduce thermal variation of workpiece dimensions and to maximize fluid life.

Cutting Fluids should be evaluated for chemical impact on the workpiece material. Specific tests are done to prove the Cutting Fluid does not induce corrosion or oxidation of workpiece material.

Cutting Fluid flow should be continuous. To ensure this, the Milling machine should include a pressure and/or flow sensor as described in Section 19.4.3. Consistent positioning of the Cutting Fluid nozzle(s) is important to ensure adequate lubrication during the machining operation. Adjustments of the nozzle(s) should be done carefully to guarantee the operation produces results consistent with the Process Validation. Rigid/fixed nozzles are more consistent than flexible nozzles. A best practice is to describe, or show with a picture, the positioning of the nozzle in work instructions.

19.6.6.3 Toolpath

The toolpath should provide, as much as practical, consistent cutting conditions (e.g., tool engagement, depth-of-cut, chip load). Large variations in cutting forces due to inconsistent toolpaths can result in accelerated tool wear, local workpiece deflection and inconsistent Surface Condition on the workpiece. Special attention should be paid to the toolpath when machining complex shapes, using multiple machine axes simultaneously, and for features with access limitations. To avoid contact between the tool holder and other elements of the machine, it is recommended to perform numerical simulations during Process Validation, making modifications to the toolpath, if necessary. After machining the first part, inspect the workpiece, fixtures, tool holder, and machine for evidence of unintended contact.

Residual stresses are generated within the material during forging and heat treatment. During machining, the residual stress state changes as supporting material is machined away. This redistribution of residual stresses can cause workpiece distortion after unclamping and, in extreme case, may cause the workpiece to loosen on the fixture. If the initial residual stress distribution within the raw material is sufficiently repeatable, the toolpath can be adapted to compensate for this movement and consistently produce a dimensionally conforming part. This type of path adaptation can also be used for other causes of distortion including clamping forces, tool forces resulting from the machining process, or by residual stresses induced during machining. Again, such toolpath adaptation will only work when the observed distortion is sufficiently repeatable.

20 Appendix N: The Grinding Manufacturing Method

Grinding is most commonly employed in applications where:

- the work material is too hard or abrasive to Mill or Turn effectively,
- a fine surface finish is required,
- tight dimensional tolerances are required.

Common aerospace Critical Rotating Part Grinding applications include shafts, bearings and bearing journals (tight tolerances and fine surface finish), high pressure turbine components (complex forms with tight tolerances on difficult-to-machine alloys), seal teeth coatings (hard materials), rotor/stator finish assembly Grinding (tight tolerances and interrupted cuts), and honeycomb seals (tight tolerances on fragile materials).

Grinding is a less efficient Manufacturing Method than other conventional machining (chip-forming) processes. Because the geometry of the cutting edge (abrasive grain) is, on average, blunt and oriented unfavourably (negative rake angle), most of the energy applied through the grinding wheel is consumed by rubbing and ploughing of the workpiece material. It is estimated that less than 5% of the applied energy results in the removal of workpiece material through chip formation in front of an abrasive grain. Therefore, Grinding process design and control should focus on energy management to avoid undesirable Surface Conditions due to overheating.

20.1 Types of Grinding – Overview

20.1.1 Surface Grinding

In surface Grinding, the axis-of-rotation of the grinding wheel is typically horizontal, and the workpiece is fed parallel to the wheel (feedrate) (see Figure 20.1). The grinding wheel can be moved down incrementally (down-feed) and the workpiece can be moved parallel to the spindle axis (cross-feed) if the work is wider than the wheel. Down-feed and cross-feed are accomplished when the grinding wheel is at the end of a feedrate stroke beyond the workpiece. Grinding wheels can also be manufactured or dressed to include a profile which is the inverse of the required workpiece geometry. The cross-feed axis is used only for initial positioning when profile Grinding.

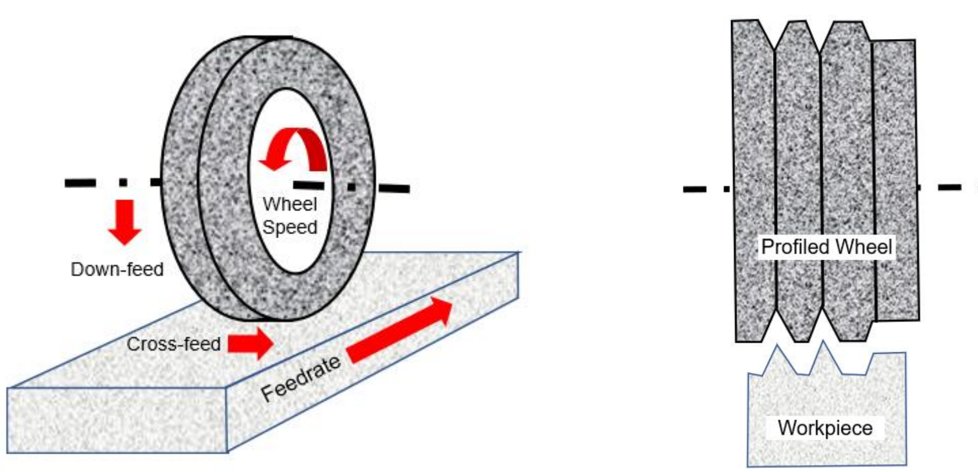


Figure 20.1: Schematic of Surface Grinding

20.1.1.1 Surface Grinding - Conventional

Conventional surface Grinding employs a very small depth-of-cut, typically 0.002 inch (0.05 mm) per pass or less. The feedrate is relatively high, ranging from approximately 20 to 1000 inches/minute (0.5 to 25 m/min), depending on the workpiece material, grinding wheel, depth-of-cut, Cutting Fluid delivery and other factors. Conventional Grinding is applicable for finishing cuts that remove small amounts of workpiece material.

Speed-stroke is a special type of surface Grinding with feedrates up to 325 ft/min (100 m/min) and a depth-of-cut less than 0.0004 inch (0.01 mm). This method may be used for Grinding nickel-based superalloys and intermetallics. However, it is associated with specialised machine tools, high maintenance, inflexibility, and a narrow operating window, and thus is rarely applied.

20.1.1.2 Surface Grinding - Creep Feed

Creep feed Grinding is distinguished from conventional surface Grinding by a substantially greater depth-of-cut and lower feedrate. The entire operation may be completed in a few passes (or even a single pass), which reduces the non-cutting time where the table reverses at the end of each pass during conventional surface Grinding. There is no industry standard definition for the depth-of-cut at which an operation is considered to be creep feed Grinding.

The depth-of-cut in creep feed Grinding depends on factors including the workpiece geometry and material, grinding wheel type and size, and the machine capability. Values of 0.4 inches (10 mm) per pass and greater are common in aerospace applications. Feedrates range from 0.1 to 20 inches/min (4 to 500 mm/min). The arc-of-contact between the workpiece and the grinding wheel becomes longer as the depth-of-cut increases, so robust wheel sharpening (dressing) and Cutting Fluid delivery strategies are critical to avoid excessive heat generation.

20.1.2 Cylindrical Grinding

While surface Grinding is the most common process in general, cylindrical Grinding is the most common Grinding operation performed on Critical Rotating Parts such as disks, drums, seals, and shafts (see Figure 20.2). Common features include tight tolerance diameters for bearing journals and seal surfaces, seal teeth, and hard-coated wear surfaces. Material removal can be accomplished either using in-feed or cross-feed, but most features are finished with a cross-feed pass to ensure cylindricity. Many grinders allow the head to be angled with respect to the axis of the workpiece to allow more favorable grinding wheel contact with faces and shoulders. Outer Diameter (OD) cylindrical grinders are also used to finish Grind the blade tips of integrally bladed rotors and to Grind the blade tips on multiple stages of assembled rotors prior to assembly into the stator.

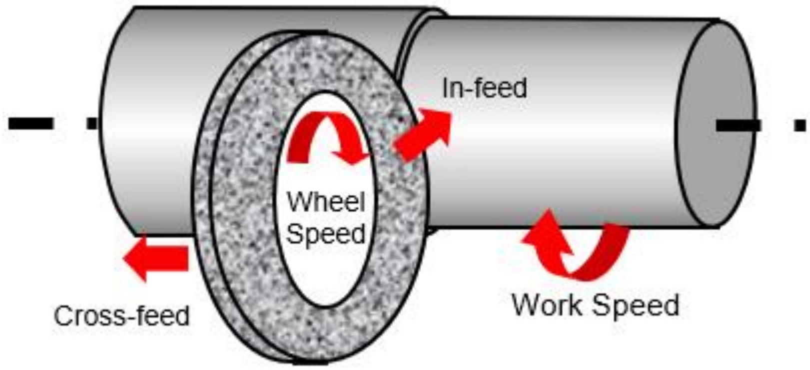


Figure 20.2: Schematic of Cylindrical Grinding

Inner Diameter (ID) cylindrical Grinding is used to produce tight tolerances on inner diameters or bores. A machine specifically designed for ID work is typically used, but, especially for larger bores, there are machines configured to Grind both inner and outer diameters. ID Grinding uses small grinding wheels which can result in a long arc-of-contact as the wheel size approaches the diameter of the workpiece. This can present challenges for Cutting Fluid delivery. For applications where it is necessary to Grind a significant distance down the workpiece bore, the high length-to-diameter ratio of the quill can result in low stiffness, leading to chatter and difficulty holding dimensional size or roundness.

