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Guidelines for the Development of Process Specifications, Instructions, and Controls for the Fabrication of Fiber-Reinforced Polymer Composites

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16. Abstract

This document provides (1) a set of guidelines for the development of process specifications for the fabrication of continuous fiber-reinforced polymer composite laminate test panels used in the generation of mechanical properties and (2) an approach for the validation of composite fabrication processes used during the certification of composite aircraft structure. These guidelines were prepared by a team of industry experts.

Guidelines are given based on processes and sound engineering practices currently used within the aerospace industry. This report is intended to advance the work that has been done through previous Federal Aviation Administration programs such as the Advanced General Aviation Transport Experiment. These programs have established methodology for developing statistical-based databases and their standardization.

The guidelines found in this document are meant to be a documentation of current knowledge and application of sound engineering principles to the composite laminate fabrication process. It is envisioned that these guidelines would be used to develop process specifications, work instructions (planning), sections within material specifications, and certification and qualification test plans.

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LIST OF ACRONYMS

AC	Advisory Circular
ACO	Aircraft Certification Office
AGATE	Advanced General Aviation Transport Experiment
AMS	Aerospace Material Specification
ASTM	American Society for Testing and Materials
CFR	Code of Federal Regulations
CTD	Cold Temperature Dry
DAR	Designated Airworthiness Representative
DSC	Differential scanning calorimetry
ETD	Elevated Temperature Dry
ETW	Elevated Temperature Wet
DER	Designated Engineering Representative
DMIR	Designated Manufacturing Inspection Representative
FAA	Federal Aviation Administration
MIDO	Manufacturing Inspection District Office
MOL	Material Operational Limit
MRB	Material Review Board
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
QA	Quality Assurance
RTD	Room Temperature Dry
RTW	Room Temperature Wet
SACMA	Suppliers of Advanced Composite Materials Association
SAE	Society of Automotive Engineers

EXECUTIVE SUMMARY

This document provides (1) a set of guidelines for the development of process specifications for the fabrication of continuous fiber-reinforced polymer composite laminate test panels used in the generation of mechanical properties and (2) an approach for the validation of composite fabrication processes used during the certification of composite aircraft structure. These guidelines were prepared by a team of industry experts.

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An important theme found within the guidelines is the importance of clearly documenting the procedures used to fabricate laminates. The ability to consistently repeat the fabrication process at a later date is necessary to minimize the variability in composite material test data and production parts. This can only be accomplished if the fabrication instructions are accurately documented.

This document can also be used to develop an industry approach so that the following goals can be achieved:

- Greatly reduce the number of material and process specifications for identical composite material systems.
- Develop property databases that uniquely define a given material.
- Establish material batch testing and process monitoring sufficient to minimize variability and preclude property changes over time.
- Reduce costs through common documentation and shared databases of basic material properties.

This document complements the recommendations and guidance for composite prepreg material specifications found in DOT/FAA/AR-02/109, Guidelines and Recommended Criteria for the Development of a Material Specification for Carbon Fiber/Epoxy Unidirectional Prepregs.

1. INTRODUCTION.

1.1 OBJECTIVE.

This document provides (1) a set of guidelines for the development of process specifications* for the fabrication of continuous fiber-reinforced polymer composite laminate test panels used in the generation of mechanical properties and (2) an approach for the validation of composite fabrication processes used during the certification of composite aircraft structure. These guidelines were prepared by a team of industry experts that have extensive experience generating material specifications, processing of composite materials, qualification program management, and design allowables development.

Guidelines are given based on processes and sound engineering practices currently used within the aerospace industry. This report is intended to advance the work that has been done through previous Federal Aviation Administration (FAA) programs, such as the Advanced General Aviation Transport Experiment (AGATE). These programs have established a methodology for developing statistical-based databases and their standardization.

The guidelines found in this document should not be viewed as policy or as the single acceptable method for composite laminate fabrication. They are meant to be a documentation or current knowledge and application of sound engineering principles to the composite laminate fabrication process. It is envisioned that these guidelines would be used to develop:

- process specifications,
- work instructions (planning),
- sections within material specifications, and
- certification and qualification test plans.

An important theme found within these guidelines is the importance of clearly documenting the procedures used to fabricate laminates. The ability to consistently repeat the fabrication process at a later date is necessary to minimize the variability in composite material test data and production parts. This can only be accomplished if the fabrication instructions are accurately documented.

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- Develop property databases that uniquely define a given material.

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* The terminology "process specification" will be used throughout this report for the instructions and controls used in test panel fabrication. However, only part of the processing information needs to be contained in a process specification, alternatively, some may appear in other documentation.

- Establish material batch testing and process monitoring sufficient to minimize variability and preclude property changes over time.
- Reduce costs through common documentation and shared databases of basic material properties.

This document complements the recommendations and guidance for composite prepreg material specifications found in reference 1.

1.2 BACKGROUND.

Steady growth in the use of composites has continued in transport aircraft and rotorcraft. General aviation has emerged recently with the growth of new composite aircraft and composite material applications in primary structures. Several new composite aircraft are undergoing the certification process. Many more aircraft are currently undergoing the design and development processes that take advantage of composite materials for primary structure applications. With this growth of composite applications, certification issues have emerged with respect to the philosophy of quality control and quality assurance methods needed to guarantee a safe and consistent material supply.

The material properties of a composite are manufactured into the structure as part of the fabrication process (process intensive material). Therefore, it is essential that material and process specifications used to produce composite materials contain sufficient information to ensure that critical parameters in the fabrication process are identified to facilitate production and adherence to standards in the final engineered part. Due to the wide variety of composite aircraft structures now emerging for certification, control of the materials is rapidly becoming a vital issue with respect to the overall assurance of safety.

In recent years, the aerospace industry, the National Aeronautics and Space Administration, and the FAA have worked together to develop a cost-effective method of qualifying composite material systems by sharing material qualification databases such as MIL-HDBK-17 and AGATE. By using shared databases, a manufacturer can select an approved composite material system to fabricate parts and validate with a smaller subset of testing for a specific application. For materials to be accepted into these shared databases, the raw materials are required to be manufactured in accordance with a material specification which imposes control of key characteristics (physical, chemical, and mechanical properties) and be processed in accordance with a process specification that controls key characteristics (processing parameters).

1.3 CERTIFICATION PROCESS.

The objective of the composite aircraft structure certification process is to validate that the design meets the applicable configuration requirements. In this context, the design validation process (to establish by proof) is accomplished through verification (to prove by evidence) and qualification (to define attributes or characteristics) of the materials, processes, and analysis tools. Verification is simply to prove by evidence, usually by test data, that the proposed design is acceptable. Material qualification is the verifying of a materials attributes and characterizations, which are typically determined through testing.

A widely acknowledged validation process used within the composite aircraft industry for the substantiation of composite structure is called the building block approach. This approach uses analysis and associated tests of increasing structural complexity [2]. The building block approach is integrated with supporting technologies and design considerations. Refer to MIL-HDBK-17F, Volume 3, Chapter 4 for a complete description of the building block approach. Key elements supporting the building block approach are the material and process specifications.

