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Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts

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16. Abstract

This report was developed by a partnership of the Aerospace Industries Association (AIA) Rotor Manufacturing Project Team (RoMan) and the Federal Aviation Administration in response to accidents and incidents caused by manufacturing induced anomalies in critical rotating parts. According to a 1997 summary from the AIA Rotor Integrity Sub-Committee, about 25% of recent rotor cracks/events have been caused by post-forging manufacturing induced anomalies.

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 nominal 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. Because critical rotating part reliability has demonstrated particular sensitivity to hole machining practices, specific recommendations for hole making are included.

In addition, a section containing industry lessons learned is included to provide guidance on issues common in the industry. The term lessons learned generally refers to useful pieces of practical wisdom acquired by experience or study.

Appendices are attached which include the team charter and vision and detailed information concerning process monitoring of holes and non-destructive evaluation.

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EXECUTIVE SUMMARY

This report was developed by a partnership of the Aerospace Industries Association (AIA) Rotor Manufacturing Project Team (RoMan) and the Federal Aviation Administration (FAA) in response to accidents and incidents caused by manufacturing induced anomalies in critical rotating parts. According to a 1997 summary from the AIA Rotor Integrity Sub-Committee, about 25% of recent rotor cracks/events have been caused by post-forging manufacturing induced anomalies.

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 coolant, 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.

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)

In addition, a section containing industry lessons learned is included to provide guidance on issues common in the industry. The term lessons learned generally refers to useful pieces of practical wisdom acquired by experience or study.

Appendices are attached which include the team charter and vision and detailed information concerning process monitoring of holes and non-destructive evaluation.

- 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 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 practice (e.g., speed, feed and use of tool)
  - Process monitoring requirements

- Drawing 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 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 should be carefully considered before being accepted.

- Quality Assurance. To assure 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, drawings, specifications, MCP, or other approved product description.

- Process Monitoring. 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 known method to detect when special cause events happen 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 that a manufacturing method varies outside its acceptable parameter limits, the process monitor should automatically shut down the process.

- 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, the people cannot be completely 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 also 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 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.

Aerospace Industries Association
Rotor Manufacturing Project (RoMan) Report

October 24th, 2002

Guidelines to Minimize Manufacturing Induced Anomalies in Critical Rotating Parts

DISCLAIMER

This report is the response of the Propulsion Committee of the Aerospace Industries Association (AIA) to a FAA initiative on Critical Rotating Part manufacturing for gas turbine aero engines. It has been written by a special project team drawn from engine manufacturers in both North America and Europe and is the result of a series of meetings and work over a three year period. While the report describes the summation of the experience and practices used in the participating companies no liability for the validity nor for the views expressed here can be accepted by either the AIA or the participating organizations.

Contents

1 Introduction and Recommendations

1.1 Introduction

The following report was developed by a partnership of the Aerospace Industries Association (AIA) Rotor Manufacturing Project Team (RoMan) and the Federal Aviation Administration (FAA) in response to accidents and incidents caused by Manufacturing Induced Anomalies in Critical Rotating Parts. An example 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 tierod bolt hole introduced during the hole machining of the disk (i.e., a Machining Induced Anomaly). According to a 1997 summary from the AIA Rotor Integrity Sub-Committee, about 25% of recent rotor cracks/events have been caused by post-forging Manufacturing Induced Anomalies.

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, see Appendix A. 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 hole machining practices (e.g., the Pensacola event), specific recommendations for hole making are included. Specific recommendations for other Critical Rotating Part feature Manufacturing Processes will depend on a detailed review of industry gathered service experience and associated manufacturing practices. If needed, specific 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.

1.2 Recommendations for the Manufacturing of Critical Rotating Parts

1.2.1 Manufacturing Process Validation and Change Control

1.2.1.1 Identification of Parts Subject to Special Control

Rotating parts whose primary failure is identified by FMEA as immediately leading to a potential 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.

1.2.1.2 Process Validation Approaches

Process Validation should be by one of the two routes described in Section 4.2, 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.

1.2.1.3 The Process Validation Function

A Process Validation Function 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 so as to ensure the part Design Intent/quality is met.

1.2.1.4 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.

1.2.2 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.

1.2.3 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.

1.2.4 Specific 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 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 AC 33.14-x (to be published) 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:

1.2.4.1 Process Monitoring

Real time Process Monitoring with automated machine shutdown is recommended for all holes identified in Section 1.2.4.

1.2.4.2 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. 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 8.1 and 8.2 in Section 8 of this report.

2 Definitions

Anodic Etch	Electrolytic etching where the part 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.
Blue Etch Anodize	An anodizing/inspection process which deposits a bluish conversion coating on titanium surfaces, providing a high visual contrast distinction for certain Anomalies.
Change Control	A process in which changes to the Manufacturing Process are evaluated, validated and documented.
Critical Rotating Parts	Rotor structural parts (such as disks, spools, spacers, hubs, and shafts), the failure of which could result in a hazardous engine condition. In this context a hazardous engine condition should be interpreted as the conditions described in FAR Part 33.75. The FAA considers such parts as Priority Parts for the purposes of production certification and surveillance.
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 on the part drawing 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 drawing and all associated specifications, including 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).
High L/D Hole	For manufacturing: Holes which have a L/D > 1. L/D is defined as the length or depth of a hole divided by its diameter based on nominal dimensions. For NDE: Holes which have a L/D > 1 when they can be accessed from one side only or a L/D > 2 if they can be accessed from both sides.
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.
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.
Material Review (MR)	Evaluation and disposition of non-conforming or Special Cause Event parts.
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 are embedded inclusions from broken tool tips which have sharply defined boundaries 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 shut down 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.
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 parts are manufactured which meet the Design Intent.
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.

3 Background

It is inevitable that there will be scatter in the performance of parts made by a controlled process due to Process Variability, fatigue scatter, etc. 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 3.1. Parts that do not have sufficient properties to meet or exceed the Service Life as a result of the Manufacturing Process are at risk to initiate fatigue cracks.

