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Guidelines for Formulating and Writing Process Control Documents and Process Specifications for Advanced Materials

October 2022

Final report

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Dr. John Tomblin, Royal Lovingfoss, Rachael Andrulonis	

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16. Abstract

This report presents a set of guidelines for information recommended to be included in process control documents and process specifications for non-metallic advanced materials. The guidelines are organized by general information that applies to all polymer-based material systems, followed by specific information listed by material type. It is intended to outline important elements/topics that must be discussed to ensure proper control of advanced materials and parts. This document includes a general process specification outline for building parts from the following material forms: polymer matrix composites based on thermosets from prepreg, polymer matrix composites based on thermosets from resin transfer molding, polymer matrix composites based on thermoplastics from a semi-preg/prepreg, bonding using adhesives (paste and film), ceramic matrix composites prepreg, and polymer-based additively manufactured materials.

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Acronyms

Acronym	Definition
ASTM	American Society for Testing and Materials
CMC	Ceramic matrix composite
CNC	Computer numerical control
CoC	Certificate of compliance
CoA	Certificate of analysis
CTE	Coefficient of thermal expansion
EBC	Environmental barrier coating
FAA	Federal aviation administration
FOD	Foreign object damage
ISO	International Organization for Standardization
MI	Melt infiltration
MPCD	Material process control document
MRB	Material review board
NADCAP	National Aerospace and Defense Contractors Accreditation Program
NDI	Non-destructive inspection
OEM	Original equipment manufacturer
OOA	Out-of-autoclave
PCD	Process control document
PIP	Polymer infiltration/pyrolysis
PMC	Polymer matrix composite
PO	Purchase order
PTFE	Polytetrafluoroethylene
QA	Quality assurance
RTM	Resin transfer molding
UV	Ultraviolet

Executive summary

Material and process control of advanced materials is critical to building high-quality parts and ensuring their safe use in aviation applications. As a critical element of material and process control, process specifications provide definition and oversight of manufacturing. A robust process specification contains documentation that supports the linkage between the various levels of control, including quality, material, safety, and work instructions. These documents work together to create a robust process that is repeatable and consistent for a given part or product. This document contains a set of guidelines to assist in the development of an advanced material process specification(s) for various non-metallic advanced material types.

The guidelines are organized by general information that applies to all polymer-based material systems, followed by specific information listed by material and/or process type. It is intended to outline important elements/topics that must be discussed to ensure proper control of manufacturing processes using advanced materials. This document includes recommended process specification outlines for building parts from the following material forms and processes:: polymer matrix composites based on thermosets from prepreg, polymer matrix composites based on thermosets from resin transfer molding, polymer matrix composites based on thermoplastics from a semi-preg/prepreg, bonding using adhesives (paste and film), ceramic matrix composites prepreg, and polymer-based additively manufactured materials. Information for this report was gathered through site visits, interviews with subject matter experts, documentation review by industry experts, and a steering committee meeting after the FAA JAMS presentation at the SAMPE conference (Charlotte, North Carolina, May 2018)

1 Hierarchy of documents

The documents that will be referenced in a process specification may include the company's quality manual, material specifications, other process specifications associated with the one being used, one or more process control documents (PCD), safety procedures, work instructions, or other documents that help maintain a level of control over the process being used to manufacture a particular part or parts. Each of these documents relates to one another as shown in Figure 1. The arrows between the documents represent the linkages between them. All documents should be traceable to one another. For example, the PCD, either in its own references or through a referenced specification, should trace itself back to the quality manual. All documents have to be in agreement and reference each other. Descriptions of each document are included in Table 1.

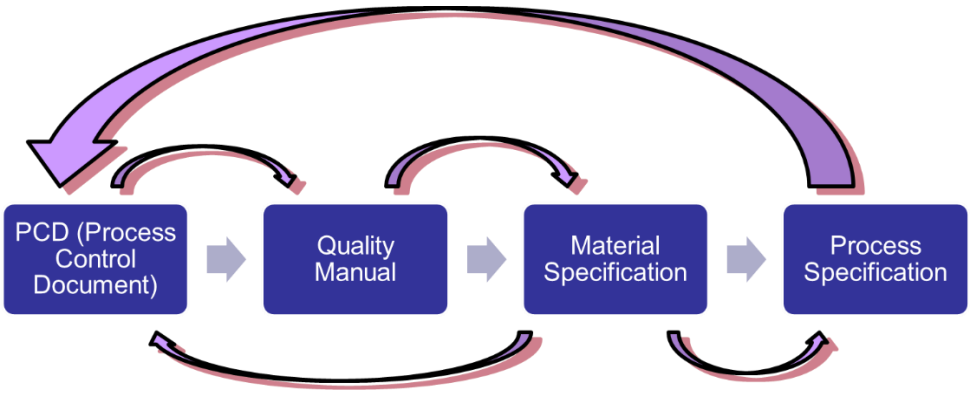

Figure 1. Hierarchy of documents

Table 1. Document definitions

Document	**Definition**
Process Control Document (PCD)	• PCDs can have multiple purposes from defining the overall process to one portion of the specification. In this report, the PCD refers to the high-level overarching document that controls the manufacturing of a particular product or associated products • Includes:

Document	Definition
	○ references to material specifications used (possibly in the form of a material process control document (MPCD), or it may call out the MPCD) ○ the process specifications used ○ the quality system used ○ safety procedures ○ specialized work instructions or procedures • Normally does not give specific instructions but is used as a document that captures all specialized documents used in the manufacturing of a product or associated product
Material Specification	• Details the materials used in producing a product • Lists the manufacture of the material, the material name, special handling/storage instructions, receiving inspection instructions, special limits the material must meet • Special limits can be attributed to shipping instructions, test data, etc., and any other specialized instructions meant for the material.
Process Specification	• Details the instructions on how to use a material or combination of materials to manufacture a product • Defines the material type and specification, the detailed instructions for equipment to be used, equipment lists, tools, environmental controls, proper personnel, in-process monitoring or testing, inspections, quality control points, etc. that are needed to appropriately manufacture the product
Quality Manual	• Overarching document that controls the quality system of a company. The following bullet points give examples of the type of information that must be able to be traced to the quality manual, either

Document	Definition
	directly or through reference documents. may be mentioned in the PCD, Material Specification, or Process Specification • Information on how the quality system works, such as how to deal with non-conforming materials/parts, training of personnel, audits, quality inspections, etc. • May also reference the written documents that control those aspects of the quality system. • Should follow procedures defined by accreditation associations such as the International Organization for Standardization (ISO) or National Aerospace and Defense Contractors Accreditation Program (NADCAP) • May have appendices, addendums, or special sections that govern explicit points or aspects required by a specific company/customer, or a governing agency such as the Federal Aviation Administration (FAA), European Union Aviation Safety Agency, Department of Defense, etc.

All the documents listed in this section are critical components to ensure a traceable and repeatable process flow of a given advanced material system. Figure 2 shows an example of this process flow for a composite material. Note that this flow is consistent across all composite manufacturing methods. Non-composite advanced materials, such as additively manufactured materials, have similar process flows.

Figure 2. Process flow of a composite material

2 Overall guidelines

This section covers the information that should be included in a process specification for any advanced non-metallic material or part. Section 3 contains additional requirements unique to a specific material system and process combination.

2.1 General requirements

2.1.1 Title page

The title page must include company name, physical address, part description, material description, specifications (if applicable), document number, authorized signatures, and the date.

2.1.2 Revision history

Include a list or table that tracks all major changes to the process document that affects the fit, form, or function of the part or material that is produced. An approved quality assurance (QA) system in place may guide the revision documentation. An example of revision tracking is shown in Table 2 below. The revision level and description of updated data or other details should appear on every page (header or footer).