The material and process specifications are interwoven throughout the certification and validation process. Material specifications are used to define the material's attributes and to define the qualification characterization tests. Materials used within the building block tests are purchased in accordance with a material specification. The material specification is used for procurement of production material. This ensures the delivered materials are of the same quality and performance standards used in the certification validation process. Process specifications define and control the processes used for the conversion of materials into structural parts. It is widely accepted that the performance properties of composite laminates are directly determined by the specific process used for their fabrication. It is critical that the test specimens fabricated through the various levels of the building block approach use the same process, which is representative of the one that will be used in the fabrication of production aircraft and rotorcraft.

Material qualification is a key element of the validation process, which occurs during the coupon level of the building block approach. It is during qualification that the composite material is fully defined and characterized. Qualification tests are planned and conducted to

- establish key material attributes,
- establish material performance properties, and
- verify material characteristics will work in the intended application.

The objective in defining material attributes is to establish the material property limits. Examples of attributes in which limits are set include

- resin content,
- fiber areal weight,
- cured per ply thickness, and
- fiber volume.

These attributes define the material and control its resulting performance properties. Other attributes that are often overlooked are related to the physical structure of the material, which affects processing characteristics. Example attributes of this type include

- fiber-sizing level and type,
- level of impregnation,
- resin impregnation method (hot-melt film or solution),
- width tolerance, and
- backing material selection.

Performance properties are established, or made stable, through statistically significant amounts of testing. It is imperative that the material's natural variability is captured at this time. The objective is not to meet a desired level of performance, but rather, establish the true performance range of the material. Mechanical properties are typically thought of as the only performance properties.

There are other performance-related properties that have a direct bearing on the more familiar mechanical properties, which include tack or handling characteristics, kinetic behavior, rheological behavior, sensitivity to ambient moisture and temperature (out-time effects), effect of freezer storage, and resistance to fluids and solvents. Multiple material batches (typically three) are tested to establish the material variability. Results obtained from these tests are used to establish minimum and maximum values within the material specification.

2. PROCESS SPECIFICATION GUIDELINES.

The objective of process specifications is to provide a means by which engineering requirements and procedures can be documented and communicated to the various organizations involved in the fabrication of composite laminates. The intent is to flow down and specify any regulatory or engineering requirements and procedures that are necessary for the fabrication process. It is imperative that the process specifications be clear and complete to ensure that the resulting laminates are consistent in quality.

For the purpose of this report, the term process specifications refers to documents such as process specifications, material specifications, planning, work instructions, or test plans. The guidelines found in the following sections can be applied to any of the above documents. These guidelines have been found to be helpful in the fabrication of continuous fiber-reinforced polymer composite test laminates but should not be viewed as the only means of control for a particular application.

The guidelines for the fabrication of continuous fiber-reinforced polymer composite test laminates are divided into the following sections:

- Work Instructions
- Personnel
- Materials
- Equipment Description
- Facility Description
- Tooling
- Panel Lamination
- Panel Acceptance
- Process Monitoring

2.1 WORK INSTRUCTIONS.

Work instructions (also referred to as planning) contain the requirements and procedures to be used in the fabrication process. Detailed step-by-step work instructions in conjunction with process specifications have been found to be a successful approach for the fabrication of repeatable quality laminates. Process specifications define the engineering requirements while the work instructions convert the engineering requirements into detailed step-by-step process instructions.

The level of detail contained within the work instructions is subjective and varies from organization to organization. While the level of detail can vary, it should always be sufficient to ensure clear communication of the procedures. Many instructions are best communicated through sketches or figures. Provisions should also be made within the work instructions for the recording of relevant observations, data, and quality assurance stamps.

2.2 PERSONNEL.

Highly skilled technicians are needed to produce quality laminates. Fabricators are encouraged to establish a comprehensive training program for technicians directly involved with the fabrication of composite test panels. Both written and practical proficiency tests are recommended for the training program. Fabrication of test panels and production parts by trained technicians increases the probability of fabricating high quality and repeatable test panels. The quality of the laminates has a direct bearing on program cost (elimination of rework due to poor quality laminates) and optimum structural performance (establishment of design allowables).

Table 1 lists suggested factors to be addressed in the selection of fabrication personnel.

TABLE 1. RECOMMENDED PERSONNEL SELECTION FACTORS

• Experience
• Inspection personnel, ratio to manufacturing personnel
• Level of training
• Personnel status identified (qualified or unqualified)

It is strongly recommended that a mentoring relationship be established between the company's technicians and engineering personnel. This mentoring relationship is best if the flow of knowledge is in both directions.

2.3 MATERIALS.

All materials (and their sources) required for the fabrication procedures and requirements relevant to the materials should be listed within the process specifications. The listing includes both consumable and structural materials. In cases where equivalent materials may be used, specific alternate materials should be explicitly stated.

Materials that can come in contact with the composite prepreg should be evaluated to verify they do not contaminate the prepreg material. It should be verified that all materials that have the potential to become a foreign object within the laminate can be detected by nondestructive inspection (NDI) methods that will be used for the inspection of production parts.

Prepreg materials should be inspected upon receipt by the purchaser, per the material specification. Test methods, types of tests required, sampling requirements, criteria (acceptance value), and retest provisions should be clearly defined. Supplier certification records should be reviewed and maintained with the laminate process instructions. Material that does not meet the established quality requirements should not be processed into test panels.

Prepreg material freezer storage conditions (temperature) and shelf life limits should be defined (controlled in the material specification). Most prepreg resins require a storage temperature of 0°F or lower. Freezer storage life can be from 6 to 18 months, with 12 months the most common. Procedures for the disposition of out-of-date material also need to be defined. This could include shelf life extension based on the performance of reinspection tests.

Ambient working life (sometimes called out-time) limits should be defined. The time period should be associated with a defined temperature and relative humidity range. This time period should have been determined during the material qualification test program.

Within the industry, two approaches are used in defining ambient working life. The first approach refers to the ambient working life as out-time. Out-time begins when the prepreg is removed from freezer storage and ends when the cure cycle begins. Depending on the resin, out-time will typically be from 10 to 30 days. The second approach is to divide the ambient working life into two sections: handling life and staging life. Handling life begins when the prepreg is removed from the freezer and ends with placement of the prepreg onto the tool. The staging life begins at placement of the ply on the tool and ends when the cure cycle begins.

Definition of the ambient environment is critical to producing quality parts and avoidance of scrapped material and parts. Figure 1 is an example schematic of the relationship between prepreg storage life, handling life, and staging life.