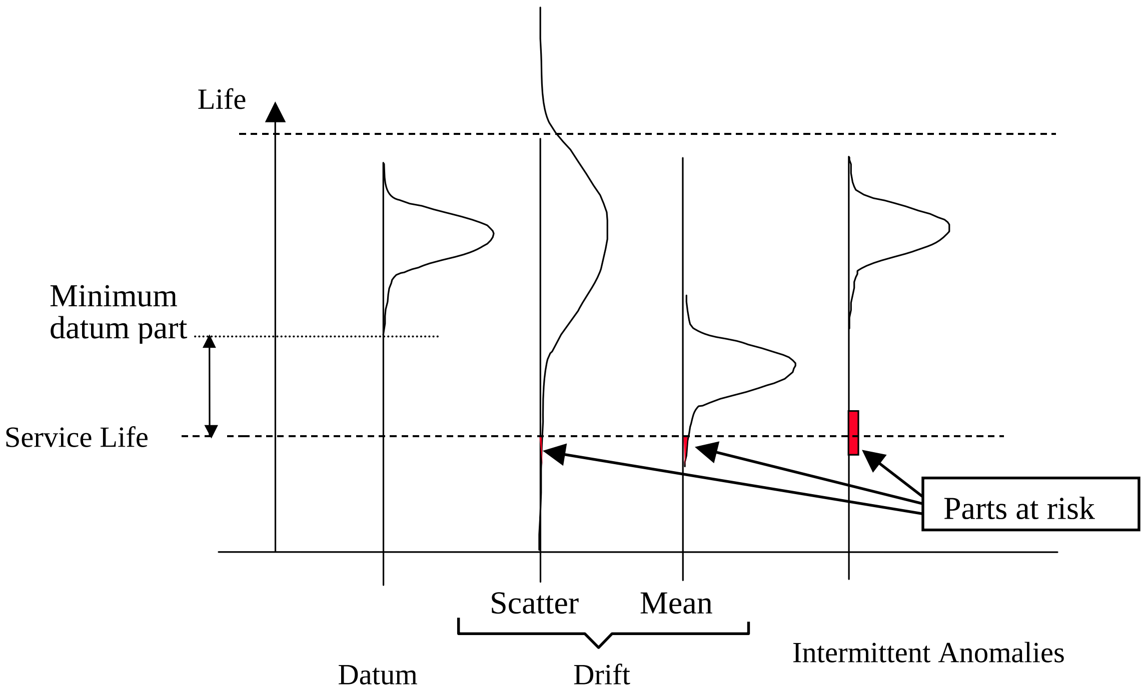

Figure 3.1: The Effect of Variation in the Product of a Manufacturing Process

3.1 Minimizing Parts at Risk

In order 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.

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 coolant, 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 3.1, 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.

3.2 Content and organization of the report

The remainder of the report is organized as follows:

- Section 4 describes practices that address the integration of the Manufacturing Process into the Service Life declaration process.
- Section 5 describes Quality Assurance best practices.
- Section 6 describes Process Monitoring best practices.
- Section 7 emphasizes the importance of Human Factors and Training in the Manufacturing Process.
- Section 8 describes Non-Destructive Evaluation best practices with tables to aid in choosing NDE Methods for holes.
- Section 9 lists some "Lessons Learned" to date by the industry.
- Sections 10-12 are Appendices

  10 - Gives the RoMan Charter and Vision statements and lists the RoMan participants

  11 - Gives specific details of Process Monitoring for holes

  12 - Gives details of current NDE criteria and capabilities

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

4.1 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 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 drawing.

Although the drawing 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 on the drawing 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 on the drawing 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 on the drawing for the:

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

4.2 Approaches to Manufacturing Process Validation

In order 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, feed rates, 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 the Part Specific Process Validation (PSPV) while the second is known as the 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 by the use of a specification or validated parameter limits, while turning operations may be controlled by PSPV. Typically, 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 4.1.

Table 4.1: 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 4.1.</td><td>FMEA of the engine leads to part classification, ¶4.1
The critical nature of the part should be conveyed to all parties concerned with manufacturing the part, ¶4.1</td></tr>
<tr><td>PVF, ¶4.3</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., AC 33.14-x). For example, an identification process may capture features with both
a. Sensitive Manufacturing Processes
b. Predicted fatigue lives that are <u>either</u> less than four times the Service Life <u>or</u> less than 100,000 cycles.</td></tr>
<tr><td>PVF</td><td>3</td><td colspan="4">Validate the Manufacturing Process for those features identified in Step 2 above</td><td>The Process Validation can be a combination of PSPV and GMPV</td></tr>
<tr><td></td><td></td><td colspan="2">PSPV ¶4.4.1</td><td colspan="2">GMPV, ¶4.4.2</td><td></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, ¶4.4.3</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 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, ¶4.5				The MCP defines all the steps & methods for manufacturing Critical Rotating Parts.
PVF	5	Change Control, ¶4.6				
		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	ME	Is change within Specification or validated parameter limits? If so, allow If not, go to 2	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 ¶4.6 All change, substantial or not substantial, should be recorded in the MCP.

4.3 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 so as 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 4.1.

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 requirements
- Drawing requirements
- NDE Method requirements
- Metallurgical examination to the materials standard
- Residual stress measurement
- Special design requirements
- Fatigue testing (specimen, sub-element 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.

4.4 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.

4.4.1 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 disk may be the first part made according to the particular 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, fixturing, 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.

4.4.2 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 dependant on the Manufacturing Method used (drilling, reaming, milling etc.), geometry (hole L/D), and part material. Other process requirements such as minimum stock removal, coolant 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 4.4.3 for each Manufacturing Method like drilling, reaming and milling, etc. This should be done for the various types of materials and various feature geometries.