Table 2. Example of revision history

Revision	Date	Description
-	3/7/2017	Initial release
A	10/4/2017	Updated part cure cycle, step two hold now is 1.5 hours +/- 10 minutes instead of 1 hour +/-10 minutes.

2.1.3 Table of contents

The table of contents should include all sections, figures, tables, and appendices.

2.1.4 Introduction

The Introduction should contain the scope of the document/specification and include an overview of what is contained in the document, including a description of the part and material. Any accreditations, such as ISO or NADCAP, can also be mentioned here. An example statement for the Introduction is "*This document is controlled and in use for the manufacturing and processing of _____ by using the materials ____ as called out here within. All processes described adhere to our quality manual and the inspection directions given. In the case of competing instructions, this document always takes precedent*." Fill in the blanks with the name of the part, parts, or family of parts being manufactured to ensure that there is no confusion on what is being produced, especially if there are other similar production processes. Reference the materials used and their limitations. Again, this removes any confusion that caused by other materials that are similar. State or reference the process and material limitations in the introduction. In this section, limitations on parts that are made (e.g., non-structural) can be identified.

2.1.5 Acronyms and definitions for advanced materials

This section lists acronyms and definitions related to advanced materials, but not necessarily used in this document. See Table 3. Definitions of terms not commonly known and used in the document should also be included in this section.

Table 3. Commonly used acronyms

AMS	Aerospace material specification
ANOVA	Analysis of variance
ASME	American Society of Mechanical Engineers
CLC	Combined loading compression
CMH-17	Composite Materials Handbook 17 (formerly MIL-HDBK-17)
CoC	Certificate of compliance

AMS	Aerospace material specification
CoA	Certificate of analysis
CPT	Cured ply thickness
CTD	Cold temperature dry
CoV	Coefficient of variation
DAR	Designated airworthiness representative
DER	Designated engineering representative
DMA	Dynamic mechanical analysis
DoD	Department of Defense
DSC	Differential scanning calorimetry
ETD	Elevated temperature dry
ETW	Elevated temperature wet
FAA	Federal aviation administration
FAW	Fiber areal weight
FTIR	Fourier Transform infrared spectroscopy
FV	Fiber volume fraction
HPLC	High performance liquid chromatography
IAB	Industry Advisory Board
ILT	Inter-laminar tension
IP	Intellectual property
IR	Infrared spectroscopy
ISO	International Organization for Standardization
NASA	National Aeronautics and Space Administration
NCAMP	National Center for Advanced Materials Performance
NIAR	National Institute for Aviation Research
NIST	National Institute of Standards and Technology
QC	Quality control
QI	Quasi-isotropic
QM	Quality manual
QPL	Qualified products list
RH	Relative humidity
RTD	Room temperature dry
SACMA	Suppliers of Advanced Composite Materials Association
SAE	Society of Automotive Engineers
SBS	Short beam strength

AMS	Aerospace material specification
Tg	Glass transition temperature
TGA	Thermogravimetric analyzer

2.1.6 Reference documents

This section contains a list of documents that are used in conjunction with the given document/specification. This may include the quality manual, inspection techniques, testing procedures, raw material / feedstock specifications, processing documents, and drawings. Below is a sample list of reference documents that contain information on various aspects of advanced materials and their possible use in aviation-related projects. These may or may not be part of the reference documents that are used in describing a controlled process.

- DOT/FAA/AR-02/109 – Guidelines and Recommended Criteria for the Development of a Material Specification for Carbon Fiber/Epoxy Unidirectional Prepregs
- DOT/FAA/AR-06/25 – Preliminary Guidelines and Recommendations for the Development of Material and Process Specifications for Carbon Fiber-Reinforced Liquid Resin Molded Materials
- DOT/FAA/AR-02/110 – Guidelines for the Development of Process Specifications, Instructions, and Controls for the Fabrication of Fiber-Reinforced Polymer Composites
- CMH-17 – Volumes 1-6 - Composite Materials Handbook, Volumes 1-6
- NADCAP AC7004 - AC7004 Rev G - Nadcap Audit Criteria for Quality Management System
- NADCAP AC7118 - Nadcap Audit Criteria for Composites
- NADCAP AC7124 - Nadcap Audit Criteria for Non-Metallic Materials Manufacturing

2.2 Standard tolerances

Tolerances on time, temperature, pressure, dimensional aspects, humidity, vacuum, force, or other key performance parameters are important in creating a repeatable and safe product. Tolerances of controlled key parameters may be included in the process specification for various steps or may be controlled in referenced documents such as the material specification, process control document, work instructions, drawings, or quality manual. Setting appropriate tolerances for a manufacturing process using advanced materials may include discussions with the material provider, the manufacturing equipment provider, and the manufacturing operations team.

Standard guidance documents from trusted sources such as ISO, ASTM, or NADCAP list tolerance settings. In some cases, trial runs of the manufacturing process may be required to ensure compatibility with all aspects of the manufacturing process. When choosing tolerance settings, it is important to understand how one tolerance setting may affect another. For example, temperature and humidity are related. As one changes, the other can change as well. This section should include all appropriate information related to tolerance settings.

2.3 Procurement of materials

This section should provide a brief description of the system used for purchasing materials. It needs to cover everything from consumables to raw material / feedstock. The purpose of this section provides an individual the necessary information needed to order materials for a specific process. Detailed ordering information would be provided in a separate document that would be referenced in the process specification. The referenced statement may say, "*For ordering of raw materials / feedstock or consumables in association with this process specification, please see the appropriate material specifications and contact purchasing,*" or something similar.

2.4 Raw materials / feedstock

This section lists approved raw materials / feedstock and suppliers used to make the specified part. Raw materials / feedstock are typically defined as materials or substances used in the primary production or manufacturing of an intermediate product or end product. The materials listed should be associated with their corresponding material specifications. If multiple raw materials / feedstock, other intermediary materials, or parts are used in the part production, a flow chart or other explanation may be added. This should explain the manufacturing process flow, as well as how the different sets of raw materials / feedstock interact. That information will be controlled in a separate process specification that may or may not be called out in a higher-level document. The supplier contact information may be included in this section or referenced in a qualified products list (QPL) or an approved suppliers list. The following items should be addressed in this section.

2.4.1 Raw material / feedstock use

Indicate the appropriate material(s) used to manufacture the product. Identify the material(s) through labeling, a designated location, and an electronic traveler that lists the batch number, lot number, or date of a specific material or another means of communication.

2.4.2 Consumable material use

Consumable materials are not to be confused with raw materials / feedstock. Consumable materials are the materials that aid in the production process, but they do not make up the final part or product and are sometimes referred to as "non-fly away materials". It could be a specific type of bagging material, breather cloth, one-time use roller, special gloves, or one-time use thermocouples. Include detailed instructions on which consumable materials to use for the personnel manufacturing the product. Identification of this material is done in the same way as for raw materials / feedstock above.

2.4.3 Inventory system

Describe how raw materials / feedstock are tracked using a check-in and checkout system so traceability of materials is maintained. Include information on how to treat partially used raw materials / feedstock and how to return raw materials / feedstock into the system.

2.4.4 Non-conforming materials

Detail how non-conforming materials are segregated in case a raw material / feedstock is found to be inappropriate at the time of usage. Include who has access to the segregation area, how long materials can stay in the area, and who can disposition them. Details in this section should be just enough to instruct the personnel on what to do and who to contact. The more detailed Material Review Board (MRB) process is found in the quality manual.

2.4.5 Storage

Detail how materials are stored, including racking, stacking, environmental conditions, shelf life, out-time, work-life, etc. State control limits for temperature, humidity, and time.