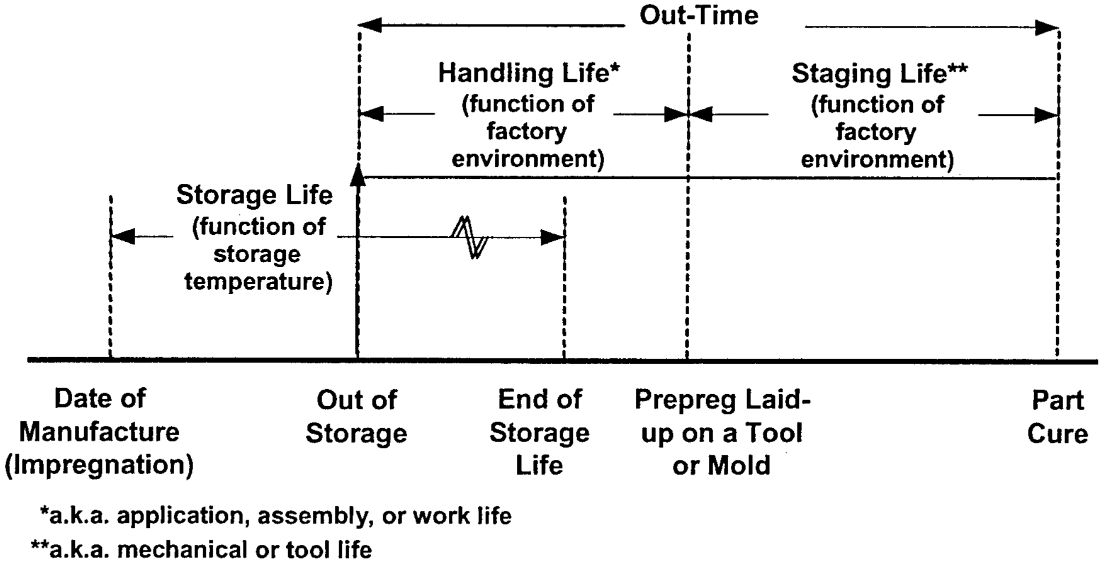

FIGURE 1. PREPREG STORAGE AND OUT-TIME LIFE RELATIONSHIP

Resins are typically perishable at ambient temperatures, i.e., they continue to react. This continuing reaction could, in time, reduce the resin kinetics and flow characteristics of the material, thus affecting producibility and properties.

Prepreg handling properties are a function of temperature. Too high a temperature and the material will be too tacky, making it difficult to position and handle the plies. Too low a temperature and the material will be stiff and again difficult to work with.

Some resins are susceptible to moisture in that the absorbed water inhibits cure kinetics. Therefore, controlling the relative humidity is important for ensuring the resin will obtain an optimal cure. High humidity will also increase the tack of the material. Prepreg materials with high tack have been shown to trap air and moisture between the plies, resulting in porosity in the laminates.

Complete records should be maintained that document traceability of the fiber, resin, adhesive, prepreg, and laminates. These records should also document the total shelf life and out-time of the prepreg and adhesive materials up to the time of panel cure. Provisions should be made within the work instructions to record material batch and roll numbers and ambient out-time at the time of collation and cure.

2.4 EQUIPMENT DESCRIPTION.

All equipment needed to perform the fabrication process with necessary requirements should be listed in the process instructions. Sources for the equipment should also be listed. Calibration and certification requirements should be defined. Equipment requiring calibration and certification typically includes ovens, autoclaves, thermocouples, vacuum gages, and ply-warming devices (e.g., hot-air guns). Provisions should be made within the process specification to record the last date of calibration (as applicable) and equipment serial number.

2.5 FACILITY DESCRIPTION.

Collation (lay-up) of plies should be performed in a clean room. The clean room is an environmentally controlled facility where, in addition to the control and monitoring of temperature, humidity, air pressure, air distribution, and air velocity, conditions are established to minimize the introduction, generation, and retention of airborne particles [3]. Good housekeeping procedures should be followed along with controlling the temperature, humidity, and airborne particles. A complete clean room discussion can be found in reference 3. Additional information on manufacturing facility controls can be found in reference 4.

Prepreg handling and curing characteristics are sensitive to both temperature and humidity and, therefore, it is critical to control and monitor temperature and humidity within the lay-up area. The temperature and humidity requirements should align with the material's ambient out-time requirements. A typical clean room temperature/humidity environmental requirement envelope is shown in figure 2.

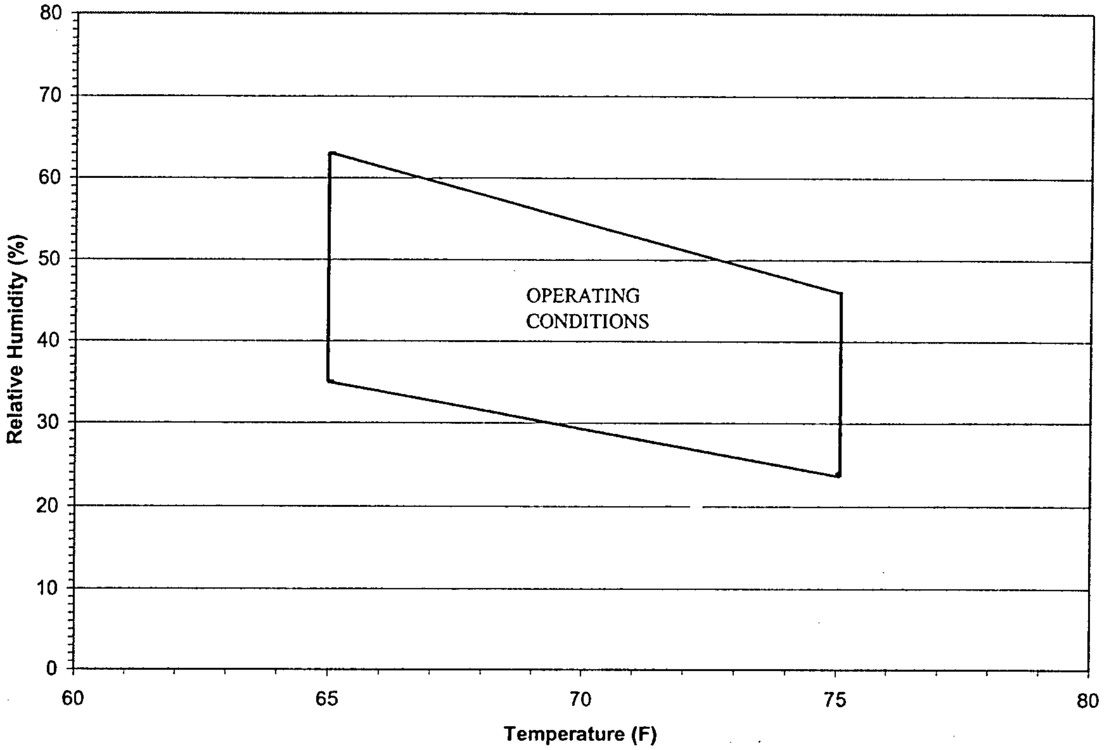

FIGURE 2. TYPICAL CLEAN ROOM TEMPERATURE/HUMIDITY REQUIREMENTS

The control of airborne particles is essential to maintaining a clean environment for the fabrication of composite laminates. Airborne particles are controlled through the use of filters, restricting dirty operations, and the establishment of positive pressure within the clean room.