Both OD and ID Grinding methods are typically used for finish passes that remove small amounts of workpiece material.

20.1.3 Curvic Grinding

A specialized Grinding process is used to produce curvic couplings, which are gear-like features used to orient and transmit torque between rotor stages on some engine designs (see Figure 20.3). The reverse shape of the tooth profile is dressed into a cup-shaped grinding wheel which plunges axially into the workpiece. The grinding wheel and workpiece are not concentric, and the wheel Grinds the leading face of one tooth and the trailing face of a different tooth simultaneously during each plunge. The workpiece indexes between each plunge of the grinding wheel until all of the curvic teeth are produced. The most significant challenge in curvic Grinding is maintaining the extremely tight tolerances which requires robust grinding wheel dressing and Cutting Fluid delivery strategies.

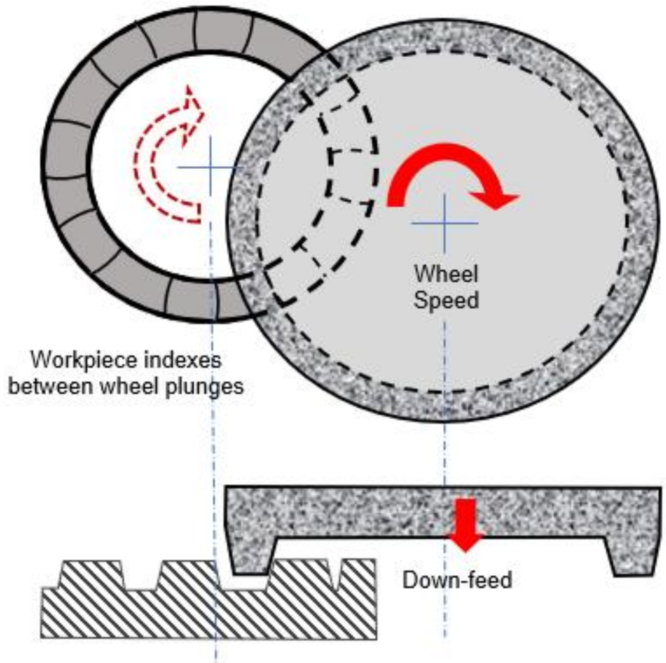


Figure 20.3: Schematic of Curvic Coupling Grinding

20.1.4 Other Grinding Processes

Other Grinding processes less commonly used on Critical Rotating Parts include spline, face, double-disk, through-feed centerless, and infeed centerless Grinding. Standard multi-axis machining centers can also be used to perform Grinding as long as the spindle is capable of sufficiently high speeds to perform efficient Grinding. While this strategy allows for machining and Grinding in a single set-up on one piece of equipment, machining centers typically lack the stiffness, accuracy, Cutting Fluid delivery and Cutting Fluid filtration of purpose-built Grinders.

20.2 Grinding - Process Overview

20.2.1 Grinding Wheels

Grinding wheels are comprised of abrasive grains/grits held together by a bonding media. Comparing Grinding to traditional machining, the abrasive grains perform the material removal and can be thought of as cutting tools, while the bond functions as the toolholder. The details associated with selecting a grinding wheel for a particular application are beyond the scope of this paper, but an overview of key wheel characteristics is important to understand the impact of wheel selection on the Grinding process performance and potential risks.

20.2.1.1 Abrasives

The key characteristics of the abrasive in a grinding wheel are the size of the individual abrasive grains and the abrasive properties. Large abrasive grains will produce deeper grooves in the workpiece resulting in a higher material removal rate and a rougher surface finish. Smaller abrasive grains remove less material and produce a finer finish. The properties of the abrasive include hardness, shape, chemical composition, friability, and thermal conductivity.

The abrasive grain size is commonly expressed using a number designation or "grit", whereby larger numbers represent smaller particles (e.g., 120 grit abrasive grains are smaller than 60 grit). Sieves are commonly used to sort abrasives by size, and any volume of abrasive particles labelled as a particular grit size will include a distribution of sizes. The specifics of sieve geometry, particle size distribution, and grading techniques are defined by various national and international standards which are not completely consistent, so a particular grit processed to one standard may be slightly different in size to abrasives processed to a different national standard.

Most abrasives used to Grind aerospace alloys are from one of four material families:

- Aluminum Oxides (Al_2O_3). Aluminum oxides are general-purpose abrasives and are available in a wide variety of formulations that provide tailored performance. They can be manufactured using fusion (thermal) or chemical processes. The latter produces a finer structure that is more durable because small pieces fracture from the abrasive grain as it wears, rather than the large cleave planes typical of the fused abrasive formulation. This type of abrasive is commonly marketed as "ceramic", although technically all the formulations are ceramics. Because ceramic abrasives are tougher, they require more aggressive dressing or more aggressive process parameters to ensure they remain sharp. Aluminum oxides of various types are the most common choice for nickel-based aerospace alloys.

- Silicon Carbide (SiC). Silicon Carbide is a general-purpose abrasive with performance similar to aluminum oxide. The geometry of the abrasive grain is sharper, and SiC tends to be less durable than Al_2O_3. Like Al_2O_3, silicon carbide is available in fusion and "ceramic" formulations. SiC is a common choice for Grinding titanium and other softer alloys.

- Diamond (PCD). Diamond abrasives can be natural or synthetic (human-made). They feature the highest hardness and best thermal conductivity of the industrial abrasives. The properties and performance of diamond abrasives are significantly better than Al_2O_3 and SiC. At high Grinding temperatures there can be a solubility reaction with workpiece materials containing iron, so diamond abrasives are not used for ferrous materials, including many of the nickel aerospace alloys containing iron. They are a common choice for Grinding ceramic components and carbide coatings.

- Cubic Boron Nitride (CBN). CBN is a synthetic material. It has hardness and thermal conductivity lower than diamond, but still significantly above the conventional abrasives. CBN does not suffer the solubility reaction with iron and is suitable for ferrous and nickel-based aerospace alloys.

  Because of their performance, Diamond and CBN are known as "superabrasives". Superabrasives have significantly lower wear rates than the conventional abrasives and are attractive for small grinding wheels and applications where frequent dressing or wheel replacement is not practical. Because they do not self-sharpen, superabrasives may generate higher cutting forces than conventional abrasives. The high thermal conductivity of the superabrasives can be advantageous when Grinding thermally sensitive materials, since a higher proportion of the thermal energy is transferred out of the cutting zone through the grinding wheel.

20.2.1.2 Bond

The purpose of the bond is to hold the abrasive grains, which perform the material removal. The two main properties of the bond are the material chemistry and the structure.

The bond material determines the grinding wheel strength, stiffness (or damping), abrasive retention, dressing characteristics, and also influences thermal conductivity.

Structure refers to the degree of "openness" or voids present in the bond. A grinding wheel with greater porosity is better able to transfer Cutting Fluid to the cut zone and has greater capacity to carry workpiece chips away from the cut without loading the grinding wheel (workpiece material clogging the wheel porosity). Conversely, a grinding wheel with more porosity has less bond to retain the abrasive and can wear more quickly.