2.5 Product manufacturing

This section may include multiple steps that all require detailed descriptions. Include step-by-step instructions throughout the process specification or reference documents that include these instructions.

2.5.1 Recipe of raw materials / feedstock

This section describes how the raw materials / feedstock are put together to produce the final product. It includes the step-by-step procedures to produce the part, comprising predominantly of material placement and consolidation. The description should include the following:

- How are the materials measured? (Units, tolerances, and instructions)

- Special timing – Do you add one ingredient and then wait a certain amount of time before adding another? Does a material need to be milled before being added and if so, is time a factor? Does milling have any time limits? Does a specific machining process need to take place before two materials can be combined? If so, is time a factor? Does machining have any time limits?
- Environmental conditions – Do materials need to be warmed or chilled, or sit at a specific temperature for a certain amount of time? Do different steps need different conditions?
- Equipment to be used – Specify tools, tool surfacing processes, specialized equipment and instructions for its use, calibration checks, start-up processes, software settings, and shutdown processes. Make sure line numbers, mixer numbers, tool numbers, and serial numbers are traced. Use a checklist in electronic or written format.
- Consumable materials to be used – Specify thermocouples, bagging materials, rollers, tackifier, special gloves, breather, or one-time use hoses. List and explain any processing material that is one-time use. Use a checklist in electronic or written format.
- Include detailed description of equipment settings. This includes temperature, pressure, feed rates, line speed, tension settings, spacing of gaps, rotation speeds of spindles, tool locations, time limits, lay-up sequences, thermocouple placement, flow rates of liquids, heat-up rates, and cool-down rates. Include tolerances when appropriate. Specify how to monitor and record settings. Add a description of how each tool type relates to each material type and product type to ensure incorrect combinations are not used. This may relate to certain equipment settings such as temperature, pressure, vacuum, line speed, etc.

2.5.2 Post-processing

In this section, identify special post-processes such as machining, post-curing, sanding, surface prep, painting, sealants, coatings, or bonding processes. Either define details here by identifying materials needed, appropriate tools, machines and settings, software settings, appropriate environmental conditions, and special training, or point to other documents (such as a post-processing specifications or work instructions) that control these steps.

Detail the post-processing installation if another product is going to be installed or attached to the main product. This may include machining, bonding, or other means of attachment. Provide the material list, appropriate equipment, or machines with settings, environmental conditions, and time limits. Post-production inspection is any testing, inspection method, specification criteria, etc. that is done after the part has been removed from the manufacturing process. This

may include non-destructive inspection (NDI) processes, review of in-process manufacturing data, in-process test data, or shipping testing.

2.5.3 Process parameters/in-process testing

This section describes the in-process data, such as the measurements described above. Include key process parameters that are critical to building a good part and therefore have a very tight level of control. Also, include key characteristics and any in-process testing. The in-process testing steps can be inline or referenced. Specify data collection and storage instructions. Specify actions to take if a key process parameter is found to be out of specification, including monitoring or in process testing. Instructions should tie in with the quality manual and MRB process, though those documents might not be listed in this section.

If specialized computer and/or controller software is used, list the software version. The operator must check the version before beginning any production run. This should be part of the start-up instructions.

2.5.4 Employee training and qualification requirements

For this section, state the required training for qualified personnel, including title/number of the training program (i.e., "Operation of this equipment per the instructions in the process spec can only be done by a person trained per training program *XXXX*"). The following qualification requirements for training should be included.

- Issues/Anomalies – How to check for them, what do they look like, and what to do if they are found. This would be geared towards visual inspection and key process parameter monitoring during the production cycle while the product is still being built.
- What should the final part/product "look" like? Include a description of key features, preferably with photographs. This is not a final inspection, just a way of describing to the trained personnel what he/she is building. Also, include a description or list of setpoints that tells personnel if the process is complete. For example, "When the part is checked, if a process control piece does not meet criteria *XXXX*, please begin part at step *X* and repeat through step *Y*." This may be part of a work instruction, a data checklist, or some other document for recording purposes.

2.6 Finished product packaging

This section should contain information on the following items:

- Packaging type – List the box type, bag type, labeling, or canister type.

- Measure type – Is it by length, weight, number of units?
- Labeling – Should contain a description of the product. Labeling can be done by job number, product type, special serialization, purchase order (PO), project code, etc.
- Package Orientation – Is the product packed horizontal, vertical, palletized, supported by one end? Include any special instructions such as, “Don’t stack over 3 units high”.
- Shipping documents – Which documents must be included in the package before shipping? Copy of the PO? Certificate of Compliance (CoC) or Certificate of Analysis (CoA)? Packing list?

2.7 Storage of finished product

2.7.1 Environmental conditions

Specify appropriate environmental conditions with ranges and acceptable limits. This can include temperature, humidity, ultraviolet (UV) exposure, etc.

2.7.2 Storage life

Include out-time, shelf life, workable time limits, and any other parameters related to storage life. Data that back up the claims will not be part of the process specification but should be available upon request. The data may be part of the Certificate of Conformance (CoC) or Certificate of Analysis (CoA) as shipping documents.

2.8 Testing of final product

2.8.1 Shipping tests

Tests or inspection processes (such as NDI) used to ensure that the product is built per the process specification guidelines should be included in this section. These tests are performed after the completion of the manufacturing process. Tests that are performed during the manufacturing process are not part of this test set. This may or may not be a requirement, as some products will require shipping tests and some will not. The process specification should only mention shipping tests if they are required.

2.8.1.1 Shipping test methods

There could be multiple tests required or none. If they are required, then the process specification should list them with the associated procedure number, work instruction, or standard test method. Do not state the details of the method. The details are contained in the referenced document. The

referenced document should have information about the number of replicates, required limits, reporting procedure, retention requirements, and any pertinent information that may be relevant to the article.

2.8.1.2 Shipping test product/part

In some cases, the manufacturing process may also produce a piece or part of the product used for conducting shipping tests. If this is the case then the process specification should instruct what to do with that piece or part. Is it stored in a certain place? Is it taken to the machine shop? Is it taken to the test lab? What documentation must accompany it?

2.9 Shipping of final product

2.9.1 Shipping instructions

This section lists the proper shipping instructions per the PO or agreement.

2.9.2 Inventory system

This section should include information on how to move the final product in the inventory system. It may be very brief.

2.10 Record retention

Include a description of which records, electronic, hand-written, or otherwise to keep and what must accompany those records. Does the process operator sign and date the work instruction used? Is there a special form for recording process parameters and ensuring that they were within specified limits? Where are these records submitted? Are there multiple forms if there are multiple steps in the process?

3 Guidelines for advanced materials by type

3.1 Guidelines for reinforced thermoset polymer matrix composite (PMC) prepreg

The outline for parts made with thermoset PMCs using a prepreg system follow the same format as the general guidelines listed in Section 2 Additional information needed for this material type is listed in the following sections.

3.1.1 Revision control

Manufacturing routings must be revision controlled, and typically include drawing and parts list revision information where applicable.

3.1.2 Approved materials

The details of the material or materials to be used (prepregs, peel-plies, adhesives, etc.) must be specified and appropriate related material specifications called out.

3.1.3 Facilities and equipment

- Specify the requirements of the environmental conditions for the facility including temperature and relative humidity conditions.
- Specify the required capabilities of process equipment including ovens, autoclaves, or presses.

3.1.4 Material thawing and preparation for use

- Specify the procedures for removing materials from frozen storage and thawing before use.
- Specify any other preparation procedures such as preparing a tackifier or adhesive to be included in the build process.
- Specify the procedures for controlling material out time once thawed.
- Specify materials and quantities to be kitted.
- Specify computer numerical control (CNC) programs used.
- Specify inspection points for ply kits.