Filtration of the air is recommended to not only ensure clean air is introduced into the clean room, but also to clean particles from the air that were generated within the clean room. ISO 14644-1 Class 9 is recommended as the minimum level of filtration for a clean room [5]. The following actions also help to minimize the generation of airborne particles:

- Clean work areas on a regular basis and inspect for potential foreign objects.
- Do not allow mold releases or other silicone-containing materials into the room.
- Do not allow sanding, machining, or any other operation that generates dirt, dust, or other debris in the room.
- Do not allow an air tool to be used without special precautions against contaminating parts with oil suspended in most shop air.

The inclusion of a positive-pressure ventilation system in the lay-up room is an effective method of preventing the introduction of airborne particles from other parts of the facility, such as machine shops.

Table 2 presents a checklist of items to consider when specifying requirements for a clean room.

TABLE 2. RECOMMENDED CLEAN ROOM REQUIREMENTS CHECKLIST

• Limit access by other equipment (gas powered fork lifts)
• Limit access by non-lay-up personnel
• Air flow through the room
• Equipment for monitoring environmental control
• No Contamination by other processes (chemical processing, painting, and sanding)
• Treatments and cleanliness of floors
• Humidity (minimum and maximum)
• Temperature (minimum and maximum)
• Isolation from other contaminates
• Lay-up area status (approved, unapproved)
• Lighting (lumens)
• Particulate count
• Pressure (positive)
• Proximity to staging area and autoclaves
• Vacuum hose status (approved, unapproved)
• Treatment and cleanliness of walls

Provisions should be made within the work instructions to record the temperature and humidity at the time of ply collation.

2.6 TOOLING.

For the fabrication of flat test panels, typically, tooling consists of a base plate and a caul plate. They should be designed for the defined process conditions (e.g., cure temperature and pressure). Surface finish and flatness requirements should be defined (as applicable). All tools should be clearly identified. Tool storage conditions that ensure the tools are not damaged over time need to be defined.

A heat survey should be performed on all tools. The survey should verify the tool can meet required heat-up rates and that the temperature is uniform throughout the tool surfaces. Thermocouples should be placed at the coldest and hottest locations.

A method for accurately positioning the plies is required. It is imperative that the ply orientation is within the engineering requirements, as strength and modulus properties are sensitive to orientation. A method must be used that allows for transfer of the tool zero direction to the panel and then to the machining equipment. Scribe lines on the tool and thin metal strips embedded along one edge of the panel are two methods that have been successfully used.

Detailed tool preparation procedures are necessary. Areas to cover include tool inspection, verification that all tooling details are available and in good working condition, mold release application procedure (acceptable mold releases should be listed in the materials section), and tool clean-up procedures. See table 3 for a checklist of tooling control items.

TABLE 3. RECOMMENDED TOOLING CONTROL CHECKLIST

- Method of cleaning, solvents, cleaning cloths
- Mold release agents
- Tool heat survey results (location of coldest and hottest thermocouples)
- Scribe marking
- Template inspection intervals
- Template surface conditions
- Template material
- Templates, number of
- Tool heat-up rate
- Tool inspection intervals
- Tool surface conditions
- Tool, method of moving, transportation
- Tooling condition (mold release applied, and no mold release)
- Tooling configuration (flat, vertical)
- Tooling status identified (approved, unapproved)
- Tooling storage conditions and locations
- Tooling, expansion and contraction rate
- Tooling material
- Location and number of vacuum ports
- Orientation rosette
- Tool repair procedures
- Tool inspection intervals

2.7 PANEL LAMINATION.

2.7.1 Lay-Up of Plies.

Frozen prepreg in sealed containers must be warmed to room temperature prior to opening to prevent condensation from getting onto the prepreg. The length of time required to warm the prepreg to ambient temperature is a function of the roll size; the larger the roll, the longer the thaw time. Small rolls (5 to 10 pounds) can reach room temperature in 2 to 3 hours, while 30- to 50-pound rolls can take over 6 hours.

Plies should be cut on surfaces specifically dedicated to cutting plies. Plies should not be trimmed or cut on the tool to ensure the tool or underlying plies are not damaged. If trimming of plies on the tool is required, a clean metal shim should be placed between the prepreg and tool surface. Individual plies should be identified and marked at the time of cutting.

The plies are collated onto the tool as defined in the detailed work instructions. Care should be taken to accurately align the plies with respect to the tool zero-degree reference direction. See reference 6 for a description of the reference bar method used to maintain ply alignment through the panel fabrication and subsequent specimen machining operations. Prior to collation, the plies are inspected for visual defects. Damaged plies are repaired or replaced as applicable. Plies are debulked (compacted with vacuum pressure) as applicable. After each ply is collated and the backing paper is removed, its surface is inspected for foreign objects.

The panel is bagged for cure as specified in the detailed work instructions. The panel should be clearly marked to ensure traceability.

Thermocouples should be placed such that the panel temperature can be directly measured. The thermocouples should be placed against the prepreg to ensure the material is heated to the specified temperatures. At least two thermocouples should be used for each panel. If the panel is large, 4 to 6 thermocouples are recommended. In cases where the tool contains embedded thermocouples, a heat survey should be performed to validate that the embedded thermocouples are an accurate measurement of the panel temperature.

2.7.2 Cure Cycle.

The panel is cured to the applicable cure cycle. Prior to cure, a leak check should be performed on the vacuum bag. All leaks should be repaired before performing the cure cycle. Leaks through the tool can create as serious problems as leaks around the edges of the bag. The cure cycle should define heat-up rate, temperature range, time, vacuum, pressure, and cool-down rate. Although oven temperature is sometimes used, ideally, the cure time and temperature should be controlled by the slowest (lagging) thermocouple in the cure run. Temperature, vacuum, and pressure should be recorded as a function of time for the complete cure cycle.

2.7.3 Panel Identification.

Each panel should be marked with a unique identification number. This identification number will provide traceability to the requesting document, prepreg batch number, cure cycle, and test type. Lines can also be drawn at an angle across the laminate surface to aid in identifying specimen location within the panel.

2.8 INSPECTION AND PROCESS MONITORING.

This section defines the recommended examinations, inspections, and tests to be performed in order to verify that the processes, as well as the equipment, specified by the engineering requirements are followed. Each inspection or examination given in this section should be tied directly to a requirement specified by the process instructions.

2.8.1 Responsibility for Inspection.

Organizations or personnel responsible for the performance of the inspections and process monitoring examinations should be identified. When personnel other than quality assurance inspectors are given the responsibility to perform inspection, they must be trained in the performance of quality assurance tasks and must be supported with complete documentation on the required inspection process.