There are three bond families:

- Vitrified Bond. Vitrified grinding wheels have a ceramic bond. They are the most common grinding wheel type and are available in a wide variety of formulations and structures. Vitrified bonds are strong, durable, and hold profiles well. They are compatible with all abrasive types. Because vitrified grinding wheels are stiff, chatter can be an issue in some applications. Because they are durable, they may hold their shape even when the abrasive grains have become dull and thus risk thermal damage to the workpiece. Very open structures may "self-dress" to some degree by releasing worn abrasive as the cutting forces increase, but most vitrified grinding wheels require proactive dressing to retain appropriate sharpness. It is desirable to balance the bond strength with the abrasive properties to allow micro-fracturing of the individual abrasive grains while avoiding unnecessary macro-fracture of the bond.
- Resinoid Bond. Resinoid (or "resin") grinding wheels have a polymer bond and are sometimes referred to as "soft". Resin bonds can provide damping and are good for fine textures. Because the bond is not as strong, resinoid grinding wheels break down as the abrasive grains dull, leading to challenges with friction, heat generation and form profile retention. They also tend to have denser, less open structures. Resin-bonded grinding wheels are not common in aerospace applications.
- Plated. A single layer of abrasive can also be plated directly to a metallic core. The plating thickness is engineered to leave approximately half of the abrasive grain protruding. Because there is only a single layer of abrasive, plated grinding wheels are made with CBN or diamond abrasives for durability. The tough metallic bond retains the abrasive even as the grains dull so there is virtually no bond or abrasive debris as the grinding wheel wears. For this reason, plated grinding wheels can be used in traditional machining centers which are generally not designed with the same protection against abrasive debris as grinders. There are a number of plated grinding wheel applications on aerospace components, particularly for features where the geometry requires a small wheel diameter and shallow material removal. Superabrasives work best on machines with high spindle speeds, good stiffness, and efficient Cutting Fluid filtration systems, so not all machines are suitable.

20.2.1.3 Grinding Wheel Designation

Most grinding wheels are labelled with a code or designation that conveys the abrasive type, grit size, wheel hardness and structure, and the type of bond. There are international nomenclature standards to provide some consistency, but much of the information referenced in the code is proprietary to each specific grinding wheel manufacturer. This makes it difficult to predict relative grinding wheel performance by examining the codes alone.

There are also standard designations for grinding wheel geometry. These are consistent between grinding wheel manufacturers to ensure consistent fit on machines from various manufacturers.

The abrasive and bond of the grinding wheel have been described previously, but the "hardness" or "grade" is also an important concept. "Hardness" is primarily a function of the bond and structure. It refers to the force required to cause a grinding wheel to erode during Grinding. Softer grinding wheels break down more quickly, while harder wheels are more durable. Grinding wheels are graded from A to Z, with letters toward the beginning of the alphabet representing "softer' grades. While the grading is calculated using physical properties of the grinding wheel, in practice it is a qualitative measure and two wheels of the same grade from different manufacturers (e.g., two "K" grade wheels) may perform slightly differently. Despite the lack of precision of the scale, the implications of grinding wheel hardness are critical.

While a hard grinding wheel will be more durable (hold form longer and require replacement less frequently), excessive hardness risks undesirable consequences, including compromised workpiece Surface Condition.

- Excessively hard grinding wheels do not release worn abrasive under typical cutting forces. Dull abrasive grains (glazing) produce higher temperatures that can lead to workpiece thermal damage (e.g., HAZ or residual tensile stress). Dull grinding wheels are also prone to loading (clogging of the wheel porosity with workpiece material), which restricts fluid delivery to the cutting zone and produces unstable Grinding conditions.
- Excessively hard grinding wheels can lead to chatter and resulting geometric inconsistencies.
- Hard grinding wheels require more force to dress and require more frequent dressing to avoid compromising the Surface Condition. Dresser diamond life is also reduced.

Conversely, excessively soft grinding wheels typically do not present risk to the Surface Condition of the workpiece. However, profile form can degrade rapidly, and the high wear rate can introduce workpiece dimensional variation.

Grinding wheel profile/form also contributes to how "hard" or "soft" a wheel of a given hardness behaves. A larger contact area between the grinding wheel and workpiece reduces the specific load on abrasive grains, resulting in a wheel acting "harder". Conversely, a narrower/smaller contact area results in higher specific forces on the grinding wheel and faster wheel erosion (i.e., the wheel acts "softer" under the same cutting parameters).

The propensity of the grinding wheel to break down is also influenced by the choice of process parameters, the effectiveness of the Cutting Fluid application, and the stiffness of the system (including the workpiece). The apparent or effective hardness of the grinding wheel is especially influenced by the wheel speed and wheel diameter. It is common to blame process variability on a presumption that the grinding wheel manufacturer is delivering wheels with inconsistent hardness, but the cause is more commonly unrecognized variation in the process.

20.2.2 Grinding Wheel Dressing

"Dressing" is a term that is used to describe two different functions – regeneration of the shape of the grinding wheel and re-conditioning or sharpening of the wheel. These functions may be performed separately or may be accomplished at the same time using the same tool. Note that dressing does not apply to plated grinding wheels. Plated grinding wheels are retired before they produce an unacceptable Surface Condition. The remaining abrasive can be chemically stripped from the core and the core replated with fresh abrasive.

20.2.2.1 Grinding Wheel Dressing – Form Regeneration

Grinding wheels do not wear uniformly. Straight/flat grinding wheels that are used in a traverse mode will wear more aggressively on the leading corner, resulting in a tapered wheel profile. On profiled grinding wheels, corners and small features will wear more quickly than larger, uniform areas.

Variation in the grinding wheel profile produces geometric variation on the workpiece. As it is easier to accurately measure the workpiece profile than the grinding wheel profile, workpiece measurements are often used to determine the necessary wheel dressing frequency. This determination should be performed during process development so that once Process Validation is achieved for production, the established dressing intervals are detailed in the Manufacturing Control Plan or incorporated into the CNC program.

20.2.2.2 Grinding Wheel Dressing – Conditioning

As with other machining methods, the most critical factor influencing process stability and workpiece Surface Condition is cutting tool sharpness (in this case, sharpness of the abrasive in the grinding wheel). Dressing a grinding wheel releases or fractures dull abrasive grains, cleans adhered workpiece material from the bond porosity, and/or removes bond material to better expose the abrasive and open the wheel structure. A properly conditioned grinding wheel will cut more efficiently, generate less heat, provide better Cutting Fluid delivery, and promote better chip evacuation.

Conditioning is usually performed using a diamond dressing tool. The most common tools include:

- Single-Point Diamond. A pointed diamond mounted on the tip of a metal shank is traversed across the face of the spinning grinding wheel. The diamond may be simultaneously moved along a radial path to profile the grinding wheel, but the profile precision and detail are limited by the size and shape of the diamond. Single-point diamond tools wear relatively quickly so they must be rotated periodically and replaced frequently.
- Cluster Diamond. A number of smaller diamonds are affixed in a pattern to the tip of a metal shank. Some cluster tools feature several layers of diamonds such that as the surface diamonds and matrix are ground away, a fresh set of diamonds is exposed. Because these tools feature a greater volume of diamond, they wear more slowly and are

appropriate for larger grinding wheels and high-volume applications. They are typically not suitable for profiling grinding wheels due to their large cross-section.

- Diamond Rolls. The most common diamond roll configuration uses diamond abrasive plated to the outer diameter of a metal roller. Diamond roll dressing presents several advantages and is the most common technique for aerospace Grinding applications.
  - The total volume of diamond is greater than either of the fixed-diamond tools and therefore the wear rate is lower resulting in a more stable process.
  - The roll may be profiled to produce an opposite profile on the grinding wheel. In addition, it is possible to vary the size or spacing of the diamond abrasive along the axial profile of the roll to condition each portion of the wheel to cut most efficiently.
  - The diamond roll is most typically mounted on a powered dressing device. In addition to the traditional dressing parameters such as infeed rate and frequency, the condition of the grinding wheel can be optimized by adjusting the relative rotational direction and speed between the dressing roll and grinding wheel (dress ratio). This optimization is performed during process development, and once a process enters production the dressing strategy and parameters shall be maintained within the Manufacturing Control Plan to ensure process stability.
- Crush Dressing. While a crush dressing roll is similar to a powered diamond roll, the device to which the roll is mounted is not powered so there is no relative rotational speed between the roll and the grinding wheel at the point of contact. The grinding wheel drives the dresser as it is fed radially inward, and the resulting force crushes the bond. This produces a very sharp wheel, but typically higher wheel consumption and lower form precision than powered diamond roll dressing.

There are various Manufacturing Methods for each of these dressers, as well as several lesser-used dressing techniques not described. Considerable skill, or expert guidance, is required to develop and optimize a dressing method that supports a stable Grinding process to ensure consistent workpiece Surface Condition. For situations where geometry degradation does not drive dresser replacement, development of the dressing process should include a strategy to ensure the dresser is replaced before it becomes dull to the point that performance of the grinding wheel is adversely affected. Because the dresser life is often much longer than that of the grinding wheel, proactive monitoring over a long period (and many wheel changes) is often required to establish an appropriate replacement interval.