3.1.5 Tool verification and preparation

- Specify the tool preparation procedures, including cleaning and application of the release agent.
- Specify additional requirements such as tooling vacuum integrity checks and the associated criteria for acceptability.
- Specify any additional requirements such as the need for and the details of tackifiers etc.

3.1.6 Layup operation

- Specify the part instructions including composite materials, adhesives, core materials, peel plies, surface films, and release agents. If a lightning strike ply or protection plan is part of the initial layup operation, be sure to specify the appropriate material type, application point, and procedure to ensure proper installation.
- Specify the details of intermediate vacuum or autoclave debulks. This includes a detailed description of bagging arrangement, debunk times, pressures, frequency, and duration, as well as permissible vacuum level as a function of altitude.
- If automated fiber placement equipment or tape-laying machines are used then describe details of how the machine is set up, loaded with material, and operated. Information such as parameter settings for force, temperature, pressure, speed, and fiber location must be described with appropriate tolerances. Document and link nesting (pre-programmed builds of the desired layup), tool type, part type, and material type for traceability and future recall if needed.
- Describe how to inspect the plies (after cutting) or rolls (before cutting) for foreign object damage (FOD), fuzz balls, resin-rich areas, dry areas, wavy toes, or fiber misalignment. Many processes may describe these as “anomalies”. A list of these anomalies should be included with acceptable limits for each. For example, “a fuzz ball is acceptable if it is less than xx square inches”, or “dry areas are allowed if there are less than *xx* of them in a *yy* area and they are less than *zz* per each one”. These are just examples and may or may not be applicable.
- Specify inspection points for layup.
- Specify the procedures for any trimming before cure.

3.1.7 Curing operations

- Specify the details of the bagging arrangement to use for the cure including the details of all ancillary materials and a schematic of the arrangement.
- Specify the cure cycle in terms of a time, temperature, pressure, and vacuum profile with appropriate tolerances on temperatures, ramp rates, pressure, vacuum, and time. Details about where the vacuum is measured (at pump versus at the port of the part), where the temperature is measured (in air versus on part, where on the part, at what time interval), and how many measurement locations. State which thermocouple controls the cure, leading, lagging, or some other. Specify if there is a limit on the amount of time the material can be subjected to a certain temperature level. This documentation ensures that material degradation that could compromise the effectiveness of the part does not occur because of over curing or post-curing.
- Specify required vacuum levels as a function of altitude. For out-of-autoclave (OOA) processing, the general guideline should be within 2”Hg of absolute.
- For parts with a multi-step cure, such as some sandwich parts, specify any intermediate steps required. This may include peel-ply removal or sanding before secondary bonding or curing.
- Provide demolding instructions. This may include the removal of peel-ply or sanding to remove a release agent.
- Provide instructions on whether trimming and drilling are permitted at this point with machining parameters and coolant selection, or whether a post-cure is required before machining.
- Specify any restrictions on additional operations for partially cured structures (e.g. solvent exposure risks if the part is not yet fully cured).
- If a separate post cure is required, specify the time-temperature profile including appropriate tolerances on temperatures, ramp rates, and time. Also, include guidelines for part support during the post-curing operation. Give details on maximum allowable time at temperature or maximum allowable number of post-cures for a specified temperature and time scenario.

3.1.8 Quality assurance operations for cured parts

- Verify that the cure time, temperature, ramp rates, etc. all meet requirements.

- Visually inspect for molded defects, such as dry spots, resin-rich zones, voids, porosity, ply wrinkles, and FOD. Specifications must have adequate size and depth limitations for each type of defect, including allowable rework criteria and methods.
- Specify if ultrasonic NDI inspection is required (sometimes after trimming operation).
- Inspect any co-produced traveler coupons if required for additional process control testing.

3.1.9 Secondary trim operations

Specify machining parameters, including any coolant requirements. This section may also include special machining processes used in preparing an article for secondary bonding.

3.1.10 Secondary bonding operations

- Include instructions on how to apply a lightning strike protection scheme, if it is not part of the initial process phase. This may require an additional ply of specialized material, bonding, or the application of a special coating. If it is a bonding or coating process then this section may refer to the appropriate bonding or coating section of the process specification.
- Provide instructions on bonding processes not covered in the initial process phase. Be sure to include surface preparation instructions, cleaning instructions, proper materials with associated material specifications, cure processes, monitoring processes, and record retention. It may be best to reference a separate bonding specification to adequately describe the needed process or reference a different section of the process specification, similar to the section below.

3.1.11 Secondary finish and paint operations

Specify details of all secondary operations including sanding, filling, and painting.

3.1.12 Storage and handling of finished product

- Specify environmental conditions for the storage and handling of the finished product. Include temperature, humidity, UV exposure, etc., along with appropriate ranges or limits for each.
- Specify storage life parameters. This can include out-time, shelf life, or workable time limits. Data that back up the claims will not be part of the process specification but should be available upon request. The data may be part of the CoC or CoA as shipping documents.

3.1.13 Shipping of final product

- Include proper shipping instructions per the PO or agreement.
- Specify the inventory system. How is the final product moved in the system? This can be very brief.

3.1.14 Record retention

Describe records; electronic, hand-written, or otherwise, which must be kept and what must accompany those records. Does the process operator sign and date the work instruction used? Is there a special form for recording process parameters and ensuring that they were within specified limits? Where are these records submitted? Are there multiple forms that are submitted because of the multiple steps in the process? Etc.

3.1.15 General process requirements for reference specifications

Ply Kitting/Layup Operation - Address NADCAP requirements for ply kitting and layup, via NADCAP AC7118 section 16c.

3.2 Guidelines for reinforced thermoplastic polymer matrix composites (PMC) prepreg/semi-preg

The outline for parts made with thermoplastic PMCs using a prepreg/semi-preg system follows the same format as the general guidelines listed above, but with additional information needed for this material type.

3.2.1 Revision control

Manufacturing routings must be revision controlled, and typically includes drawing and parts list revision information where applicable.

3.2.2 Approved materials

The details of the material or materials to be used (prepregs, peel-plies, adhesives, etc.) must be specified and appropriate related material specifications called out.

3.2.3 Facilities and equipment

- Specify the environmental condition requirements for the facility including temperature and relative humidity conditions.
- Specify the required capabilities of process equipment including ovens, autoclaves, or presses.

3.2.4 Material thawing and preparation for use

- Specify the procedures for removing materials from frozen storage (if applicable, most thermoplastics do not require cold storage) and thawing before use.
- Specify any other preparation procedures or special processes needed for some raw materials / feedstock.
- Specify the procedures for controlling material out time once thawed.
- Specify materials and quantities to be kitted.
- Specify CNC programs to be used.
- Specify inspection points for ply kits.

3.2.5 Tool verification and preparation

- Specify the tool preparation procedures, including cleaning and the application of the release agent.

- Specify the tool size (length, width, and thickness), material type, and any pre-heating that may be required.
- Specify additional requirements such as tooling vacuum integrity checks and the associated criteria for acceptability.
- Specify any additional requirements such as the need for and the details of tackifiers etc.

3.2.6 Layup operation

- Specify the instructions to be used for the part construction including composite materials, adhesives, core materials, etc.
- Specify the details of intermediate vacuum or autoclave debulks if applicable, including a detailed description of bagging arrangement, debulk times, pressures, frequency, and duration as well as permissible vacuum level as a function of altitude.
- If automated fiber placement equipment or tape-laying machines are used then describe how the machine is set up, loaded with material, and operated. Information such as parameter settings for force, temperature, pressure, speed, fiber location, etc., must be described with appropriate tolerances. Document and link nesting (preprogrammed builds of the wanted layup), tool type, part type, and material type for traceability and future recall if needed.
- Specify inspection points for layup.
- Specify the procedures for any trimming before cure.