4.4.3 Guidelines for Manufacturing Method Evaluation

The objective of this step is to qualitatively and quantitatively understand the impact of the identified Manufacturing Method 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 machining parameters anticipated for the material, compliance with the company’s standards, set by experience of:

- Microstructure (highly distorted grain boundaries, slip lines, cold work, white layer)
- Surface finish (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.

<u>Near Surface Microstructure</u>

A number of specimens, cut and polished, representing the following should be evaluated:

- Materials condition anticipated
- New and worn/dull tools
- Corner points of anticipated machining parameter window
- Adverse machining parameters, if applicable (max. speed/min. feed; min. speed/max. feed)
- Tool make, material and geometry (if applicable)

Where possible, the cutting location should be determined by means of NDE.

<u>Surface Finish</u>

Surface finish quality evaluation should consider:

- New and worn/dull tools
- Minimum and maximum speeds/feeds

<u>Residual Stress Profile</u>

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 and should consider:

- New and worn/dull tools
- All rotor materials involved
- Cutting speeds and feeds
- Adverse machining parameters (if applicable)
- Tool make

Results should be within the company's Approved Lifing Method fatigue database. The fatigue specimens may be cut from machined parts using a process similar to those used in production, or may be machined in a lab using production-like cutting tools. 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.

4.5 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 type and make
- Cutting parameters and scatter allowed
- Machining device
- Coolant 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)

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

4.6 Guidelines for Manufacturing Change Control

4.6.1 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 considered 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 route
- Process parameters
- Machine, fixturing, 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.

4.6.2 Guidelines to Validate Manufacturing Change

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, ¶ 4.4.3 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 that have both the new and the old Surface Condition. 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).

5 Quality Assurance

5.1 Quality Assurance in Manufacturing

To assure 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 (Section 4.2), the MCP (Section 4.5) and manufacturing Change Control (Section 4.6) should be covered by written procedures.

All manufacturing parameters identified in Section 4.4 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 insure 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.

5.2 Material Review (MR)

5.2.1 Introduction

The Material Review 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, drawings, specifications, 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.

5.2.2 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 so as 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.

6 Process Monitoring of Machining

6.1 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 coolant 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 coolant 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 known method to detect when a Special Cause Events happen 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 coolant
- 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. In the event that a Manufacturing Method varies outside its acceptable parameter limits, the process monitor should automatically shut down the process.

6.2 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 shut down the method 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 method development by helping select the optimum tool geometry and machining parameters resulting in optimized tool life.

6.3 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., AC 33.14-x) 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 drawing 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 on part drawings. 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.

6.4 Recommendation

Over the years there have been a number of cracks and ruptures 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 AC 33.14-x (to be published) is considered an acceptable means, but not the only means, to decide whether Process Monitoring should be required for holes. 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 Section 11 (Appendix B: Process Monitoring for Holemaking) for detailed guidance on the application of Process Monitoring for holes.

Process Monitoring for 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.

7 Human Factors and Training

7.1 Human Factors

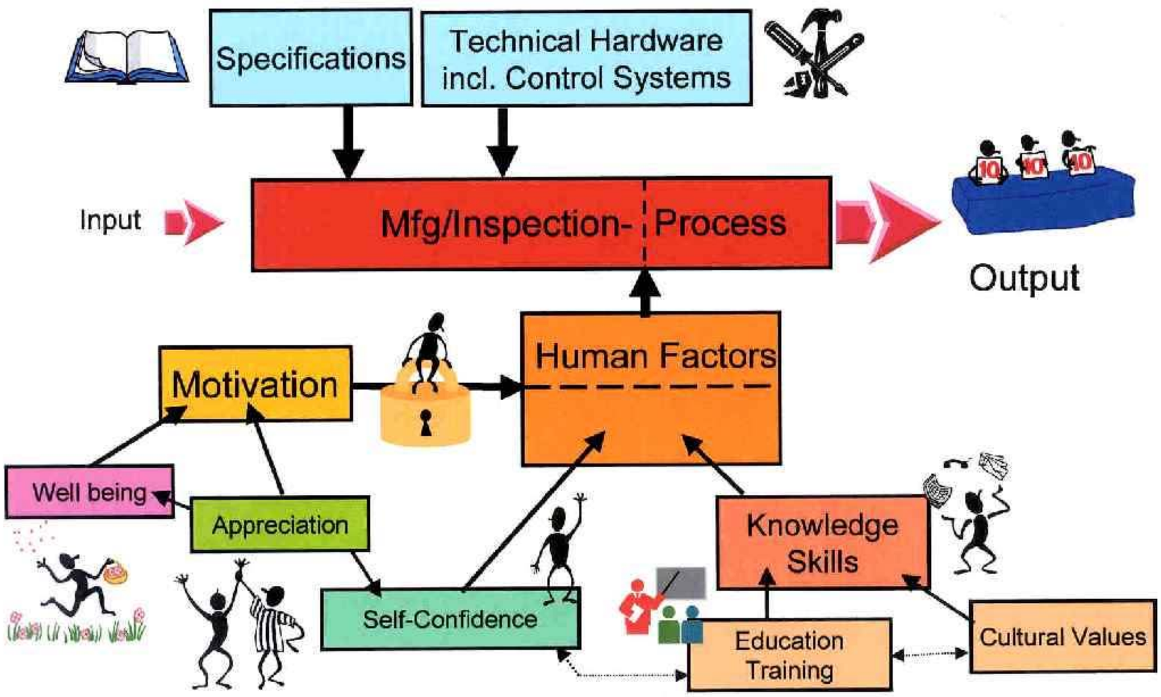

Figure 7.1: How Different Human Characteristics Influence the Manufacturing / Inspection Process

It is apparent from other sections of this report that our ability to minimize Machining 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 7.1, 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. He or she is 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 coolant flow, determine if tools are wearing properly, etc. Even if the machine operator is running multiple machines, he or she is 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.