2.8.2 Panel Inspection.

After cure, it is strongly recommended that the panel be inspected to ensure all engineering requirements have been met prior to machining test specimens. Inspections or tests are performed on each panel to verify they are acceptable for submission to the machining step. They include panel thickness, surface flatness, completeness of cure, and NDI for internal defects and embedded materials. Test panels that fail to meet these requirements will result in test data that is not representative of the material.

The tests recommended in this section are not necessarily applicable to production parts (though they are often used for developmental parts and first part qualification). They are used to verify that the panel is acceptable for further testing and are required to provide a complete database.

The panel should be visually inspected for surface defects that could be sources for premature test failures. If possible, specimens should be machined from areas outside of these defects. Panel density and resin content (fiber volume) should also be determined. This requires that small samples (1/2 by 1/2 inch) be machined from the panel.

Panel thickness is verified at a number of locations. The measurement locations should be equally spaced (within reason) around the panel. The actual thickness is converted to a per ply thickness by dividing the average measured thickness by the number of plies. The panel should not be tested if it fails to meet the required per ply thickness. The thickness data can also be interrogated to determine degree of flatness. Again, failure to meet engineering thickness requirements, results in the panel not being tested.

Each panel should be nondestructively inspected for internal defects, such as porosity, foreign objects, or delaminations. NDI standards should be fabricated as early as possible within the certification process. These NDI standards consist of panels fabricated with known defects so that the nondestructive methods and criteria can be calibrated relative to defect severity and panel thickness. It is imperative that NDI indications (such as sound loss for ultrasonic through transmission) be tied to a known physical defect type, location, and size. See SAE ARP 5605 for guidance in the fabrication of solid laminate NDI references and SAE ARP 5606 for guidance in the fabrication of honeycomb sandwich NDI standards [7 and 8].

Completeness of cure can be verified by measuring the glass transition temperature (Tg) and in some cases degree of cure using differential scanning calorimetry (DSC).

Ply lay-up orientation can be verified by polishing an edge for examination under a microscope (20 to 50X).

All records should be reviewed to verify the panels were fabricated in compliance with the engineering requirements. The records should include material batch/lot traceability, panel identification, cure cycle parameters, and ply count.

Machining diagrams should be developed for each panel and included in the detail work instructions. The type of machining equipment used to machine the panels into specimens is recorded along with cutting tool type, speeds, and feed rates. After machining, the specimens are inspected for damaged edges and dimensionally inspected. Specimens failing to meet engineering requirements should be replaced.

Table 4 is a list of items to control for the machining of test specimens.

TABLE 4. RECOMMENDED ITEMS TO BE CONTROLLED FOR MACHINING

• Use of and type of coolant
• Marking of trim lines
• Type of tools for trimming, hole drilling
• Tools for control of cutting surfaces
• Tools, inspection intervals
• Method for transferring the 0° direction to each specimen

2.8.3 Monitoring Procedures.

The following areas should be reviewed and monitoring procedures instituted.

- Equipment—All equipment requirements requiring verification should be listed for inspection. Calibration frequency is also defined.

- Materials—All material requirements requiring verification should be listed for inspection. This would include freezer storage temperature, storage life, out-time life at time of collation and cure, performance of receiving inspection tests, use of approved consumable materials, and batch numbers.

- Facilities—All facility requirements requiring verification should be listed for inspection. This would include clean room temperature and humidity and cleaning schedule.

- Tooling—All tooling requirements requiring verification should be listed for inspection. This would include performance of heat surveys to document temperature uniformity during the cure cycle, performance of tool visual inspections, and monitoring of storage conditions.

2.8.4 Documentation.

All information required to be recorded and reported should be listed. The time span all process records should be retained is also specified. A period of 7 years is recommended.

2.8.5 Test Methods.

All test methods specified within the process instructions should be listed. The preferred practice is to reference industry test method specifications or standards such as those published by ASTM. Exceptions to standard methods should be clearly documented.

3. PRODUCIBILITY VALIDATION GUIDELINES.

Certification and qualification test programs typically concentrate on the validation of mechanical properties and allowables. Of equal importance is the validation of processing parameters and part producibility. This section presents recommended producibility validation guidelines, which address (1) verification of material attributes that affect producibility and (2) qualification and verification of fabricator processes to ensure the part meets the expected properties.

3.1 PRODUCIBILITY QUALIFICATION TESTS.

An important element of the material qualification effort is the verification of the material's producibility. During the material qualification test program, thin flat constant thickness test panels are used to develop material performance properties, i.e., strength and stiffness. It is the inherent characteristics, or attributes, of the prepreg that govern the material's producibility. Some of the material attributes that influence producibility are tack, level of impregnation, resin flow properties, and surface texture.

In addition to validating the influence of prepreg attributes, scale-up effects on producibility must also be addressed during the qualification process. The fabrication of constant thickness flat panels does not fully demonstrate the material's ability (or inability) to be fabricated into large-scale production laminates. These scale-up effects could include laminate thickness, part area, internal ply drop off features, and in the case of sandwich structure, core density, ramp angle, and prepreg surface characteristics. Due to their nature, the performance of mechanical property tests obtained from flat test panels does not assess the impact of processing scale-up effects. But these effects can have a major impact on producibility of large-scale components and thus the structural performance of the component.

There typically exists a need for a panel design that will discriminate these material attributes and their ability or robustness to accommodate scale-up effects. This panel can then be fabricated as part of the qualification test program. The objective of the Discriminator Panel is to distinguish one material from another similar (or like) material by exposing their differences as related to producibility. The difference in material attributes is often quantified by the amount of porosity within the Discriminator Panel. For example, significant porosity may occur when the material is used to fabricate complex, contoured components even though small test panels made with the same material were void-free. In many cases, prepreg materials suitable for fabrication of monolithic laminates will not produce high-quality honeycomb sandwich panels. Therefore, the Discriminator Panel needs to be representative of the intended application. It must be representative in thickness and contour and contain ply drop off features representative of the proposed component designs. It must be fabricated with procedures representative of production methods (e.g., do not use hand layup for the panel when the production method is automated tape laying).

Instead of fabricating a Discriminator Panel, an actual part can be fabricated to address prepreg material processing attributes. This allows a direct evaluation of scale-up effects. The down side to using an actual part is that the performance of any evaluation is tied to tool availability. It is rare that a part is designed, and applicable tooling is available, when the material qualification program is being performed. Material selection decisions are typically made prior to the start of the design process.

Tests typically performed on the Discriminator Panel could include NDI and thickness, glass transition temperature, degree of cure, and mechanical property tests.

The Discriminator Panel can also be used in conjunction with test panels to assess the impact of processing or material changes. In cases where there is the need to assess a change in impregnation processing parameters, the Discriminator Panel often will be more discerning to the changes than mechanical properties from test panels.