3.2.7 Consolidation operations

- Specify the details of the molding (consolidation) process to be used, including details of all ancillary materials, equipment, software, and a schematic of the arrangement. Be sure that the parameter details are specific to the consolidation process chosen, for example, autoclave vs. press forming.
- Specify the consolidation cycle in terms of a time-temperature, pressure, and vacuum profile with appropriate tolerances on temperatures, ramp rates, cool down rates (this step is of particular importance to thermoplastics), and time.
- Specify required vacuum levels as a function of altitude.
- For parts with a multi-step consolidation, such as a press-molded process that uses an infrared oven for pre-consolidation of the part, describe the pre-consolidation steps in detail. Include a flow chart showing the steps and how they are integrated may be useful.

- Be sure to include tool material and geometry. Discuss how the tool is heated (oil or electric), and how heat is kept uniform. Describe platen parallelism, press accuracy requirements, and temperature requirements/zones. If a shuttle or robot system is used, time allotment for material between steps is important. Is draping a concern? What cooling requirements must be met? This could be during and after consolidation.
- Provide demolding instructions.
- Provide instructions on whether trimming and drilling are permitted at this point with machining parameters, coolant selection, etc., or whether a post-cure is required before machining.
- Specify any restrictions on additional operations for partially cured parts (e.g. solvent exposure risks if the part is not yet fully cured).
- If a separate post cure is required, specify the time-temperature profile including appropriate tolerances on temperatures, ramp rates, and time, as well as guidelines for part support during the post-curing operation.

3.2.8 Quality assurance operations

- Verify that the part temperature, oven temperature, vacuum and part vacuum readings throughout the cycle meet all the requirements.
- Visually inspect for warpage, dry spots, butt joint or overlap, broken yarn/fiber, damaged edge, brown stain, white mark, and delamination. Specifications must have adequate size and depth limitations for each type of defect, including allowable rework criteria and methods.
- Specify ultrasonic NDI inspection if required (sometimes after trimming operation).
- Inspect any co-processed traveler coupons if required for additional process control testing.

3.2.9 Secondary trim operations

Specify machining parameters including any coolant requirements.

3.2.10 Secondary finish and paint operations

- Specify details of all secondary operations including sanding, filling, and painting.
- Specify any bonding processes that may need to take place.
- Specify any instructions for lightning protection schemes. This may include referencing multiple work instructions and other documents as needed, with information on materials,

surface preparation, cures, and bonding. This may be discussed in section 6, layup operations if the lightning protection is part of the ply layup.

3.2.11 Storage and handling of finished product

- Specify appropriate environmental conditions for storage and handling of the finished product. This may include temperature, humidity, and UV exposure, etc., with ranges or limits for each.
- Specify storage life parameters. This can include out-time, shelf life, or workable time limits. Data that back up the claims will not be part of the process specification but should be available upon request. The data may be part of the CoC or CoA as shipping documents.

3.2.12 Shipping of final product

- Specify shipping instructions per the PO or agreement.
- Specify the inventory system used. How is the final product moved in the system? This can be very brief.

3.2.13 Record retention

Describe records; electronic, hand-written, or otherwise, which must be kept and what must accompany those records. Does the process operator sign and date the work instruction used? Is there a special form for recording process parameters and ensuring that they were within specified limits? Where are these records submitted? Are there multiple forms that are submitted because of the multiple steps in the process?

3.3 Guidelines for reinforced resin transfer molded (RTM) composites

The outline for parts made with reinforced RTM composites follows the same format as the general guidelines listed in Section 2. This section contains additional information needed for this material type.

3.3.1 Revision control

Manufacturing routings must be revision controlled, and typically include drawing and parts list revision information where applicable.

3.3.2 Approved materials

The details of the material or materials to be used (fiber forms, peel-plies, resins, binders, veils, etc.) must be specified and appropriate related material specifications referenced.

3.3.3 Ply kitting operation

- Specify materials and quantities to be kitted. This may include kits of dry fiber, kits of resin to be used, or a combination, depending on the application.
- Specify CNC/cutting programs to be used if material cutting is part of the kitting process. Also, include machining instructions or work instructions as needed.
- Specify inspection points for ply kit.

3.3.4 Layup operation

- Specify layup tool number. The tool number should correlate to a specific tool material and size. Note that layup tool may not be the same as the RTM cure tool
- Specify tackifier product to use and process for application.
- Include ply layup table indicating ply numbers, material type, ply orientation.
- Specify vacuum debulk points in the layup, debulk duration, vacuum level, and temperature.
- Provide a system for tracking and verifying any poly film/backer removal if required.
- Specify inspection points for layup.

3.3.5 RTM operation

- Specify RTM tool number.

- Specify mold release agent to use and provide instructions for application and required application frequency. Include system to verify that work has been completed due to the non-visible nature of release agents.
- Specify mold preheat temperature.
- Specify preform loading instructions.
- Specify allowable vacuum leak rate and required vacuum level.
- Specify allowable mold gap.
- Specify resin system to be injected.
- Specify resin injection flow rate, pressure, and other process variables.
- Specify cure time and temperature.
- Provide demolding instructions.

3.3.6 Quality assurance operation for RTM molded details

- Verify cure time, temperatures, and ramp rates meet requirements.
- Verify pot-life expiration within infusion time (unless using a continuous meter mix machine).
- Verify meter-mix machine ratio, pressures, and flow rates meet requirements (unless using pressure pot infusion).
- Visually inspect for molded defects, such as dry spots, resin-rich zones, voids, porosity, ply wrinkles, and FOD. Specifications must have adequate size and depth limitations for each type of defect, including allowable rework criteria and methods.
- Specify if ultrasonic NDI inspection is required (sometimes after trimming operation).
- Inspect any co-molded traveler coupons if required for additional process control testing.

3.3.7 Secondary trim operations

Specify machining parameters, including any requirements. This can include machines, materials, settings, speeds, coolants, and bit/blade types.

3.3.8 Secondary finish and paint operations

- Include the same type of information as for prepreg composite finish and paint.

- Lightning protection may be included as part of the RTM process or as part of the layup process. It may also be a stand-alone section if it is a post-process situation. Discuss materials, cures, bonding, surface preparation, etc.

3.3.9 Storage and handling of finished product

- Specify environmental conditions for storage of finished product. This can include temperature, humidity, UV exposure, etc., with ranges or limits for each.
- Specify storage life parameters. This can include out-time, shelf life, or workable time limits. Data that back up the claims will not be part of the process specification but should be available upon request. The data may be part of the CoC or CoA as shipping documents.

3.3.10 Shipping of final product

- Provide proper shipping instructions per the PO or agreement.
- Specify the inventory system used. How is the final product moved in the system? This can be very brief.

3.3.11 Record retention

Describe records; electronic, hand-written, or otherwise, which must be kept and what must accompany those records. Does the process operator sign and date the work instruction used? Is there a special form for recording process parameters and ensuring that they were within specified limits? Where are these records submitted? Are there multiple forms that are submitted because of the multiple steps in the process?

3.3.12 Reference documents

- Ply Kitting/Layup Operation
    - Address NADCAP requirements for ply kitting and layup, AC7118 section 16c.
- RTM Operation
    - Address NADCAP requirements for mold preparation, AC7118 section 13.
    - Address NADCAP requirements for cure preparation, AC7118 section 17
    - Address NADCAP requirements for resin preparation and mixing, AC7118 section 18a
    - Address NADCAP requirements for Liquid Resin Infusion, AC7118 section 19a.
    - Address NADCAP requirements for Cure, Heated Press, AC7118 section 21f.