7.2 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, the higher the human involvement in the process, the greater the potential for variation in 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 7.1.

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 common sense 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.

7.3 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 part of current programs and should be included in the initial training given to people that are new to an area and also as part 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. With regard to the manufacture of Critical Rotating Parts this training should include:

1. **The importance of remaining within the validated parameter limits**
    - Follow the operation sheets exactly
        - Use approved cutting tools
        - Change tools as directed
        - Do not override programmed speeds or feeds
    - Assure proper coolant application
        - Maintain continuous coolant flow along the tool shank
        - Do not allow chip ‘birds nests’ to form

  - A minimum coolant concentration is required (reference process sheets)

- Report any Special Cause Events such as:
  - Chip packing, wrapping and/or welding to the tool
  - No coolant flow to the cutting edge(s)
  - Dull or improperly ground tools
  - Broken or squealing tools
  - Abnormal indications of heat buildup on the tool or part such as smoke or discoloration

2. <u>Change Control process</u>

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

3. <u>Process Monitoring equipment</u>

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.

8 Non-Destructive Evaluation (NDE)

8.1 NDE Method Selection– Key Factors to be Considered

8.1.1 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 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. Additional details on this subject are presented in Section 12.1, Appendix C : Criteria for Selection of NDE Method.

8.1.2 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 12.2, 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.

8.1.3 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.

8.1.4 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 12.3, Appendix E: Guidelines for the Qualification and Validation of NDE Techniques and Systems.

8.1.5 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 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 12.4, Appendix F : General NDE Guidelines.

8.2 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 counter productive. 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.

8.3 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.

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

Relative capabilities of NDE Methods for Low L/D Holes are summarized in Table 8.1. 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 8.1: 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.

8.3.2 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 8.2. 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).

8.3.2.1 Non-Geometric Anomalies

Etch inspection is currently the most effective method for Detecting Non-Geometric Anomalies such as heat affected zones, 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.

8.3.2.2 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 8.2: 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.

8.3.2.3 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 8.2 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 12.5, Appendix G: Recommendations for Inspection of Holes.

9 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, coolant 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 part. Severe chip congestion or reduction in the cutting ability of the tool are the scenarios where sufficient heat or smearing can cause Anomalies. If sufficient heat is generated over a period of time the titanium will react with oxygen and nitrogen from the air to form a hard 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 part 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 or not 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 8. 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 is beneficial in improving 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.

10 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.

The following organizations have participated in the RoMan Project Team:

Organization	**Address**
The Aerospace Industries Association – Propulsion Committee	
The Federal Aviation Administration	Burlington, MA
FIAT Avio	Torino, Italy
General Electric	Cincinnati, OH
Hamilton Sundstrand	San Diego, CA
Honeywell International	Phoenix, AZ
MTU Aero Engines	Munchen, Germany
Pratt & Whitney	East Hartford, CT
Pratt & Whitney Canada	Longueuil, Quebec
Rolls-Royce Corporation	Indianapolis, IN
Rolls-Royce plc	Derby, United Kingdom
SNECMA Moteurs	Evry, France
Volvo Aero Corporation	Trollhattan, Sweden

Preface for Appendices B through G

The following appendices are not formal recommendations, but do provide additional 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.

11 Appendix B: Process Monitoring for Holemaking

11.1 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., AC 33.14-x).
    - Refer to part classification in Section 4.1.
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 withdraw the cutting tool
    - Ability to prevent Machining Induced Anomalies
    - Ability to detect 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 11.2.
3. The following Process Monitoring systems are currently in use for holemaking (January 2002)
    - Power monitors
    - Force monitors (drill only)
    - Vibration monitors
    - Coolant Flow
    - Coolant 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 the amount of surface damage 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 5.2, Material Review.

11.2 Determining Power Monitor Limits – Best Practice

11.2.1 Setting Power Monitoring Limits

Power monitor limits are determined by monitoring the power for a series of work piece features produced by a well-behaved process. For Process Validation, three tools that are randomly acquired from the source that will be supplying tools for the production components are utilized. If regrinding is permitted on these tools a reground tool should be included. These tools are then run to the Tool Change Point plus 12 additional machined features, if possible. The power response is monitored for each machined feature to evaluate consistency between the three tools. Figure 11.1 shows a typical consistent power response for three tools.