20.2.2.3 Grinding Wheel Dressing Parameters

- Infeed. Infeed is the radial overlap between the dresser and the grinding wheel. It can be a fixed distance (e.g., for a cluster diamond which is traversed across the grinding wheel face) or a radial infeed rate per wheel revolution (e.g., diamond roll form dressing). Aggressive infeed produces higher dressing forces, a more open grinding wheel, and higher wheel consumption.
- Traverse Rate. The traverse rate is the speed at which the dresser progresses axially along the face of the grinding wheel. It applies mostly to flat grinding wheels, but a narrow tool or roll may be traversed while simultaneously varying the radial position to

produce a profile on the wheel. A more aggressive traverse rate produces higher dressing forces and a rougher grinding wheel surface. Traverse rate does not apply to form dressing.

- Dress Ratio. The dress ratio applies to diamond roll dressing and is the relative speed between the dressing wheel and grinding wheel at the point of contact between the two. It is expressed as a ratio of dresser speed over grinding wheel speed (e.g., crush dressing has a dress ratio equal to 1). The relative motion can be unidirectional (both wheels turning in the same direction at the point of contact but at different speeds) or counter-directional (opposite directions at the point of contact). The latter produces a smoother grinding wheel surface which can result in a finer workpiece surface texture. However, because this is the result of the abrasive grains being polished flat, the grinding wheel is not optimally sharp and needs to be dressed more frequently to avoid a poor workpiece Surface Condition. For most aerospace applications, a dress ratio of approximately 0.8 unidirectional is considered optimal. Note that for a formed dressing wheel, the dress ratio varies depending on the radius at each location along the profile.
- Dressing Frequency. For each of the dressing methods, it is critical to understand the wear rate of the grinding wheel and to implement a dressing frequency appropriate to ensure that the cutting condition and geometry of the wheel stay within stable ranges. The optimal dressing frequency to maintain the workpiece Surface Condition will depend on the specific application and can range from one dress cycle per hundreds of parts to continuous dressing.

20.2.3 Grinding Parameters

The material removal rate is a function of the feedrate and depth-of-cut. Proper grinding wheel speed is critical to the performance and stability of the process. The cutting speed is related to heat generation and therefore to the Surface Condition of the workpiece. The grinding wheel speed affects the chip-thickness and wheel self-sharpening, but only relates to the material removal rate indirectly. The following parameters are typical of finish Grinding operations, which have the greatest influence on the workpiece Surface Condition.

- Depth-of-Cut. The depth-of-cut per pass in conventional Grinding is generally in the range of 0.001 – 0.002 inch (0.2 – 0.4 mm). The exception is creep feed Grinding where the depth-of-cut can be much higher – with correspondingly lower feedrates.
- Feedrate: Feedrate is expressed in in/min or inches/revolution (mm/minute or mm/revolution). The feedrate can be axial/traverse (surface Grinding or cylindrical Grinding where the grinding wheel width is less than the length of the workpiece) or radial/plunge (cylindrical plunge Grinding or curvic Grinding). Feedrate ranges from microns/revolution to inches/minute (cm/minute) depending on the application.
- Cutting Speed. The cutting speed is expressed as the relative speed of the wheel at the point of contact with the workpiece in feet/minute (m/minute). The optimum grinding wheel speed depends on the application, work material, and wheel type. Most processes run in the range of 3,300 – 8,200 ft/minute (1,000 - 2,500 m/minute) but there are applications that utilize significantly higher grinding wheel speeds.

- Speed Ratio. The speed ratio is defined as a ratio between the grinding wheel cutting speed and the workpiece rotational speed or linear feedrate. It relates to the process stability with respect to flatness/roundness/lobing, but also can influence surface texture and Surface Condition. A low speed ratio may result in chatter, while a high speed ratio poses a risk of surface burning/thermal damage.

  As the cutting speed changes, the performance of the grinding wheel changes. For example, increasing the grinding wheel speed causes a reduction in chip thickness and smaller loads on abrasive grits, causing the wheel to perform as if it was a harder grade. Because the grinding wheel becomes smaller as it wears (or is dressed), it is important to increase the spindle RPM in proportion to the change in diameter to maintain a constant cutting speed at the wheel periphery and thus a consistent, stable process. This "constant speed mode" is an automated function on most modern grinders.

  The cutting speed can also influence the dynamic stability of the process and may need to be adjusted during process development to avoid vibration and chatter on the workpiece. This is especially an issue for long shafts, workpieces with thin cross-sections, and applications that use hard grinding wheels. The grinding wheel speed to work speed ratio also influences the roundness of the workpiece (ability to avoid or correct lobing) in cylindrical and centerless Grinding.

- Grinding wheel rotation direction. The direction of the grinding wheel rotation is described as "up Grinding" or "down Grinding" as shown in Figure 20.4. For most Grinding operations, the direction of rotation has no measurable impact on performance. As the depth-of-cut becomes larger (e.g., creep feed Grinding), the direction of the grinding wheel rotation can significantly influence the ability to deliver Cutting Fluid into and through the Grinding zone depending on the location of the Cutting Fluid nozzles and the geometry of the cut. The direction of rotation can also have an impact on the surface finish, cutting forces, and heat distribution as the forces in down Grinding are 10% to 15% lower than in up Grinding. It is more common to use down Grinding for finish passes, as effective cooling is delivered at the maximum chip thickness, which can reduce thermal loads and the risk of a compromised workpiece Surface Condition.

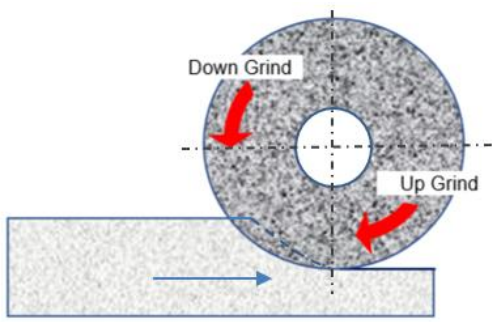


Figure 20.4: Schematic of Down Grinding and Up Grinding

The material removal rate in Grinding is designated by the variable Q and is measured in inches^3/min (mm^3/sec). The specific material removal rate Q', measured in inches^3/min/inch wheel width (mm^3/sec/mm wheel width), accounts for the fact that a wider wheel will remove proportionally more material, so Q' is convenient to compare processes that use different grinding wheel widths. Q can range from less than 0.004 inches^3/min (1 mm^3/sec) to greater than 0.37 inches^3/min (100 mm^3/sec) depending on the type of grinding wheel, dressing strategy, machine capability, and, most importantly, the workpiece material. Basic relationships related to Q include:

- Work material and thermal damage threshold. The energy associated with high material removal rates can cause thermal damage to the workpiece material including localized changes in hardness or ductility and the formation of micro-cracks in the surface. Thermal damage is often accompanied by the formation of a dark oxide layer on the surface but may be present even if the workpiece is not visibly "burned". The propensity for overheating is a balance between the energy applied (a function of Q'), the energy extracted (through the Cutting Fluid and grinding wheel), and the sensitivity of the workpiece material. Workpiece materials with low thermal conductivity, including many aerospace alloys, are sensitive to thermal damage.
- Grinding force. The grinding force increases as the material removal rate increases. The force can be resolved into two components: the tangential (cutting) force and the normal (radial) force. The tangential component determines the torque/power required of the grinder. The normal force, in conjunction with the stiffness of the machine, fixture, and workpiece, affects the ability to hold size tolerance, and the risk of chatter.
- Surface texture. Higher material removal rates produce a rougher surface texture. Surface texture is also influenced by the grinding wheel dressing strategy, cutting speed, feedrate and system stiffness.
- G-ratio. The G-ratio is defined as the volume of workpiece material removed divided by the volume of grinding wheel consumed. High material removal rates correlate to lower G-ratios (faster grinding wheel consumption). Other factors, including the grinding wheel formulation and dressing strategy, also impact the G-ratio.

20.2.4 Cutting Fluid

The Cutting Fluids previously described in other sections of this paper (e.g., Section 17.1.5) are also used for Grinding. However, due to the inherent inefficiency of Grinding, the performance of the fluid is critical to avoid workpiece thermal damage or excessive grinding wheel and dresser wear.

Because of the heat generated by Grinding, it is often incorrectly assumed that a Cutting Fluid with maximum heat transfer capacity (i.e., a synthetic water-based fluid) will be most effective. In fact, a fluid with maximum lubricity (e.g., oil) often performs best, because the lubricity reduces the friction that is responsible for the heat generation and reduces grinding wheel loading. Addressing friction reduces the amount of heat which can result in an unacceptable Surface Condition. In practice, all classes of Cutting Fluids are used successfully in aerospace Grinding operations, although the Grinding versions of those Cutting Fluids typically employ extreme-pressure (high-lubricity) additives to enhance their performance.