3.4 Guidelines for adhesives: bonding process for both paste and film

The outline for parts made with adhesives, both paste and film, follows the same format as the general guidelines listed above, but with additional information needed for this material type. Please note that particular sections may not be applicable, or may hold more importance, depending on the parent material and adhesive system chosen. The manufacturing process specification should be written accordingly.

3.4.1 Revision control

Manufacturing routings must be revision controlled, as well as typically including drawing and parts list revision information where applicable.

3.4.2 Approved materials

The details of the material or materials to be used (laminate, metal, adhesive type, shims, carriers, peels plies, primers, etc.) must be specified and appropriate related material specifications referenced.

3.4.3 Facilities and equipment

- Specify the environmental conditions for the facility, including temperature and relative humidity conditions, light emission requirements, positive pressure, etc.
- Specify the required capabilities of process equipment including ovens, autoclaves, or presses.
- Be sure the area is free of any contaminating substances such as solvents (that are not part of the bonding process), foreign objects, silicon-based products/tools, dust, etc.

3.4.4 Material thawing and preparation for use

- Specify the procedures for removing materials from frozen storage, if applicable. Most paste adhesives do not require cold storage. Most film adhesives do require cold storage. Also, specify thawing procedures before use.
- Specify any other preparation procedures or special processes needed for uncured adhesives.
- For two-part paste adhesives, include a detailed description of mixing operations. The description will need to cover measuring of components, mixing times, mix speeds, set times, out-times, glass beads, shims, scrim cloth use, and the materials that can be used to mix components. Any special mixing tools such as mix-guns need to be listed as well.

- Specify the procedures for controlling material out time once thawed or mixed.
- Specify materials and quantities to be kitted (film adhesive) or mixed (paste adhesive).
- Specify CNC programs to be used for cutting film adhesives.
- Specify inspection points for ply kits for film adhesives.

3.4.5 Substrate preparation

- The substrate can consist of any material that will be bonded using a form of adhesive. The type of substrate must be specified, for example; metal type, plastic-type, composite type, or a different adhesive type. The thickness and limits of the substrate material must also be stated. The appropriate area of the substrate that is to be used for the bonding operation must be detailed. A drawing or written description could be used.
- Include detail for the surface preparation of the substrate. This may include sanding operations, priming, coatings, plasma treating, acid etching, washing, solvent etching, etc.
- Specify if sanding operations are performed by hand sanding or mechanical tool. If mechanical, list the tool-type. Specify the grit size and type, and how to know the substrate is sanded appropriately. Is there is a color change Are thickness measurements used? Is surface energy data used? Does the surface lose a luster or gloss, or does it gain a certain appearance? Is time a factor and does it need to be constrained? These are topics to think about and control if applicable.
- Acid etching operations must specify acid type, exposure times, number of exposures, rinse cycles, drying times, and drying procedure. It may be beneficial to follow a known standard practice such as American Society for Testing and Materials (ASTM) or other.
- Solvent etching operations must specify solvent type, exposure times, number of exposures, rinse cycles, drying times, and drying procedure. It may be beneficial to follow a known standard practice such as ASTM or other.
- Priming or coating operations must specify primer/coating type, how it is applied (spray on, brush-on, dipping, etc.), thickness with tolerances, number of applications, curing times with tolerances, cure temperatures with tolerances, and any other pertinent information such as allowed anomalies like drips, runs, or scratches.
- Washing or rinsing operations must specify the fluid used, such as a solvent, water, degreaser, or a combination. It must detail the number of washes/rinses, the cloth type used if used, the dry time, and how to determine if the wash or rinse was successful.

- Plasma treating operations must specify the head height, head speed, substrate surface temperature, and carrier-gas type. Appropriate tolerances must also be included. A process test such as contact angle or some other way of measuring appropriate surface energy needs to be conducted to show the surface is appropriately prepared. For example, the contact angle will decrease after plasma treating, so a “not to exceed” limit on contact angle must be set.
- Once the surface is prepared, instruction must be given on how to protect it if applicable. UV exposure, temperature exposure, humidity exposure, time constraints, etc. may need to be considered.

3.4.6 Bonding operation

- Specify tool/mold type and/or tool/mold number when applicable.
- Specify mold release agent to be used if applicable, and provide instructions for application and required frequency required. Include the system that verifies work has been completed due to the non-visible nature of release agents.
- For a film adhesive, give details on how many plies are to be used in the bond area, if there is a specific orientation or stacking sequence, and how the plies are to be stuck to the substrates. This may include the use of special tools such as rollers, heat guns, shims to help control bond lines, and torque clamps. Document any special materials or tools used to protect the un-bonded area from squeeze out.
- For a paste adhesive, list bond line thickness with tolerances. Also, include information on how the adhesive is applied to the substrate. Is it brushed, squeegeed, poured, troweled, or through some other special tool? Are shims used? If so, then detail shim material type and thickness. Document any special materials or tools used to protect the un-bonded area from squeeze out.
- Include instructions on how the bonded area is held together before cure. There can be many methods; a few examples are listed below.
    - Bagging scheme – list materials used such as bag material, breather material, breather string material, tape type, thermocouple type, etc. Show in a drawing or detail in words the bagging design/technique.
    - Mechanical clamping – List tool/mold material and the tool/mold type or number. It may also be called a jig. List the clamping mechanism, c-clamps, torqued bolts, spring clamps, etc. If a load or force is specified, it must include limits or tolerances.

- Fasteners – Fasteners may be used in the bond area along with the adhesive. If this is the case, the fastener installation process specification should be listed.

- Specify allowable gap with tolerances. A gap may be present to allow for adhesives that expand upon heating.
- Specify cure time and temperature. Ramp rates, hold times, thermocouple control (lagging vs. leading), and cool down rates must be discussed along with appropriate limits or ranges. A figure showing the cure cycle may be useful in relaying the information.
- Provide demolding/debagging instructions.

3.4.7 Quality assurance operations for cured adhesives

- Verify cure time, temperatures, pressures, vacuum readings, and ramp-rates meet requirements.
- Measure bond-line thickness and check that it meets requirements to ensure that squeeze out was not an issue. This can be done through microscopic analysis, mechanical measurements, or some other approved and repeatable method.
- Perform NDI inspection if required (sometimes after trimming operation). NDI inspection can be difficult to accomplish on bonded parts. “Kissing” bonds can be difficult to detect. The NDI inspection method must be able to show that the bond is fully integrated into the parts across the bond line and be able to detect any voids, foreign objects, or other anomalies.
- If a process panel for mechanical testing verification is used, be sure to state the test method, test condition, specification requirements, and limits. This data must be included in the quality assurance packet (CoC or CoA) associated with the part.

3.4.8 Secondary trim operations

Specify machining parameters. Include any requirements for machines, materials, settings, speeds, coolants, or bit/blade types.

3.4.9 Secondary finish and paint operations

- Include painting and coating information in the specification associated with the substrate material.
- Include lightning protection information in the specification associated with the substrate material.

3.4.10 Storage and handling of finished product

- Specify environmental conditions for the storage and handling of the finished product. Include temperature, humidity, UV exposure, etc., with ranges or limits for each.
- Specify storage life parameters. This can include out-time, shelf life, or workable time limits. Data that back up the claims will not be part of the process specification but should be available upon request. The data may be part of the CoC or CoA as shipping documents.

3.4.11 Shipping of final product

- Provide proper shipping instructions per the PO or agreement.
- Specify the inventory system used. How is the final product moved in the system? This can be very brief.