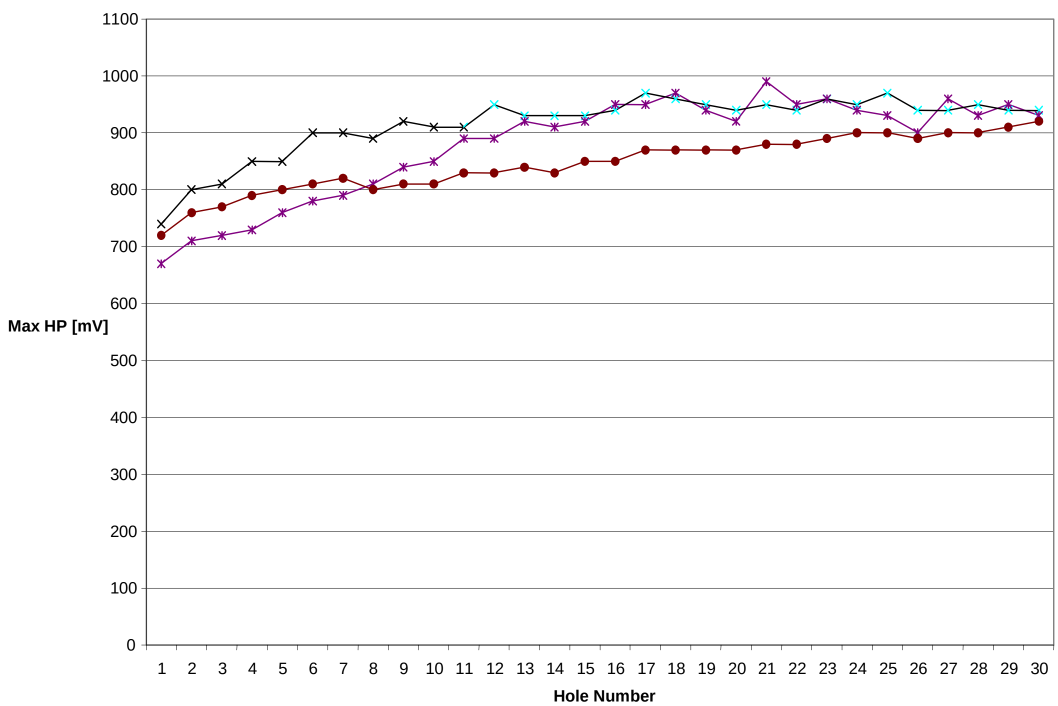

Figure 11.1: Consistent Power Response for Three Tools

Figure 11.2 shows an inconsistency between three tools. The high power tool had poor geometry, which caused more tool rubbing.

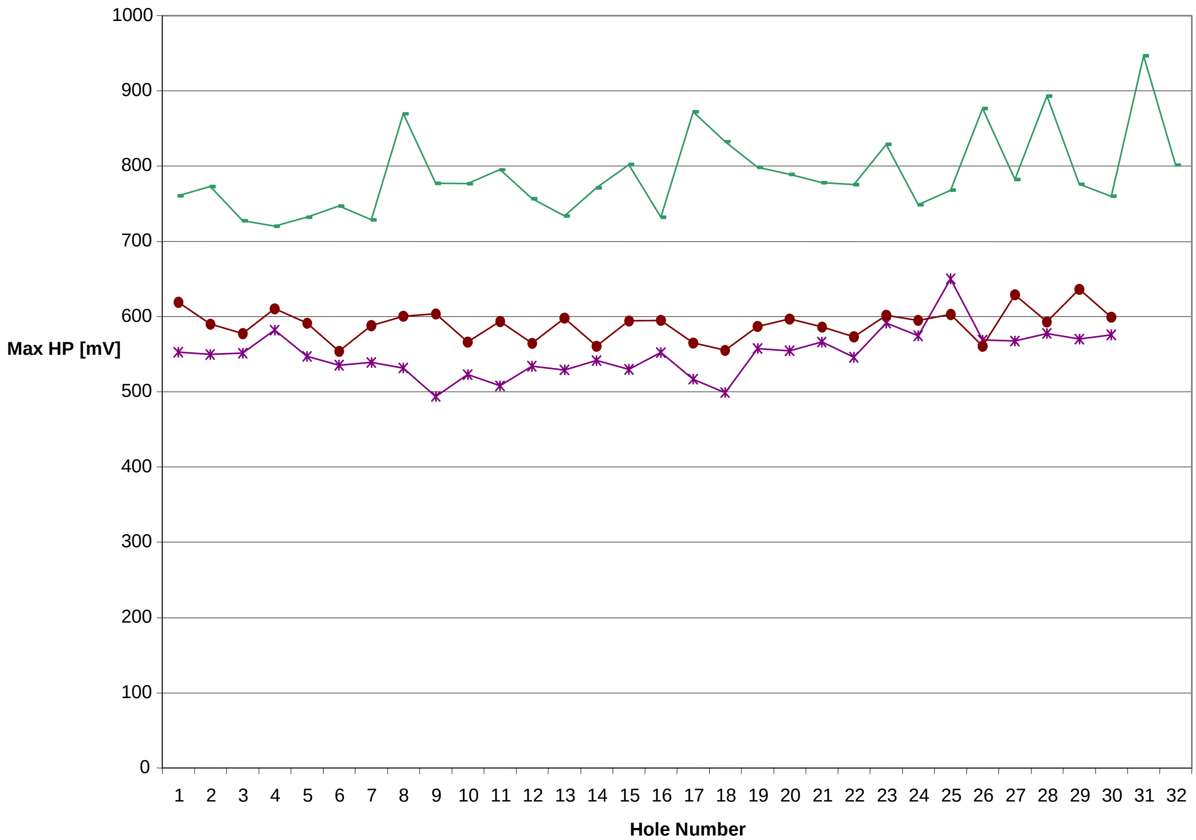

Figure 11.2: Inconsistent Power Response for Three Tools

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 millivolt (mV) reading of the three, within the Tool Change Point, is used to set what is known as the Tool Change Point limit.

Two limits are established based on the Tool Change Point limit. The first limit is a cautionary limit (yellow limit) used to warn of impending problems and should be set 100mV above the Tool Change Point. The second limit is a reactionary limit (red limit) which should cause immediate action to stop the process and should be set 300mV above the Tool Change Point. How these two limits are established is presented in Figure 11.3. These mV levels apply when using power cells made by Load Controls, Inc. or equivalent. The 100mV and 300mV levels may need to be adjusted when using other power monitor devices.