Regardless of the type of Cutting Fluid, proper delivery is critical to ensure the lubricating and cooling effects of the Cutting Fluid are present through the full arc-of-contact between the grinding wheel and workpiece (see Figure 20.5). While the arc-of-contact is short for OD and surface Grinding, it can be long for creep feed and ID Grinding applications. Applications with a long arc-of-contact or obstructed line-of-site can require significant engineering of the fluid delivery system.

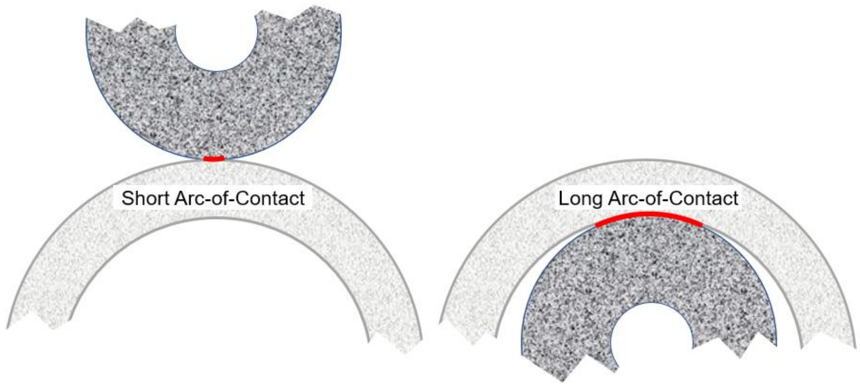


Figure 20.5: Representative Arc-of-Contact in OD and ID Grinding Applications

Laminar flow, high pressure Cutting Fluid delivery just ahead of the grinding zone is recommended to clean the debris (swarf/chips) from the wheel, break the air barrier surrounding the rotating wheel and to inject fluid into the wheel porosity to be carried into the contact zone. For effective Cutting Fluid delivery, it is recommended the Cutting Fluid velocity match or exceed the grinding wheel speed. Complex grinding wheel profiles not only require Cutting Fluid coverage across the total wheel width, but the direction of Cutting Fluid delivery along the profile is important to ensure adequate lubrication of difficult-to-reach areas (e.g., steep profiles).

A chiller may be required to maintain a consistent Cutting Fluid temperature, typically +/- 2 ^{o}F (+/-1^{o}C). This is especially the case for high Q' Grinding operations that consume significant power. Constant fluid temperature contributes to process stability and is often required to attain tight workpiece tolerances.

Because the swarf/chips removed in Grinding are much smaller than those produced by other conventional machining Manufacturing Methods, specialized Cutting Fluid filtering systems are often required. Inadequate Cutting Fluid filtering can cause workpiece material or grinding wheel abrasive particles to be reintroduced into the grinding zone, resulting in small scratches and a non-conforming surface texture or Surface Condition. Periodic machine and Cutting Fluid tank cleaning is required to remove accumulated fine debris that is too small to be removed by the standard Cutting Fluid filtration system.

The Cutting Fluid condition must be proactively maintained, including the concentration and chemical balance of the fluid. Tramp oil from the machine or workpiece adversely affects Cutting Fluid performance and must be managed. Oil-based Cutting Fluids require chemical analysis to measure the degree of tramp oil contamination and determine fluid replacement frequency. Checks for presence of bacteria should also be performed regularly to reduce Environmental Health and Safety (EH&S) risks.

20.2.5 Grinding Process Set-up and Validation

Developing and optimizing a new Grinding application typically requires greater expertise compared to other conventional machining Manufacturing Methods. The major phases of process development for Grinding are:

- Grinding wheel selection. The first decision is typically whether to use a conventional or superabrasive grinding wheel. In some cases, only a superabrasive grinding wheel is practical (e.g., applications that require a small wheel or machines without dressing capability that require a plated wheel), but in many cases it is an economic calculation. There are myriad available combinations of abrasive type, bond material, structure and grade, the selection of which is based on experience or on the advice of the grinding wheel supplier. A wide range of grinding wheel types will work for most applications, but a sub-optimal wheel selection may result in unfavourable workpiece material removal rates and require excessive dressing.
- Process parameters. Process parameters are selected to maximize the material removal rate while ensuring a stable process that produces an acceptable Surface Condition. The grinding wheel must remain sharp and hold form throughout the cut.
- Dressing. The grinding wheel dressing strategy (except for plated wheels) is developed in conjunction with the process parameters. The two main components of the dressing strategy are the dressing parameters (e.g., dress ratio, infeed or traverse rate, dressing amount) and the dressing frequency. Criteria must also be developed for maintaining the dresser media (e.g., diamond cluster or diamond roll) to ensure replacement before the dresser wears to the point of introducing undesired Process Variability.
- Cutting Fluid. Maintaining constant Cutting Fluid delivery is critical to process stability and repeatability. Fixed Cutting Fluid nozzles are recommended over flexible/adjustable nozzles. Custom nozzle systems, including shaped nozzles or multiple nozzles, may be required. Programmable nozzles that track the contact zone as the diameter decreases may be necessary to ensure consistent performance in some applications. Control of critical Cutting Fluid parameters such as nozzle geometry, temperature, flow, pressure, or velocity should be specified in the Manufacturing Control Plan.

In addition to measurement of geometry and surface finish, many aerospace Grinding applications require validation to demonstrate there is no damage to the workpiece Surface Condition. Non-destructive evaluation (NDE) techniques include Fluorescent Penetrant Inspection (FPI), Magnetic Particle Inspection (MPI), Barkhausen Noise (evaluation of residual stress and hardness in ferromagnetic materials), and chemical etch (e.g., Blue Etch Anodize for titanium). Destructive testing of initial parts or coupons may also be required to fully validate the Grinding process. Common destructive tests may include metallographic examination and residual stress measurements. Metallographic examination can be used to evaluate the workpiece material grain deformation depth, Heat Affected Zone (HAZ), and surface Anomalies such as white layer, microcracks, plucks, swept material grains, laps, re-bonded material and embedded abrasive particles. If the workpiece is coated or plated, an evaluation of the thickness of the coating or plating after Grinding is typically performed.

Process Validation may require evaluation of samples produced at the extremes of the expected process range. Examples include maximum vs. minimum grinding wheel diameter, Cutting

Fluid delivery set just above the low alarm limits, low Cutting Fluid concentration, end-of-life dressing media, workpiece material at the top hardness limit, and maximum incoming stock condition.

Once a process has received initial Process Validation, a Manufacturing Control Plan for ongoing verification of the process is required. This may include visual examination, NDE, and measurement of key dimensions. Unexpected geometry variation (especially of tight tolerance features and small radii) can be a leading indicator of Grinding process degradation that should be addressed.

20.3 Grinding – Surface Finish and Surface Condition

Grinding is an energy inefficient process that can generate significant localized heat. Most aerospace alloys have a low coefficient of thermal conductivity which causes concentration of the heat in the immediate surface layer of the workpiece. This can lead to undesirable workpiece material property changes or unacceptable Surface Condition. Poor Process Validation or Manufacturing Control Planning can result in a process prone to Geometric Anomalies and Non-Geometric Anomalies (i.e., a non-conforming Surface Condition).

20.3.1 Surface Finish and Geometry

20.3.1.1 Surface Finish

Surface finish is related to the material removal rate, the abrasive grit size, and the grinding wheel dressing strategy. It can also be influenced by the system stiffness, which, if inadequate, can result in vibration and chatter. Assuming there is adequate access to the workpiece feature, issues with surface finish are usually visually apparent and can be measured non-destructively using contact or non-contact metrology. There are a variety of surface finish parameters used to characterize ground surfaces, as well as numerous techniques and devices, each of which has various filter settings. It is critical that the supplier and customer agree on the acceptance criteria for surface finish measurement.

20.3.1.2 Flatness, Roundness and Taper

Grinding operations can produce very accurate geometry. However, if the workpiece, fixture, or machine do not have adequate stiffness, the ground surface profile can mimic the profile of the incoming material. This is especially true of cylindrical surfaces, which can be prone to lobing (evenly spaced high spots within each revolution of the workpiece). If the incoming surface is lobed and the Grinding set-up is not extremely stiff, it is difficult to round up the workpiece during the Grinding operation. Taper on cylindrical surfaces (a change in diameter along the length of the ground surface) can be caused by geometric set-up errors, stiffness issues, or by grinding wheel wear. The nature of the taper typically suggests the cause.

20.3.2 Surface Condition and Anomalies

20.3.2.1 Heat-related Conditions

Most of the undesirable Surface Conditions generated by Grinding are the result of thermal energy. Thin workpiece sections that cannot provide an adequate heat sink are especially susceptible to thermal effects. In some cases, overheating results in a dark oxide layer on the surface of the workpiece. Depending on the application, this may, or may not, represent an unacceptable workpiece Surface Condition. However, intermittent appearance of colour is a sign of an unstable process and the appearance of colour in an unexpected location indicates a process shift which should be investigated. Note that deleterious thermal effects can still exist even when surface indications are not present. This is one reason thorough Process Validation is essential.