3.4.12 Record retention

Describe records; electronic, hand-written, or otherwise, which must be kept and what must accompany those records. Does the process operator sign and date the work instruction used? Is there a special form for recording process parameters and ensuring that they were within specified limits? Where are these records submitted? Are there multiple forms that are submitted because of the multiple steps in the process?

3.5 Guidelines for reinforced ceramic matrix composite (CMC)

The outline for parts made with CMCs follows the same format as the general guidelines listed in Section 2. This section contains additional information needed for this material type.
Two categories of CMC systems will be described here: SiC/SiC (non-oxide) and Oxide/Oxide. SiC/SiC composites are commonly made via a chemical vapor infiltration process, polymer infiltration/pyrolysis (PIP) process, melt infiltration (MRB) process, or hybrid process. Oxide/Oxide CMCs are commonly made via slurry infiltration, sol-gel processing, vacuum/pressure infiltration, reaction bonding, electrophoretic deposition, and freeze forming. Each process includes unique steps and parameters that need to be controlled.

3.5.1 Revision control

Revision Control: Manufacturing routings must be revision controlled, and typically including drawing and parts list revision information where applicable.

3.5.2 Approved feedstock (raw material)

The details of the material or materials to be used (prepregs, fibers, interphase/fiber coatings, resins, gases, slurries, etc.) must be specified and appropriate related material specifications called out.

3.5.3 Facilities and equipment

- Specify the requirements for the environmental conditions for the facility including temperature and relative humidity conditions.
- Specify the required capabilities of process equipment including sintering ovens, autoclaves, or hot isostatic pressing equipment.

3.5.4 Material thawing and preparation for use

- Specify the procedures for removing materials from cold storage (if applicable, depending on material and process used) and thawing before use.
- Track out-time of material (if applicable) and shelf life per approved quality documentation.
- Specify any other preparation procedures such as restrictions on applied or direct heat.
- Specify the procedures for controlling material out-time once thawed (if applicable).
- Specify materials and quantities to be kitted.
- Specify CNC programs to be used.

- Specify inspection points for ply kits or fiber preforms.

3.5.5 Tool verification and preparation

- Specify the tool preparation procedures including cleaning and application of the release agent.
- Specify additional requirements such as tooling vacuum integrity checks and the associated criteria for acceptability.
- Specify any additional requirements such as the need for and the details of tackifiers etc.

3.5.6 Layup operation

- Specify the instructions to be used for the part construction including composite materials, breather, polytetrafluoroethylene (PTFE), sealant tape, etc.
- Specify the details of intermediate vacuum or autoclave debulks including a detailed description of bagging arrangement, debulk times, pressures, frequency and duration, as well as permissible vacuum level as a function of altitude.
- Specify inspection points for layup.
- Specify the procedures for any trimming before cure.

3.5.7 Curing and sintering operations

- Specify the details of the bagging arrangement to be used for the cure, including the details of all consumable materials and a schematic of the arrangement
- Specify the cure cycles in terms of a time-temperature, pressure, and vacuum profile with appropriate tolerances on temperatures, ramp rates, and time.
- Specify required vacuum levels as a function of altitude. For out of autoclave processing, the general guideline should be within 2″ Hg of absolute.
- For parts with a multistep cure, such as some that have multiple pyrolysis and PIP steps, specify any intermediate steps required such as coating removal or additional ceramic matrix infusion that is needed to ensure a well-produced part.
- Provide demolding instructions.

- Provide instructions on whether trimming and drilling are permitted at this point with machining parameters, coolant selection, etc., or whether sintering is required before machining.
- Specify any restrictions on additional operations for unsintered structures (e.g., solvent exposure risks if the part is not yet sintered).
- Specify the sinter cycle in terms of a time-temperature, pressure, and vacuum profile with appropriate tolerances on temperatures, ramp rates, and time.
- Post-processing for the addition of more ceramic material will depend on material type and material manufacturing process. Include information on this if applicable.

3.5.8 Quality assurance operations for cured and sintered parts

- Verify that the cure and sintering times, temperature, ramp rates, etc. all meet requirements.
- Visually inspect for defects, such as dry spots, warpage, resin-rich zones, voids, porosity, ply wrinkles, and FOD. Specifications must have adequate size and depth limitations for each type of defect, including allowable rework criteria and methods.
- Perform NDI if required (sometimes after trimming operation).
- Inspect any traveler coupons if required for additional process control testing.

3.5.9 Secondary trim operations:

- Specify machining parameters, including any coolant requirements.
- Specify any heat cleaning requirements.
- Detail any information regarding shimming (materials, cures, thickness ranges, etc.)

3.5.10 Secondary operations

- Specify details of all secondary operations including sanding, filling, and application of external coatings.
- Specify details on lightning protection of part if applicable (materials, cures, orientation, machining, etc.).
- Specify details on environmental barrier coatings (EBCs) if applicable (materials, processing, finishing, etc.). This is normally used with SiC/SiC materials, not with Ox/Ox materials. These coatings may also function as a coefficient of thermal expansion (CTE) fillers so that

CTE is not an issue. If a separate CTE coating is used, details of the material type and application are required.

- If thermal protection coatings are used, details on their application, material type, and processing need to be included.
- If aerodynamic fillers are used, details on their application, material type, and processing need to be included. This could be in conjunction with the EBC and thermal coatings, or a standalone process.
- Seal coats, which can be used in conjunction with EBCs or as a standalone process, will need to be detailed to include an application process and material type. This may be considered an aerodynamic filler, but may not function in that manner and be used as an alternative to EBCs.

3.5.11 Storage and handling of finished product

- Specify environmental conditions for storage and handling of the finished product. Include temperature, humidity, UV exposure, etc., with ranges or limits for each.
- Specify storage life parameters. Include out-time, shelf life, workable time limits, etc. Data that back up the claims will not be part of the process spec but should be available upon request. The data may be part of the CoC or CoA as shipping documents.

3.5.12 Shipping of final product

- Provide proper shipping instructions per the PO or agreement.
- Specify the inventory system used. How is the final product moved in the system? This can be very brief.

3.5.13 Record retention

Describe records; electronic, hand-written, or otherwise, which must be kept and what must accompany those records. Does the process operator sign and date the work instruction used? Is there a special form for recording process parameters and ensuring that they were within specified limits? Where are these records submitted? Are there multiple forms that are submitted because of the multiple steps in the process?

3.6 Guidelines for non-metallic additively manufactured/printed material

The outline for parts made with non-metallic (filled/unfilled), additively manufactured material follows the same format as the general guidelines listed previously, but with additional information needed for this material type.

3.6.1 Revision control

Manufacturing routings must be revision controlled, and typically include drawing and parts list revision information where applicable.

3.6.2 Approved feedstock (raw material)

- List approved materials and suppliers (including addresses/contact information).
- Specify the incoming receiving inspection tests: equipment, test methods, the material amount needed, trained personnel, and data analysis.
- Incoming receiving test methods will change depending on the additively manufactured process used. Some tests to consider for raw material / feedstock include verification; moisture, melt flow, pull force, diameter, particle size, ovality, differential scanning calorimetry (thickness, high-performance liquid chromatography, Fourier-transform infrared spectroscopy, density, and others as needed.
- Mechanical test methods such as tension, compression, and flex may also be used for incoming receiving inspection for solid material forms such as filament.
- Record information from CoC and CoA with critical characteristics identified, limits determined, and the method to determine the statistical comparison of results and specification limits. Documentation is required from each supplier contributing to the feedstock material. Information should contain characterization of the constituents proving the material is what is expected and a statistical comparison to a certain specification and the limits set within it. Provide key information from the CoC and CoA as part of the technical data package associated with the final product.
- Specify storage conditions for material and consumables to include environmental conditions, racking/stacking, shelf life, out-time.
- Specify the definition of non-conforming materials. Document the MRB process, including how the non-conforming materials are segregated.