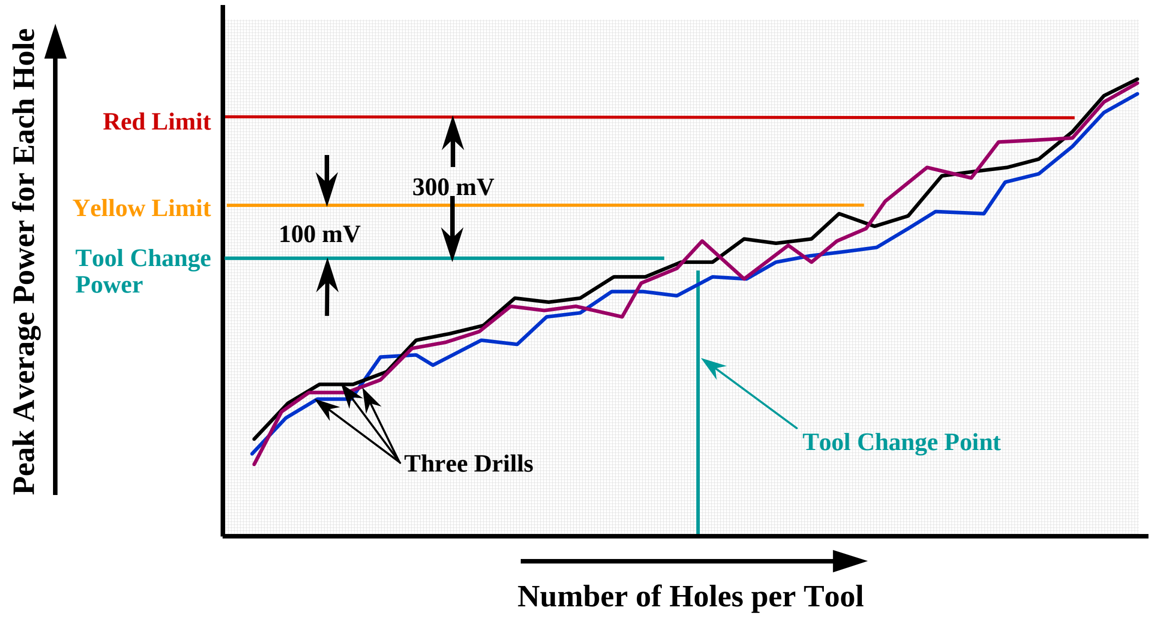

Figure 11.3: Establishing Yellow and Red Limits for Power Monitoring

11.2.2 Transferring Power Monitor Limits Between Different Machines

When using the load cell (power monitor) the part program carries information about the power limits expressed in mV. The values are noted in the part MCP and are all dependent on the machine tool to be used for each specific case. This procedure works well until an operation is moved to another machine tool, or if the same part is qualified for more than one machine tool.

Different machine tools can share power monitor values if the calibration values of the machines are compared. To calibrate different machines, the power cell on each machine is correlated to spindle load utilizing a device to load the spindle (i.e. air brake, electrical brake, etc.) Power cell readings for a known load can be compared between machines and the power monitor values ratioed accordingly. This allows a known, qualified process to be transferred to a different machine without going through the testing of three tools as recommended in section 11.2.1.

11.2.3 Applying Power Monitors to Small Holes Machined with Large HP Machines

The size of the machine spindle and motor vs. the diameter of the hole and amount of metal removal can cause Power Monitoring methods to be ineffective. Experience has shown that when cutting nickel, if the spindle motor is greater than 30 HP (22 KW) and the hole diameter is less than 0.300”(7.6 mm) and the machine has a large gear box, the effectiveness of the power monitor is greatly diminished. This is due to the fact that the power needed to remove the material from small diameter holes is small relative to the power required to drive just the gear box. For titanium and steel parts, these limits will be even more restrictive. Metal removal power signals for holemaking in general range from fractions of a horsepower to 1.5 HP.

11.3 Process Monitoring Questions and Answers

11.3.1 Machine Operator Training

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

  None. The process is fixed per an approved manufacturing 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.

- If so, what happens when the number of allowable holes is greater than the part has?

  A tracking system is required. This can be a paper logging system at the workstation or if the machine control has the capability, then the part programmer through the control can keep track of the number of holes a tool has made.

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

  While an individual company might be able to develop process monitors for this purpose, that is currently not the best practice. The monitor is in place to detect Special Cause Events. Although it will catch a well-worn tool eventually, depending on the monitor to detect when the tool should be changed is not recommended.

- Does the machine operator save the drill for the next time a part is run?

  Yes, if an adequate tool use tracking system exists. Often it is simpler and more robust to insist on fresh tools before starting any part.

- If so, how does the controller know the number of holes left on a drill?

  See tracking answer above. Some machine controllers can count cut time, number of times a tool is placed in spindle, etc. as a means of tracking tools.

- 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 your local procedures for documenting, reporting and dispositioning Special Cause Events and product non-conformances.*

11.3.2 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:

Coolant flow

Coolant 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 part 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 11.2.3)

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 11.4.

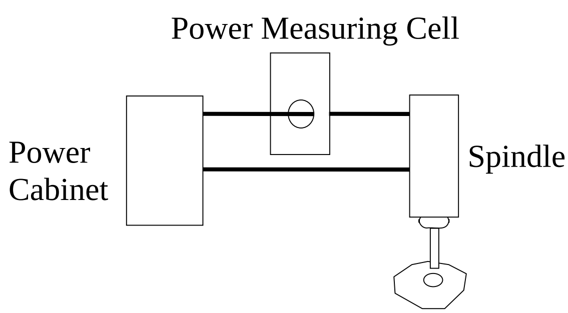

Figure 11.4: The Power Monitor Concept

- What is actually measured in power monitoring? Is power, voltage or current the measured parameter(s) from the sensor(s), or is it a combination?

  Both current and voltage (see previous question and answer)

- What are the minimum requirements for the machine?

  The machine needs to have a 'power' feed either through an electrical servo or a mechanical gear feed from the spindle motor. No hydraulic drives and hand feeds *for rough and finish operations should be allowed. If possible, these features should be built into the machine.*

11.3.3 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: Coolant flow, coolant pressure, power, and rotational speed.

- What is actually done to calibrate the power monitoring system?

  A controllable brake is mounted to the machine tool spindle in order to simulate the cutting process. The power transducer output is read at several speeds and loads and compared to the output from a reference transducer put in series to the power train (between the brake and the spindle). The spindle speed is measured simultaneously by a speed transducer also put in series to the power train. A computer controls the set up.

How is calibration performed for the other monitors?

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

Coolant Flow:

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

Coolant Pressure:

A reference pressure transducer is connected to the coolant feed line.

Rotational speed:

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

- How long does it take to calibrate?