3.2 FABRICATOR QUALIFICATION.

During many building block certification efforts, the initial fabrication of coupon test panels, elements, and components is performed at a different location or fabricator than the production components. This could result in material property values that are not representative of those produced by the full-scale production facility. It is recommended that the part fabricators also be qualified as part of the certification process. The fabricator qualification consists of three elements: (1) verification of coupon performance property equivalency, (2) verification of component structural equivalency, and (3) verification of engineering compliance. Each of these elements is discussed below.

3.2.1 Performance Property Equivalency.

Performance property equivalency is verified by the fabrication and testing of test panels. The purpose of this is to validate that their processes yield properties, which are from the same statistical population as the qualification and allowables data. The process of validating the material properties for an alternate process or facility is termed equivalency testing (see references 1 and 6). An audit to verify the compliance with the process specification requirements is also recommended as part of the fabricator qualification process.

3.2.2 Component Structural Equivalency.

Verification of component structural equivalency can only be accomplished by the destructive testing of a full-scale component. This is not the same as testing an element specimen or subcomponent. As a rule, the design of elements and subcomponents includes provisions for load introduction that would not be a part of the production design. In addition, the tooling concepts are not always identical between test parts and production parts. Therefore, it is typically necessary to destructively inspect a part fabricated with production tooling and processes.

The objectives for performing a destructive inspection on a part are to

- verify the performance properties established during coupon- and element-level testing (qualification and allowables) are the same in the component.
- quantify internal (hidden) defects or indications detected by NDI, i.e., validate NDI methods.
- validate laminate physical properties (resin content and thickness).
- verify fiber path continuity within joints and complicated geometries (typically features that cannot be verified through a Discriminator Panel or by NDI).

A typical geometric feature that can only be evaluated by a destructive inspection is a cocured joint. Cocured joint quality is strongly dependent on the tooling approach and design features. It is only through the fabrication of full-scale hardware with the actual production tooling that cocured joint strength can be evaluated. Another design feature that is difficult to evaluate without the assistance of a destruct article is the honeycomb sandwich panel where foaming adhesive is used to splice honeycomb core to solid structure (such as ribs or spars). In many cases, the foaming adhesive will migrate from the core to spar bond line into the skin to spar bond line. This migration is detrimental to bond line strength and almost impossible to detect by standard NDI techniques. It is only through destructive inspection that it can be verified that the processing techniques imposed to prevent foaming adhesive migration actually work.

The fabrication of a destruct article provides a great opportunity to access the impact of anticipated manufacturing defects on structural performance. Known defects can be placed within the destruct article during fabrication. NDI procedures can then be validated through the detection and identification of these known defects. Element test specimens can then be machined from the article such that the test section contains the known defects. The impact of the defect on structural performance can then be determined. Data of this nature is very valuable to the material review board disposition process. In some cases, the defect can be repaired prior to testing. Typical defects to include within the destruct article include:

- Delaminations
- Wrinkles or ply waviness
- Thickness variation
- Tool mark off (resin ridge or surface wrinkle)
- Porosity or voids
- Foreign inclusions

The destructive inspection process typically includes:

- Full dimensional inspection
- NDI

- Section cuts through areas indicted by the NDI and areas of complex geometry and layup, and bonded or cocured joint regions

- Excising coupons for mechanical property testing

Coupons typically excised include glass transition temperature, degree of cure as determined by DSC, resin content, short beam strength, compression strength, open hole tension or compression strength, and flexural strength. If possible, element or joint specimens should also be excised for testing.

Prior to the performance of any mechanical property coupon or element tests, it is critical that the pass/fail criteria be established. These criteria must be tied to the analysis approach and allowables used to design the part and also must account for part configuration effects. Thought must be given to what action will be taken if the criteria are not met. Do not go into these tests without thinking through the benefits and consequences of these tests. Selection of which tests to perform is also a critical element of this process.

If other fabrication techniques, such as bonding or mechanical fastening, are used, they should also be verified. The development of requirements for those additional fabrication techniques is beyond the scope of this document but should be included in the destructive inspection process.

Destructive inspections should be performed on part families. A typical part family might be all cocured assemblies and another might be all honeycomb sandwich assemblies. A destructive inspection is typically performed on one part that is representative of a given process, design, and tooling approach. The destructive inspection is repeated for each major change in tooling, design, alternate materials, fabricator location (or company), or process. A Discriminator Panel can be used to assess minor material and process changes. The destructive inspection does not have to be performed on the first assembly (component) produced, but it should be performed such that the results are evaluated prior to the assembly of the component on the first aircraft assembled.

3.2.3 Engineering Compliance.

The final step in the producibility validation process is to verify that the as-produced parts comply with engineering drawings and specifications. This can be accomplished through a First Article Inspection (FAI). The objective of the FAI is to verify that everything has come together (specifications, tooling, process instructions, process parameters, and design details) to produce a conforming part. The FAI is a physical examination of the part to verify engineering design (fit, form, and function, e.g., as fabricated weight, finish, physical interfaces, and workmanship). This is normally accomplished by NDI in conjunction with an expanded dimensional inspection and a through audit of the fabrication records. The FAI should expand the types, number, and locations of physical measurements beyond those identified as key characteristics. Each part type should go through the FAI process.

4. REFERENCES.

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8. ARP 5606, "Composite Honeycomb NDI Reference Standards," SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

Related Information

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AIR 5278, "Composite and Bonded Structure Engineer: Training Document," SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

AIR 5279, "Composite and Bonded Structure Inspector: Training Document," SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

ARP 5089, "Composite Repair NDT/NDI Handbook," SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

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ASTM D 3878, "Standard Terminology for Composite Materials," ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19429-2959.

ASTM D 3993, “Standard Terminology Relating to Fabric Defects,” ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19429-2959.

ASTM D 5687, “Standard Guide for Preparation of Flat Composite Panels with Processing Guidelines for Specimen Preparation,” ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19429-2959.

ASTM D 6507, “Standard Practice for Fiber-Reinforced Orientation Codes for Composite Materials,” ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19429-2959.

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ASTM D 907, “Standard Terminology of Adhesives,” ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19429-2959.

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5. GLOSSARY.

This glossary is a compilation of terms with their definitions used within this report and of general interest. Definitions for this glossary were obtained from a variety of sources, which are noted at the end of the definition. Refer to MIL-HDBK-17 for a more complete listing of terms and their definitions.

Autoclave, n—a closed vessel for conducting a chemical reaction or other operation under pressure and heat (Handbook of Composites).

B Stage, n—an intermediate stage in the reaction of a thermosetting resin in which the material softens when heated and swells when in contact with certain liquids but does not entirely fuse or dissolve. Materials are usually procured to this stage to facilitate handling and processing prior to final cure. See also C Stage (MIL-HDBK-17).

bag, v—the process of enclosing the ply layers within a flexible container. See also vacuum bag (ASTM D 5687).

baseplate, n—a flat plate on which a laminate is laid up. See also mold (ASTM D 5687).

bleeder, n—cloth that allows matrix to flow into it for the purpose of removing excess matrix from the laminate. Net resin prepreg systems do not require the use of bleeder materials (ASTM D 5687).

braided fabric, n—a cloth constructed by a braiding process (ASTM D 3878).

breather, n—cloth which allows even gas flow over the layup surface. The breather also helps minimize bag punctures by protecting the bag from sharp points (ASTM D 5687).