Temperatures can be high enough to create a Heat Affected Zone (HAZ). Rapid quenching of the surface heated material by the Cutting Fluid can also lead to microhardness changes in the near-surface region.

Heat causes the material of the workpiece surface layer to expand during Grinding, while the subsurface material does not. This can result in a residual tensile surface stress and, in extreme cases, microcracking in the surface layer when it cools. Even absent immediate cracking, residual tensile stress can have a negative impact on fatigue life and in these instances the workpiece surface should be evaluated to ensure the Design Intent is met.

Thermal effects are usually relatively shallow, on the order of 0.008 inch (0.2 mm) or less. However, many Critical Rotating Parts run at elevated stress levels and are particularly sensitive to material property degradation at the surface (poor Surface Condition).

20.3.2.2 Other Surface Conditions

The Grinding process will drag the workpiece material grain structure at the surface in the direction of the grinding wheel rotation. Some amount of material grain deformation is inevitable, but excessive material grain deformation depth may be considered an unacceptable Surface Condition in some applications.

Small marks or “fish tails” roughly parallel to the grinding lay pattern can result from inadequately filtered Cutting Fluid. Swarf or released abrasive grit from the grinding wheel are carried from the sump back through the cutting zone by the Cutting Fluid. Depending on the application, these Anomalies are of a size that may not impact performance of the part, but they are typically considered an unacceptable visual condition.

20.3.3 Examples of Ground Surfaces with Manufacturing Induced Anomalies

There have been a number of cases in the aerospace industry of Manufacturing Induced Anomalies attributed to Grinding and manual abrasive finishing processes. Representative examples include:

- <u>Overheated nickel alloy due to creep feed Grinding</u>. Creep feed Grinding was used to rough machine axial blade attachment slots prior to a finish broaching operation. The initial process was evaluated to determine the maximum HAZ, and sufficient stock was left between the rough and finish profile to ensure the final profile would not include material that had been affected by the roughing operation. Over time, progressively harder grinding wheels were introduced to improve wheel life and reduce the number of wheel changes, but the effect of these changes on the workpiece material condition was not evaluated. The harder grinding wheels produced a deeper HAZ, which eventually exceeded the depth of the material removed by broaching, leaving thermally affected material in the slots. This is an example of inadequate Change Control of a previously validated process.

- Cracked nickel alloy parts due to surface finish. There have been several cases of Critical Rotating Parts found at overhaul with cracks attributed to rough surface finish produced by the Grinding operations at original manufacture. In one instance, the Manufacturing Process used a rough Grinding operation followed by a finish Grinding operation to improve the surface finish. The finishing operation flattened the surface finish peaks produced by the roughing operation resulting in an acceptable surface finish measurement. However, the deepest scratches produced by the relatively large abrasive grit during the roughing operation contributed to reduced fatigue performance. This is an example of inadequate Process Validation.

- Cracked nickel disk due to excessive material grain deformation. Cracks were discovered randomly distributed in a band around the ID circumference of the bore of a Critical Rotating Part. All cracks were aligned in an axial direction. Destructive evaluation of the cracks indicated a cold-worked layer approximately 0.01-0.015 inch (0.25 – 0.4 mm) deep. A cold worked layer and cracks of a similar nature were replicated via aggressive hand Grinding of a scrapped version of the same part. This is another example of inadequate Process Validation.

- High Spots. Plating and coating processes do not produce perfectly uniform thickness, resulting in locally thicker material or “high spots”. When Grinding such surfaces, it is important to set the initial depth-of-cut based on the highest location. If the baseline for the first pass is set based on a thinner location, the high spot will experience an unacceptably high depth-of-cut that can result in local damage to the plating or coating. This is an example of inadequate process development.

- Cracked curvic on a nickel alloy disk. Cracks initiated from the HAZ due to abusive Grinding during a hand finish operation on the curvic balance ring. While hand Grinding, sometimes referred to as “benching”, is typically a low energy operation, it represents a particular risk due to inherent Process Variability. There are numerous examples where hand Grinding has resulted in Anomalies, including localized deep scratches and unacceptable geometric conditions. This is an example of unacceptable Process Variability. Wherever possible, hand operations should be replaced with machine or robotic automated processes to reduce Process Variability.

- Cracked titanium disk with embedded abrasive grit. During overhaul, a disk was found to have a 22 inch (55 cm) circumferential through-thickness low cycle fatigue crack in the web. The crack initiated from scratches which included embedded grit. Waviness was present on both the forward and aft surfaces. The directionality of the polishing marks suggests a rotary hand power tool was used to polish the web. Fatigue cracks initiated from scratches with embedded abrasive, indicating the scratches occurred during the polishing procedure to remove chatter marks resulting from prior Turning. This example resulted from an unstable roughing (Turning) Manufacturing Method, followed by a manual Grinding Manufacturing Method with insufficient Process Validation.

- Manual Operations. Aggressive (or inadequate) hand-operated (manual) Grinding operations used to remove burrs, produce edges, or remove local Anomalies, can introduce microcracks or HAZ to the workpiece which adversely impact the workpiece fatigue life capability. In addition to the Process Variability inherent in human control, hand operations frequently allow operators considerable leeway in tool selection, including abrasives, high speed steel or carbide. Hand operations on Critical Rotating Parts should be replaced by automated Manufacturing Methods in order to reduce Process Variability and minimize the risk of unintended damage to adjacent areas of the workpiece.

20.4 Grinding – Process Monitoring

Commercially available systems to monitor the Grinding process include Cutting Fluid flow, pressure and temperature, acoustic emission, spindle power/torque and vibration measurement. In-process geometric gaging/probing is also widely employed. Advanced systems may also have integrated optical measurement (e.g., laser) for grinding wheel and dresser diameter/profile checks, and to verify Cutting Fluid nozzle position relative to the wheel/grinding zone.

- Cutting Fluid Flow, Pressure, and Condition. Systems to detect unfavourable Cutting Fluid delivery are employed on most modern grinders. Low flow and/or pressure limits are programmed by the user and if the Cutting Fluid delivery falls below a limit the process is automatically interrupted. More advanced systems include full in-line Cutting Fluid quality monitoring and control (pressure, flow, temperature, pH, concentration, and debris).
- Acoustic Emission. Acoustic emission sensing is an available option on many modern grinders. An acoustic emission system detects impending contact between the grinding wheel and the workpiece or dresser by monitoring the acoustic signature coupled through the Cutting Fluid. In addition to minimizing potential impact due to programming errors or an oversize raw material condition, this strategy allows cycle time reduction by rapidly feeding the grinding wheel toward the workpiece or dresser and slowing the feedrate just prior to contact.
- Power or Torque. Electric energy supplied to the spindle motor can be monitored to detect unusual Grinding conditions such as an overly dull or glazed grinding wheel. While such systems could be used to adaptively dress the grinding wheel as needed, in most aerospace applications the dressing frequency is pre-determined, and the system would only be used to detect Special Cause Events. The electric energy supplied to a rotary diamond dresser can similarly be monitored to detect unusual conditions including an overly worn dresser. While commercially available, such systems are not currently in wide use.
- Vibration. Vibration monitoring systems can be used to detect chatter. The vibration monitoring system can stop the process or adjust process parameters away from dynamically unstable conditions, thus avoiding the occurrence of chatter. Vibration monitoring systems are not in common use on conventional grinders, but they are increasingly employed on machines which perform multiple Grinding operations in a single setup.

- Balance. Systems are available to automatically fine-tune the balance of grinding wheels and rotary dressers during setup. These systems can also be used during the Grinding operation to detect imbalance arising during operation.

20.5 Grinding - Alternate Manufacturing Methods

Conventional Machining. Grinding has traditionally been employed in applications where a fine surface finish is required, where tight tolerances are required, or where the workpiece material is too hard to machine. In the first two instances, conventional machining processes such as Turning and Milling are alternatives to Grinding, particularly as advances in design and technology have improved the stiffness and accuracy of machine tools. Achieving tight tolerances and fine surface finishes require more time-consuming conventional machining (i.e., lower feedrate and depth-of-cut), so an analysis of cycle time and consumable costs are used to determine whether Grinding is a more cost-effective process.