  All positions: Approximately 4 hours.

- 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, Power Monitors catch spindle and gearbox problems, spindle motor problems, and coolant flow problems that may result in 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.

- Where is the calibration data stored?

  Current company practices should be followed. This could include storing records in the respective department that is responsible for the calibration such as inspection standards, instrumentation, metrology or quality control.

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

  Two ways. Indicator lights and digital display of the power cell output level.

- How does the machine operator verify proper operation for audit purposes?

  On a day to day basis, indicator lights and digital display of the power cell output level.

  On an audit basis, periodically an auditor can verify that the power monitor is working per the indicator lights and digital displays and can assure the machine operator is making the daily checks.

11.3.4 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 part 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 process (drilling) for holes with a L/D < 1.0 is very robust and power monitoring is not always applied.

- Is power monitoring effective for single point boring of holes?

  Single point boring (SPB) is classified as holemaking, but power monitoring is not applied. The amount of power used to SPB a hole is so small that it is not feasible to monitor it. This also indicates SPB consumes an amount of power that is not able to create Anomalies.

- Should a drill-bore be monitored on the drill or the bore step or both?

  Both

- How are new drill point geometries reviewed?

  Drill geometry changes require new Power Monitor limits to be set. (i.e. new drill point geometry)

- How are new drill coatings reviewed?

  To date, coatings have shown no impact on Power Monitor limits. Tools with new coatings should be evaluated.

- What are the smallest hole sizes for meaningful power monitoring data?

  Monitoring down to 0.125” diameter drills and reamers is possible.

- 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.

- Are there acceptable temporary methods for power monitoring systems?

  Power monitors with strip charts can be used. However, the ability to automatically stop the process when a Special Cause Event is detected is lost, and exceeding a strip chart limit will almost always result in a scrap part.

- Is there a "factor of safety" used between satisfactory & unsatisfactory limits?

  Power monitor limits are set conservatively. The estimated margin is about 300mV.

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

  The limits are set based on tool wear at the Tool Change Point and the 100/300 mV scheme at the Tool Change Point (see Section 11.2.1).

- How is a new process qualified with monitoring?

  Either by performing a process study (see Section 11.2.1) or from the laboratory database on the machine correlation curves.

- How are monitored holemaking processes audited (interval, etc.)?

  Through internal and external audits performed annually.

  Audits are done per quality procedures including a review of the MCP for compliance to those procedures.

- Are the cutting tools reviewed or is monitoring relied on to flag tool problems?

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

  Tool control is important and should be part of the hole making 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 part of a monitoring plan?

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

11.3.5 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.

- What is actually done on a "flagged" hole (i.e., a hole which exceeded the red limit)?

  Some manufacturers allow holes with red limits to be salvaged by removing .002” to .004” per side with a monitored reaming process. This is possible only when the design can tolerate oversized holes.

  Directed dispositions via the MCP should be used when possible to avoid Material Review activity.

  Holes that can not be oversized are evaluated on Material Review using the peak power monitor value of the red limit hole and its correlation to fatigue data to make the disposition.

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

  To minimize the affect of recutting chips in the hole and other short duration signal spikes, a 1 second delay is utilized before an alarm is generated. That is, the power signal should stay above the alarm limit for a continuous period of 1 second before the alarm is generated. In addition there is a response time for the controller to take the appropriate action. This varies from controller to controller but in general is less than 2 seconds.

- What is the method for flagging a bad hole?

  Mark with a paint (Dykem) or physically tag the hole with a metal tag.

- How many times per second should the power be reviewed/recorded?

  It varies from monitor to monitor depending on the processor speed. The minimum requirement is 10 samples per second. Preferably 50 to 100 samples per second.

  Only the peak power value is recorded.

11.3.6 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. This is why 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

- Do monitors work well in both titanium and nickel?

  Yes

- Are the same monitoring techniques effective for Ti and Ni?

  Yes

- Is there a power limit or an algorithm for the power consumption curve for each hole? (Power changes as a drill enters a hole, is fully engaged & begins to exit a hole.)

  Not really. The typical hole, whether undergoing a rough or finish operation, usually increases as the tool enters the material, plateaus at some level and then decreases as the tool exits the back side of the hole. Minor power spikes may occur at entry or exit, but these are typically less than one second and will not trigger a response from the power monitor. The key is to establish a 'no load' power monitor baseline before entering the hole and base all measurements from this baseline.

- How is a peck drilling cycle monitored?

  The same way. The only difference is the cycle is chopped into small increments. The small increments should be at least 2 seconds in duration. Otherwise the time delay scheme would not work.

12 Appendices for Non-Destructive Evaluation

12.1 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.

12.1.1 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 type Anomaly, etc.

12.1.2 Geometric Considerations

Hardware configuration/shape plays an important part 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 12.1.

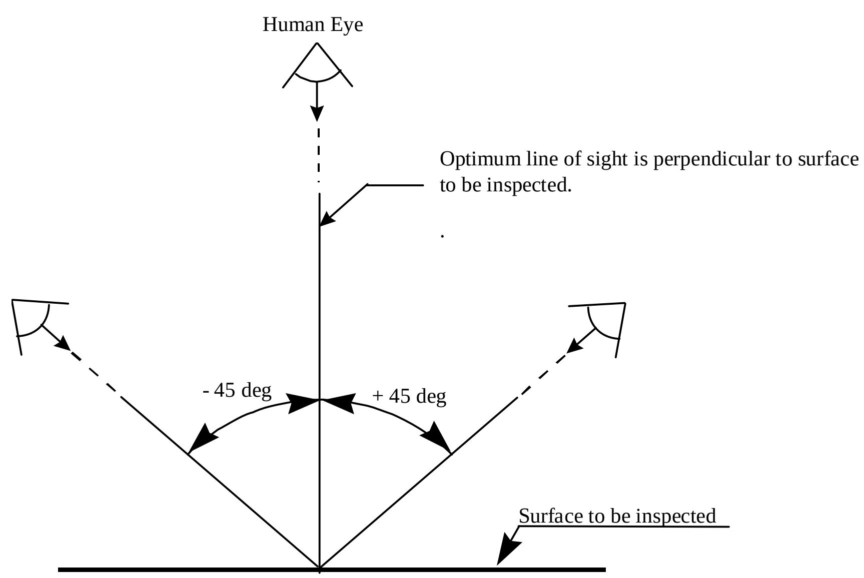

Figure 12.1: Line-of-Sight Range for Acceptable Detection Capability

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 12.2.4, 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.