> Discussion: Typically within the bagging layup sequence, the breather material is a mixture of materials. The layer closest to the laminate is a lightweight glass fabric, such as Style 120, in order to minimize mark off on the laminate. The remaining layers are materials selected for their ability to transport gasses under pressure and elevated temperature. Typical materials are heavy weight glasses such as Style 1000 or synthetic nonwoven materials.

breather string, n—a glass string connected from the laminate to a breather in the bagging lay-up. It provides a path for gasses to be transferred from the laminate while minimizing matrix flow (ASTM D 5687).

broadgoods, n—prepreg material (fabric or unidirectional) where the width is greater than 24 inches. See also tape.

C Stage, n—the final stage of the curing reaction of a thermosetting resin in which the material has become practically infusible and insoluble. See also B Stage (MIL-HDBK-17).

caul plate, n—a flat plate used to provide a flat surface to the top of the laminate during laminate consolidation or cure (ASTM D 3878).

CFR—Code of Federal Regulations.

cloth, n—a piece of textile fabric containing woven reinforcement without a load transferring matrix (ASTM D 5687).

composite material, n—a substance consisting of two or more materials, insoluble in one another, which are combined to form a useful engineering material possessing certain properties not possessed by the constituents. Composites are subdivided into classes on the basis of the form of the structural constituents; Laminar: Composed of layer or laminar constituents; Particular: The dispersed phase consists of fibers; Flake: The dispersed phase consists of flat flakes; Skeletal: Composed of a continuous skeletal matrix filled by a second material (ASTM D 3878 and Handbook of Composites).

consolidation, v—the process of forming individual plies into one solid composite laminate. For polymeric based composite materials, consolidation is the compaction of the plies under pressure at elevated temperature until the polymer matrix material is cured.

cure, v—to change the physical properties of a polymer by chemical reaction, which may be by condensation, polymerization, or vulcanization; usually accomplished by the action of heat and catalyst, alone or in combination, with or without pressure (ASTM D 907).

cured ply thickness (CPT), n—the theoretical thickness of an individual ply, which is a function of the fiber areal weight, resin content, fiber density, and resin density.

> Discussion: cured per ply thickness is determined from the fiber areal weight, fiber volume, and fiber density:
>
> $$CPT = \frac{FAW}{25400\rho_f FV}$$
>
> Where:
>
> CPT is theoretical cured ply thickness (inches)
> FAW is fiber areal weight (g/m^2)
> 25400 is a units conversion factor
> ρ_f is the fiber density (g/cc)
> FV is fiber volume (fraction, e.g., 0.61)
>
> Or cured per ply thickness can also be determined from the fiber areal weight, resin content, fiber density, and resin density:
>
> $$CPT = \frac{FAW}{25400}\left[\frac{1}{\rho_f} + \frac{RC}{\rho_r(1-RC)}\right]$$

Where:

CPT	is theoretical cured ply thickness (inches)
FAW	is fiber areal weight (g/m^2)
25400	is a units conversion factor
ρ_f	is the fiber density (g/cc)
ρ_r	is the resin density (g/cc)
RC	is resin weight content (fraction, e.g., 0.33)

The actual cured ply thickness is determined by measuring the laminate thickness and dividing it by the number of plies (see SACMA SRM 10).

Fiber volume and resin content are related by the fiber and resin densities:

$$FV = \frac{1-RC}{\rho_f}\left[\frac{1}{1-RC/_{\rho_f} + RC/_{\rho_r}}\right]$$

Where:

FV	is fiber volume (fraction, e.g., 0.61)
ρ_f	is the fiber density (g/cc)
ρ_r	is the resin density (g/cc)
RC	is resin weight content (fraction, e.g., 0.33)

dam, n—a solid material (such as silicone rubber, steel, or aluminum) used in the lay-up to contain the matrix material within defined boundaries during laminate consolidation (ASTM D 5687).

DAR—Designated Airworthiness Representative. FAA designees authorized to conduct conformity inspections on behalf of the FAA.

debulk, v—process of decreasing voids between lamina before laminate consolidation through use of vacuum or by mechanical means. Lamina can be debulked at ambient or elevated temperature (ASTM D 5687).

degree of cure (α), n—in thermoset polymers, the quantity of heat of reaction of the unreacted resin remaining after a reaction (cure cycle) compared to the total available quantity of heat of reaction expended by the complete reaction (cure) of a reacted resin.

> Discussion: The degree of cure of a laminate can be obtained from differential scanning calorimetry (DSC) data. In order to obtain the degree of cure of a laminate, the baseline or total heat of reaction released by the complete curing of the resin (or prepreg) must first be obtained. This total heat of reaction is determined from the DSC curve. It is important to obtain the total heat of reaction from a sample that is of the same resin content as the laminate in question. This is typically accomplished by testing a sample of

the prepreg used to fabricate the laminate. The laminate in question is then tested to determine the partial heat of reaction. The DSC heating rate used to determine the baseline heat of reaction and partial heat of reaction must be the same. Typically a heating rate of 10°C per minute is used. The degree of cure is calculated as follows:

$$\alpha = 100 - \left(\frac{\Delta H_P}{\Delta H_T} \times 100 \right)$$

Where:

α is the percent degree of cure (ranges from 0% to 100% with 100% being fully cured)

ΔH_P is the heat of reaction released by the partially cured sample (laminate in question) expressed in Joules

ΔH_T is the total heat of reaction released by the uncured resin expressed in Joules (baseline)

Resin formulations commonly used in the aerospace industry rarely reach a degree of cure of 100%. Values of 95% to 98% are common. It should be noted that determining degree of cure by DSC is not considered the most repeatable test and is best limited to research investigations and not used as a production test. Depending on the circumstances, measurement of the glass transition temperature may be the best method to determine if a laminate is fully cured.

DER—Designated Engineering Representative. FAA designees authorized to approve engineering data.

differential scanning calorimetry (DSC), n—a technique in which the temperature difference between the substance and a reference material is measured as a function of temperature while the substance and reference material are subjected to a controlled-temperature program (ASTM E 473).

DMIR—Designated Manufacturing Inspection Representative. FAA designees authorized to conduct conformity inspections on behalf of the FAA.

end, n—in fabric, an individual warp yarn (single or ply) or cord (ASTM D 123).

ETD—Elevated Temperature Dry.

ETW—Elevated Temperature Wet.

FAA—Federal Aviation Administration.

fabric, n—in textiles, a planar structure consisting of yarns or fibers (ASTM D 123).

FEP, n—fluorinated ethylenepropylene.