Hard Machining. Hard Machining commonly denotes a Manufacturing Method using cutting tool materials including Cubic Boron Nitride (CBN) and whisker-reinforced ceramics that allow machining of workpiece materials up to approximately 70 Rockwell C hardness. In particular, hard Turning is becoming a more common alternative process to cylindrical Grinding. In some applications hard Turning can be more productive than Grinding, but Grinding is generally more capable if the requirements also include tight tolerance, fine surface finish, or geometry with fine geometric detail. Hard Turning and Grinding are capable of producing equivalent Surface Condition and process stability.

Non-Conventional Machining. Electrical-Discharge Machining (EDM) and Electrochemical Machining (ECM) Manufacturing Methods are alternatives to Grinding in cases where the workpiece material is too hard to machine conventionally. However, they are not widely used for Critical Rotating Parts for a variety of reasons.

- EDM leaves a recast layer and tensile residual surface stress that are unacceptable for most locations on rotating parts. A secondary operation is required to remove the recast material.
- While ECM does not produce a recast layer, it is an electrically activated process with the risk of arc-out. Intergranular (chemical) attack can also be a concern.
- Non-conventional machining process are not typically configured for round components such as bearing journals and bores.

21 Appendix O: Development of Manufacturing Credits for Damage Tolerance Assessments

This is a summary of the process and rationale used to establish manufacturing credits promoting enhanced Manufacturing Methods.

21.1 Manufacturing Credit Definition Approach

The finds (observed cracks), events (fractures) and Manufacturing Induced Anomaly rotor incidents are gathered and reviewed relative to the feature location. As an example, the feature locations identified by the AIA RISC for axial blade attachment slots are presented in Figure 21.1.

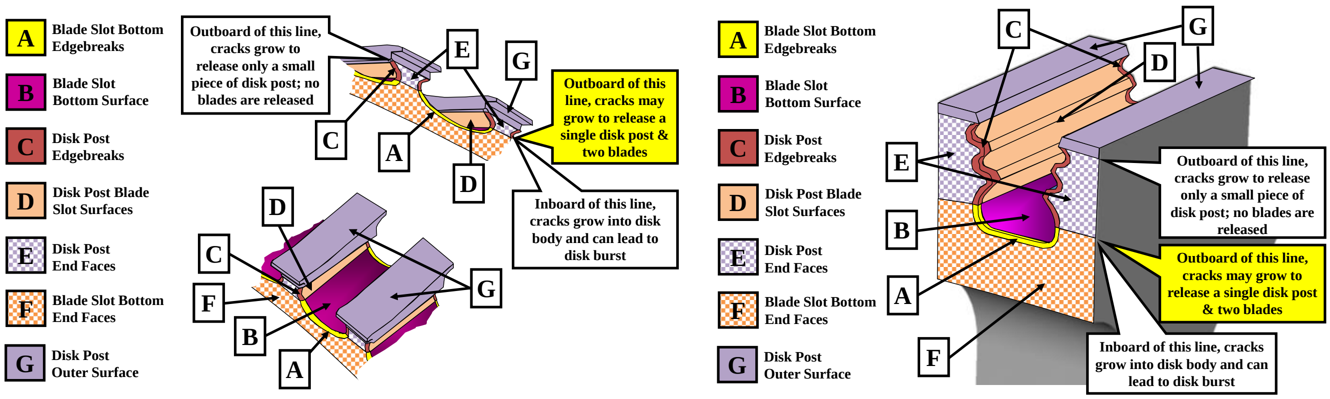


Figure 21.1: Detailed Locations of an Axial Blade Attachment Slot

The following strategies are considered to have the capability, either independently or in combination, to prevent the Manufacturing Induced Anomalies which relate to the incidents observed:

- Feature Method of Manufacture
    - Process Validation and Manufacturing Control Plan
    - Machine Condition, Fluid and Fluid Condition, Tooling and Setup Validation
    - Fluid Monitoring
    - Process Monitoring
- Edge Processing
    - Process Validation and Manufacturing Control Plan
    - Semi-Automated Processing

    - Automated Processing
- Geometry Inspection
    - Edge Inspection
    - Feature Inspection
- Surface Condition Inspection
    - Non-Destructive Inspection
    - Periodic Metallographic Cutup
    - Etch Inspection

Repair Process Validation (Materials Review Board and Overhaul) was originally included in the Manufacturing Method strategy list. It was removed from the list because:

- Enhanced Manufacturing Methods for the feature at new part manufacturing should reduce the need for such repairs.
- Manufacturing Method actions should follow FAA Advisory Circular 33.70-1 (Reference 2) and the practices of this RoMan Report and should involve all necessary engineering disciplines.
- A successful repair Process Validation Function (or plan) means the Design Intent is met.

Relative to manufacturing credits, each feature incident is assessed vs. the above list of Manufacturing Method strategies and an incident weighting process is used to appropriately weight one incident relative to another. Each Manufacturing Method strategy weighted score is then summed for all the incidents and the resulting weighted strategies score is scaled to establish the relative initial manufacturing credit values for further consideration. Final relative manufacturing credit values are assigned based on the initial values and team discussion, which includes acceptance by manufacturing experts. The assessment process steps are summarized as follows:

1. Define the feature incident damage

    Each feature incident is reviewed in detail and categorized with respect to the type of damage (Geometric, Non-Geometric or both), incident type (Anomaly, crack or fracture) and damage location.

2. Assign the appropriate Manufacturing Method strategy or strategies which may have prevented the incident

    Each feature incident is reviewed by manufacturing and lifing experts. The appropriate Manufacturing Method strategies from the above strategy list are identified for each incident by using a nominal group technique. This results in a list of strategies most likely to reduce or eliminate the root cause of each incident.

3. Assign an appropriate relative weighting to each feature incident

    Two weighting factors are used to quantify a flight safety metric.

The first is an equivalent fracture event (EFE) weighting factor which accounts for the relative non-containment threat of fracture events, crack finds and Manufacturing Induced Anomaly finds. For this weighting factor, the safety pyramid concept is used with three levels: major consequences is a fracture event, minor consequences is a crack find and an incident and observation is a Manufacturing Induced Anomaly, as presented in Figure 21.2.

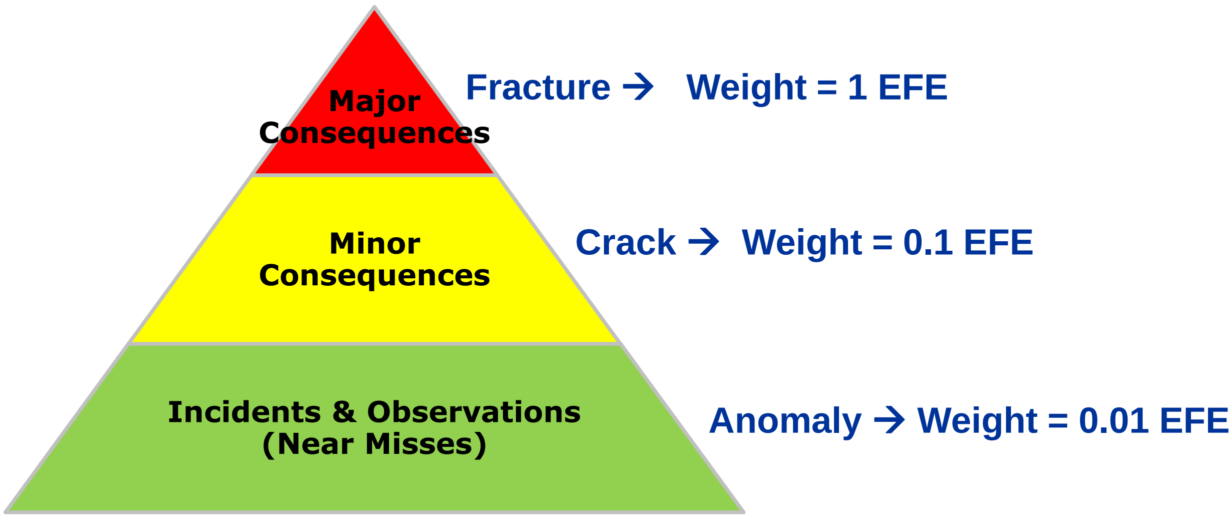
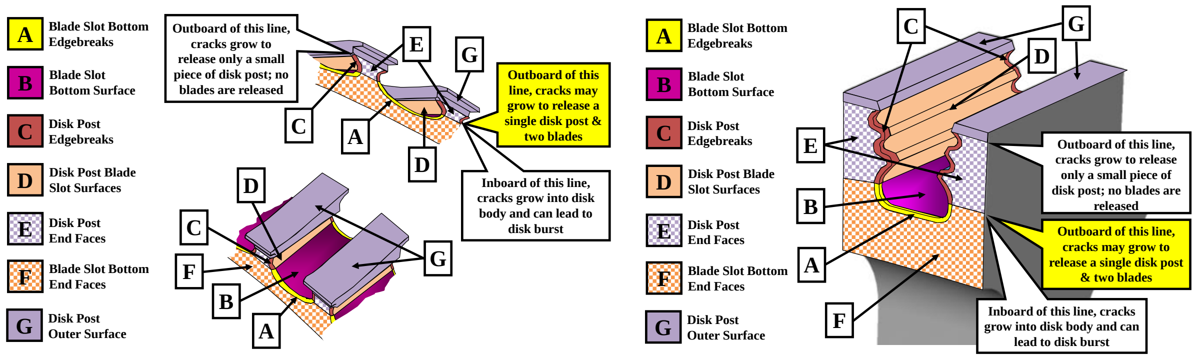


Figure 21.2: Equivalent Fracture Event Pyramid Used to Weight the Incidents

The second factor is a non-containment risk (NCR) weighting factor which addresses the consequence of fracture. The non-containment risk weighting factor is assigned based on the feature location where the incident damage was observed. As an example, the non-containment risk factor assessed for axial blade attachment slots is presented in Figure 21.3.