- Specify safety precautions related to the handling of the material in its feedstock form. Describe personal protective equipment necessary for transporting and handling before processing.
- Specify allowance of reusable feedstock. Include procedures for reclaiming and returning materials to service and controls and limits on material re-use.

3.6.3 Product manufacturing

3.6.3.1 Recipe of raw materials/feedstock

This section includes the steps and descriptions to manufacture the product. Steps can include the following.

- Describe how the raw materials or feedstock are put together to produce the final product.
- Specify the procedure to combine and prepare raw material / feedstock constituents. Include recycled or reclaimed material usage
- Specify environmental conditioning of the material(s) before processing. Include humidity limits, and/or any other conditions required for the material.
- Specify procedures to meet environmental condition state
- Define the equipment to be used with the proper checks and calibrations spelled out for testing pre-operational characteristics of the final feedstock.
- Specify lot acceptance criteria and testing procedures.

3.6.3.2 Pre-processing

- For pre-processing, file preparation software(s) versions must be listed along with a description of how to determine a major or minor change in the software version. Describe what must be done if there is a major or minor change.
- Specify changeable parameters and limits of allowable changes for EACH parameter. NOTE: Programming build files have a large impact on the final part performance and can alter things like density, center of gravity, edge distances, or hole locations. Programming controls must be in place to maintain the designer's intent as best as possible.
- Specify maintenance and revision control procedures for expected files in the pre-processing chain. Define each file type created during production of the product. Intermediate file type examples can range from but are not exclusive to slicing files such as .STL, .AMF, or .OBJ;

build parameter files such as .GCODE or .SVG; and build location or pack files such as .CMB or .CLI.

3.6.3.3 Printer hardware setup, maintenance, and qualification retention

- Specify how facility hookups are compliant with Original Equipment Manufacturer (OEM) installation and maintenance guides.
- Specify the environmental conditions in which the hardware should be located for operation.
- Specify calibrations, calibration tools, and equipment used to validate that the proper configuration for the hardware has been achieved
- Perform and document preventative maintenance procedures. Ensure maintenance complies with the OEM maintenance guide and manual for procedures and frequency.
- Define a checklist to show that the hardware is worthy of being brought up for production. It is common to fabricate a physical part to validate mechanical performance and geometrical tolerances. Provide statistical guidance to determine equivalency to a baseline for a given material.
- Document all steps to show that the additively manufactured machine was brought online correctly and ready for production use such as qualification procedures (initial, operational and part), cleaning procedures, etc.

3.6.3.4 Printing operations

- Specify material loading procedures, checks, and validation of feedstock conditions
- Specify procedure for machine startup.
- Specify procedure on handling and loading of feedstock.
- Specify procedure for loading build or pack files.
- Specify procedure for machine operation.
- Specify actions in the event of a machine flag or error.
- Specify location and access to machine diagnostics for r post-build data analysis.
- Specify accompanying documentation to track information from the build, which should be provided as part of the tech data package.
- Specify whether witness coupons are included as part of the build. Lot acceptance testing can occur before operations and can replace the use of witness coupons. The use of witness

coupons has an impact on the build and should not be added or removed without understanding the impact on the other components in the build, bed, or chamber.

- Specify means for determining trending performance within a given system.
- Specify instances or scenarios that would require requalification of the system. This can consist of critical repairs, physical relocation of the systems, or upgrades to the system.

3.6.3.5 Post-processing

- Describe special post-processes such as machining, post-curing, sanding, shimming, surface prep, painting, sealants, coatings, bonding processes, and lightning protection. Must state materials needed, appropriately controlled tools, and needed machines with settings.
- Specify part-removal procedures for taking the build from the chamber, bed, or oven. This sometimes can include a temperature ramp and dwell that should have times and limits associated with them.
- Specify procedures for removing a part from consumables such as build sheet or support material.
- If another product is going to be installed or attached to the product, the post-processing installation must be described. It may include machining, bonding, or other means of attachment. Include material list, appropriate equipment, machines, and any required settings.
- Specify procedures for part cleanup or other hands-free support removal processes.
- Specify finishing and paint operations. Reference additional documentation or other procedures for t steps that are process-specific or agnostic.

3.6.3.6 Employee training and qualification requirements

- State how trained personnel who have completed training program *XXXXX* must be included.
- Include proof of operational training for loading, starting, and ending jobs.
- Include proof of processing training on how to set processing parameters and manage the intermediary files.
- Include proof of quality experience and training on process-specific procedures for conforming parts. What should the final part/product “look” like? Provide a description of key features with accompanying photographs. This is not a final inspection, just a way of describing to the trained personnel what he/she is building.

- Include proof of maintenance training for preventative maintenance, repairs, machine setup, and configuration before certifying machine qualification

3.6.4 Quality assurance operations

Specify how to detect issues or anomalies. Include how to check for them, what they look like, and what to do if they are found. This should be geared towards visual inspection and key process parameter monitoring during the production cycle while the product is still being built.

3.6.5 Finished product packaging

- Specify approved packaging type – box type, bag type, labeling, canister type, etc.
- Specify what measurements to take - length, weight, number of units, etc.
- Specify proper labeling procedures. Include contain a description of the product and how to do the labeling. Labeling can be done by job number, product type, special serialization, PO, or project code.
- Specify package orientation and any special instructions such as, “Don’t stack over 3 units high.”

3.6.6 Storage of finished product

- Specify finished product environmental conditions for storage to include ranges and limits for temperature, humidity, UV exposure, etc.
- Specify storage life. Include out-time, shelf life, workable time limits and data that back up the claims.

3.6.7 Testing of final product

Define quality checks Quality checks ensure that the product is built per the specification guidelines. Quality checks may include the following.

- There can be many methods associated with testing of the final product. Ensure methods are up to date and acceptable for the data being produced. NDI methods would be included here.
- Reference or detail the calibration cycle. Make sure the equipment is suitable and calibrated.
- The number of coupons per test type and condition should be clear.
- Reference the appropriate method for data tracking.

- Define the quality inspection process. How is the data and product signed off? How is the quality department involved? Is there a checklist or stamps? How do we know that the product is of good quality and can be used by the customer?
- Is a CoC or CoA included and what is the format?
- Specify the trained personnel performing the tests.
- Define any non-conforming materials. How are they tracked, segregated and dispositioned? What is the MRB process for the finished product?

3.6.8 Record retention

Describe records; electronic, hand-written, or otherwise, which must be kept and what must accompany those records. Does the process operator sign and date the work instruction used? Is there a special form for recording process parameters and ensuring that they were within specified limits? Where are these records submitted? Are there multiple forms that are submitted because of the multiple steps in the process?

4 Conclusion

Material and process control of advanced materials is critical to building high-quality parts and ensuring their safe use in aviation applications. As a critical element of material and process control, process specifications must provide appropriate guidance and oversight of manufacturing. This document serves as a guideline to assist in the development of an advanced material process specification(s) for various material types.

The parts or products produced can be small or large, intricate or simple, but in all cases, an appropriate process specification must be in place to control the manufacturing process from raw materials / feedstock to finished product. The links between the PCD, material specification, quality manual, and process specification must be clear, consistent, and appropriate. These documents work in concert with each other to ensure that the products are of good quality and design.

Proper details and supporting documents must substantiate that the products produced can meet all design requirements regardless of when the product is built. Understanding the pedigree of all materials and controlling the entire process through the final manufacture of the end product are vital steps in determining its safe use.

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