12.1.3 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 a NDE-specialist to be involved in early steps of the part design.

12.1.4 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 to re-evaluate 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 individual Indications Detected may be recorded manually on paper or cards, or they may be summarized on paper or cards, which only contain the inspection results for the part. The papers or cards may be boxed for storage and future reference. These records are typically not entered into an electronic system for extended storage. The Indication information, if recorded, usually consists of Indication size and general location on the part. Typically, there is no permanent image (photograph or digital image) of the Indication available 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.

12.2 Appendix D: NDE Method Descriptions

12.2.1 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.

12.2.2 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 insure 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.

12.2.3 Inspection Requirements

12.2.3.1 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.

12.2.3.2 Inspection Aids

Among the most commonly 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 hand held 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 7.2.

12.2.4 Method Descriptions

12.2.4.1 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.

12.2.4.1.1 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.

12.2.4.1.2 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 7.2.
- *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 at a later date. However, the increasing availability of digital camera technology can help to alleviate this difficulty.

12.2.4.2 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).

12.2.4.2.1 Advantages:

- *Can Detect surface microstructure Anomalies* – Currently the most commonly 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" any existing surface Anomalies such as cracks by removing any smeared material left by machining.

12.2.4.2.2 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 at a later date. However, the increasing availability of digital camera technology can help to alleviate this difficulty.

12.2.4.3 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.

12.2.4.3.1 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.

12.2.4.3.2 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 fluorescense 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 at a later date.

12.2.4.4 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 by the use of 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.

12.2.4.4.1 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.

12.2.4.4.2 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 at a later date.

12.2.4.5 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 as a result 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.

12.2.4.5.1 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 at a later date for re-evaluation.

12.2.4.5.2 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.

12.2.4.5.3 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.

12.2.4.5.4 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 also 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.

12.2.4.5.5 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.

12.3 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.

12.3.1 Establishing Inspection Requirements

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

12.3.1.1 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.

12.3.1.2 Selection of Potential NDE Methods

- *What NDE Methods allow Detection of Anomalies* - Using both past 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.

12.3.2 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.

12.3.3 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 8.1 and 8.2 for holes).
- *Additional considerations* – Should include data acquisition and storage, Human Factors, cost/productivity considerations and reliability.

12.3.4 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.

12.3.5 Implementation of Production NDE Method

The manufacturing procedures need to 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)*

12.4 Appendix F: General NDE Guidelines

12.4.1 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 12.2). 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.

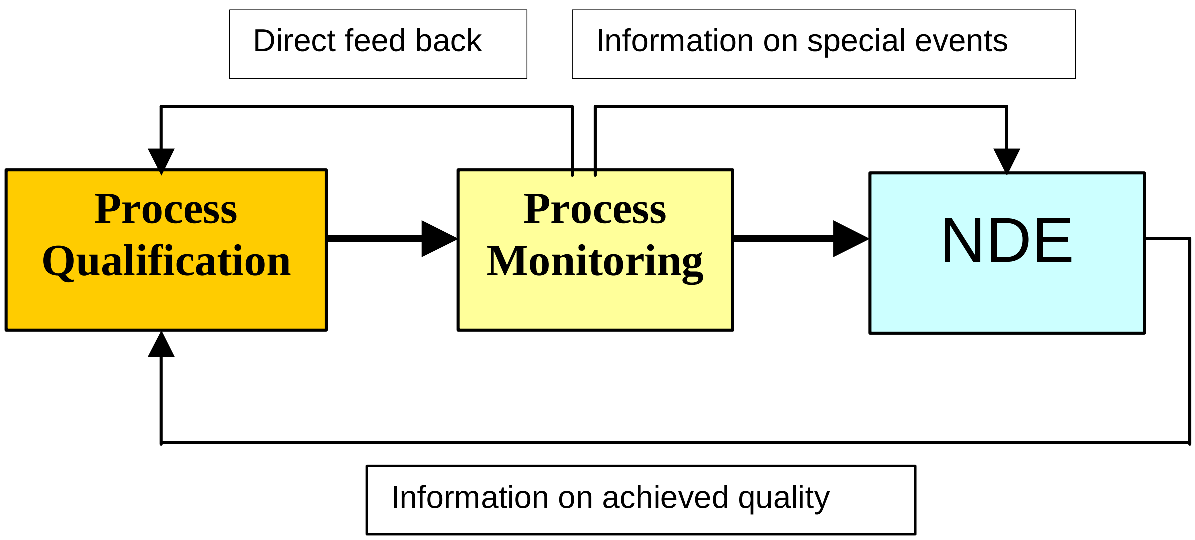

Figure 12.2: Process qualification with the aid of Process Monitoring and NDE

12.4.2 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.

12.4.3 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.

12.4.4 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 assure 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)

12.4.5 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.

12.4.6 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 represent all 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 needs to be measured for each set of inspection parameters, inspectors, equipment, etc., and remeasured 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.

12.5 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 8.1 and 8.2 in Section 8 of this report.

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

12.5.1 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 12.2.4. In some cases, the effectiveness of FPI/MPI and etch can be enhanced through the use of 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 7.2.

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 is capable of Detecting 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.

12.5.2 Method Characteristics

Several factors are included in Tables 8.1 and 8.2, 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 that 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.