Locations A, B & F → Weight = 1 ; Non-contained 100% of the time

Locations C, D & E → Weight = 0.5 ; Non-contained 50% of the time

Location G → Weight = 0.0 ; Contained

Figure 21.3: Non-Containment Relative Risk Weight Factor

The product of the equivalent fracture event weighting factor (EFE) and the non-containment risk weighting factor (NCR) is a measure of the relative risk between two incidents and is used as the flight safety metric.

4. Assign a relative risk to each manufacturing strategy of an incident

   To provide an equally weighted risk for each incident relative to another incident, the flight safety metric of Step 3 is divided by the number of Manufacturing Method strategies assigned to the incident. For each incident, the resulting equally weighted relative risk factor (RRF) for each manufacturing strategy is thus defined as follows:

$$RRF = \frac{(EFE)(NCR)}{Number\ of\ Manufacturing\ Attributes\ Assigned\ to\ the\ Incident}$$

5. Define Initial Manufacturing Credit Values

   To define initial manufacturing credit values, the RRF of each specific manufacturing strategy is summed for all incidents. A manufacturing credit value of five (5) is assigned to the Process Validation and Manufacturing Control Plan strategies based on the Manufacturing Process Validation value assigned for circular holes provided in FAA Advisory Circular 33.70-2 (Reference 3). The remaining initial manufacturing credit values are determined relative to these values based on the Step 4 score of each strategy.

6. Define Final Manufacturing Credit Values

   The initial manufacturing credit values obtained in Step 5 form the basis of manufacturing credit value discussions. These discussions provide finalized manufacturing credit values which appropriately balance engineering Design Intent with Manufacturing Method capability. This discussion recognizes that the initial manufacturing credit values do not completely quantify the capability of a specific Manufacturing Method strategy and also the importance of promoting enhanced Manufacturing Methods.

21.2 Manufacturing Method Strategy Definitions

The Product Definition should contain adequate notes or specifications which ensure the Manufacturing Methods applied to the part are capable of achieving the selected manufacturing credit values. The following definitions were created to guide the Product Definition development for each of the Manufacturing Method strategies. The following definitions may not completely represent the final definitions. The final (official) definitions are those provided by regulatory material such as an FAA Advisory Circular or similarly accepted or approved data, if available.

21.2.1 Feature Method of Manufacture

Manufacturing Intent: The feature-specific Manufacturing Method produces a feature with conforming geometry and Surface Condition (for example, metallography and finish) consistent with the feature lifing process, and an appropriate edge condition (including any necessary maximum burr size limit and edge metallographic condition) for all downstream part processing such as deburring, edge breaking, edge finishing or shot peening.

Restrictions:

- The credits defined for feature method of manufacture requires an edge processing Process Validation and Manufacturing Control Plan.
- Credits for feature method of manufacture do not apply to edge processes.

Process Validation and Manufacturing Control Plan: This report should be used to define an appropriate means of Process Validation and associated Manufacturing Control Plan. A successful Process Validation and Manufacturing Control Plan means the manufacturing intent will be met throughout the part production run.

Machine Condition, Fluid & Fluid Condition, Tooling, and Setup Validation:

- *Machine Condition:* The machine condition is periodically evaluated to validate it is capable of delivering product meeting the manufacturing intent.
- *Fluid & Fluid Condition:* The fluid is directed to the cutting zone during machining operations. The fluid condition is maintained.
- *Tooling:* Cutting tool design, material properties, manufacture (new and reconditioned) and geometry are controlled. Cutting tool condition is monitored to preclude excessively worn or broken cutting tools.
- *Setup Validation:* A cutting trial is used to validate the setup produces acceptable part geometry and prescribed material removal.

Fluid Monitoring: A real-time automated monitoring strategy which has the capability to ensure the fluid volume and flow to the cutting zone are maintained within validated process limit(s) and can interrupt the process when the established limit(s) are violated.

This includes directional control of the fluid without human intervention and maintaining the fluid condition.

Process Monitoring: A real-time automated monitoring strategy which has the capability to identify when the process varies outside the established validated process limit(s) and can interrupt the process when the established validated process limit(s) are violated. Feedback from the monitoring should be used to ensure the process remains within the acceptable validated range. Credit for process monitoring requires the use of fluid monitoring.

21.2.2 Edge Processing

Manufacturing Intent: The edge break method produces a feature edge with conforming geometry and Surface Condition (for example, metallography and finish) consistent with the feature edge lifing method, and an edge form appropriate for all downstream part processing such as shot peening.

Restrictions:

- Manufacturing Methods used to remove the burr for safe part handling or to facilitate feature inspection are not considered edge processing as defined in this section and must not introduce conditions detrimental to the edge processing method(s).
- The edge processing credits require a feature method of manufacturing Process Validation and Manufacturing Control Plan.
- Credits for edge processing do not apply to the feature method of manufacture.
- Only one of the three options (two semi-automated and one automated) may be selected for a specific feature.

Process Validation and Manufacturing Control Plan: This report should be used to define an appropriate means of Process Validation and associated Manufacturing Control Plan. Process Validation of edge processing method(s) should include upstream operations to ensure incoming edge conditions are not detrimental to the edge Manufacturing Method(s). A successful Process Validation and Manufacturing Control Plan means the manufacturing intent is met throughout the part production run.

Semi-Automated Method of Manufacturing:

- *Manual Deburr and Pre-Form:* A manual process is used to deburr and pre-form the edge geometry prior to final edge geometry generation and finishing by automated method(s). The automated method(s) at time of Process Validation should demonstrate the ability to remove the damage caused by the prior manual preparation method. It is recognized the full range of manual method variation may not be captured at the time of Process Validation; thus, this process is not as robust as one which includes an automated edge preparation method.
- *Manual Finishing:* An automated deburring and edge break method(s) is (are) used to form the edge geometry and produce a nearly finished edge condition. Final finishing is completed by manual method(s) involving soft tooling such as

paper or cloth, without the use of power tools. It is recognized the full range of manual method variation may not be captured at the time of Process Validation; thus, this method is not as robust as one which includes an automated final finishing method.

Automated Method of Manufacturing: Automated method(s) is (are) used for deburring, edge geometry generation and finishing.

21.2.3 Geometry Inspection

The credit applies only to the location(s) where the inspection is applied.

Edge Geometry Inspection: An automated edge inspection method in combination with an inspection strategy which can confirm the geometry of the feature edges meets the manufacturing intent. The credit applies only to the edge and not the feature.

Feature Geometry Inspection: An automated feature inspection method in combination with an inspection strategy which can confirm the geometry of the feature surfaces meets the manufacturing intent. The credit applies only to the feature and not the edge.

21.2.4 Surface Condition Inspection

The credit applies only to the location(s) where the inspection is applied. For example, if applied to the edge, then the credit only applies to the edge; likewise, if applied to the feature, then the credit only applies to the feature.

Non-Destructive Method: A quantitative non-destructive evaluation method(s) to ensure the surface condition (that is, metallography, finish, and residual stress) of the feature or feature edge remains within the acceptable range to meet the manufacturing intent.

Cutup: A representative periodic test sample cutup to ensure the surface metallography of the feature or slot edge remains within the acceptable range to meet the manufacturing intent.

Etch: Etchants which can detect distorted surface metallography are a useful non-destructive evaluation method when combined with an appropriate visual reference standard. Blue Etch Anodize (BEA) for titanium is an example of an etch inspection with sufficient capability of detecting distorted surface metallography. Caution: Etched surfaces can reduce the fatigue capability of the material and should be evaluated as a portion of the Approved Lifing Method for the part.