> Discussion: fluorinated ethylenepropylene is a fluorocarbon polymer commonly known by its DuPont trade name Teflon® FEP.

fiber, n—in textiles, a generic term for any one of the various types of matter that form the basic elements of a textile and that is characterized by having a length at least 100 times its diameter (ASTM D 123).

fiber areal weight (FAW), n—the weight per area of the fiber reinforcement within a composite, expressed as grams per square meter or ounces per square yard. See also prepreg areal weight.

fiber content, n—the amount of fiber present in a composite expressed either as a percent by weight or percent by volume. This is sometimes stated as a fraction, that is, fiber volume fraction (ASTM D 3878).

fiber volume fraction (FV or V_f), n—see fiber content (ASTM D 3878).

filament, n—a fibrous form of matter with an aspect ratio >10 and an effective diameter <1 mm (ASTM D 3878).

fill, n—in a woven fabric, (1) the yarn running from selvage to selvage at right angles to the warp and (2) fiber inserted by the shuttle during weaving also designated as filling (ASTM D 3878, MIL-HDBK-17, and ASTM D 5687).

flip/flop, v—the process of alternating plies through an angle orientation of 180° during laminate lay-up. This practice is commonly used if the material of the same width as the laminate has a recurring flaw. The process changes the location of the flaw so that it does not unduly affect the laminate structure (ASTM D 5687).

glass transition, n—the reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from (or to) a viscous or rubbery condition to (or from) a hard and relatively brittle one (MIL-HDBK-17).

> Discussion: The glass transition generally occurs over a relatively narrow temperature region and is similar to the solidification of a liquid to a glassy state; it is not a phase transition. Not only do hardness and brittleness undergo rapid changes in this temperature region but other properties, such as thermal expansibility and specific heat, also change rapidly. This phenomenon has been called second order transition, rubber transition, and rubbery transition. The word transformation has also been used instead of transition. Where more than one amorphous transition occurs in a polymer, the one associated with segmental motions of the polymer backbone chain or accompanied by the largest change in properties is usually considered to be the glass transition (ASTM D 883).

glass transition temperature (Tg), n—the approximate midpoint of the temperature range over which the glass transition takes place (MIL-HDBK-17).

> Discussion: The glass transition temperature can be determined readily only by observing the temperature at which a significant change takes place in a specific electrical, mechanical, or other physical property. Moreover, the observed temperature can vary significantly depending on the specific property chosen for observation and on details of the experimental technique (for example, rate of heating and frequency). Three common methods for determining Tg are Thermal Mechanical Analysis, Differential Scanning Calorimetry, or Dynamic Mechanical Analysis.

knit, v—a textile process that interlocks, in a specific pattern loop, by means of needles or wires (ASTM D 3878).

knitted fabric, n—a cloth constructed by a knitting process (ASTM D 3878).

lamina, n—a subunit of a laminate consisting of one or more adjacent plies of the same material with identical orientation (ASTM D 3878).

laminate, n—any fiber or fabric-reinforced composite consisting of lamina (plies) with one or more orientations with respect to some reference direction (ASTM D 3878).

lamination, v—see consolidation.

laminate coordinate axes, n—a set of coordinate axes, usually right-handed Cartesian, used as a reference in describing the directional properties and geometrical structure of the laminate. Usually the x-axis and the y-axes lie in the plane of the laminate, and the x-axis is the reference axis from which ply angle is measured (ASTM D 3878).

laminate principal axis, n—the laminate coordinate axis that coincides with the direction of maximum in plane Young's modulus (ASTM D 3878).

lay-up, n—(1) the stack of plies in specified sequence and orientation before cure or consolidation; (2) the complete stack of plies, bagging material, and so on before cure or consolidation; and (3) a description of the component materials, geometry, and so on of a laminate (ASTM D 3878).

lay up, v—to stack plies of material in specified sequence and orientation (ASTM D 3878).

lay-up code, n—a designation system for abbreviating the stacking sequence of laminated composites (ASTM D 3878).

mandrel, n—a form, fixture, or male mold used as the base for production of a part in processes such as lay-up or filament winding (ASTM D 3878).

material form, n—the contour, arrangement, and structure of an unconsolidated composite material, especially with regard to the geometry and nature of the reinforcement. Factors considered part of the material form include, but are not limited to, reinforcement length (for discontinuous reinforcements), tow size or count, fabric areal weight, fabric style, reinforcement content, and ply thickness (ASTM D 3878).

matrix, n—the continuous constituent of a composite material, which surrounds or engulfs embedded filler or reinforcement (ASTM D 3878).

matrix content, n—the amount of matrix present in a composite expressed either as a percent by weight or percent by volume. Standard practice is to specify matrix content as weight percent (ASTM D 3878).

MIDO—Manufacturing Inspection District Office for the FAA.

MOL—Material Operational Limit.

mold, n—the support structure that holds the laminate or lay-up during laminate consolidation process (ASTM D 5687).

MRB—Material Review Board.

NIST—National Institute of Standards and Technology.

nondestructive inspection (NDI), v— to identify and measure abnormal conditions within a laminate without degrading or impairing the utility of the laminate.

nonperforated FEP, n—a nonporous fluorinated ethylenepropylene film used as a release film in the bagging lay-up.

> Discussion: fluorinated ethylenepropylene is a fluorocarbon polymer commonly known by its DuPont trade name Teflon® FEP.

nonperforated TFE, n—a nonporous tetrafluoroethylene film used as a release film in the bagging lay-up (ASTM D 5687).

> Discussion: tetrafluoroethylene is a fluorocarbon polymer commonly known by its DuPont trade name Teflon® TFE.

nonporous TFE-coated cloth, n—a cloth coated with tetrafluoroethylene used as a release material in the bagging process (ASTM D 5687).

nonwoven fabric, n—a cloth constructed by bonding or interlocking, or both (but not interlacing), fiber by any combination of mechanical, chemical, thermal, or solvent means (ASTM D 3878).

panel, n—a uniformly contoured composite laminate, typically flat (ASTM D 5687).

peel ply, n—a cloth with release capabilities, usually used in conjunction with laminates requiring secondary bonding (ASTM D 5687).

perforated FEP, n—a porous fluorinated ethylenepropylene film used in the bagging process that allows gasses or excess matrix materials to escape (flow) from a laminate during consolidation while protecting the laminate from physical bonding to other items such as caul plates.

perforated TFE, n—a porous tetrafluoroethylene film used in the bagging process that allows gasses or excess matrix materials to escape (flow) from a laminate during consolidation while protecting the laminate from physical bonding to other items such as caul plates (ASTM D 5687).

plied yarn, n—a yarn formed by twisting together two or more single yarns in one operation (ASTM D 3878).

ply, n—in laminar composites, the constituent single layer as used in fabricating or occurring within a composite structure (ASTM D 3878).

ply coordinate axes, n—a set of Cartesian coordinates, two of which lie within the plane of the ply, one axis of which is parallel to the principal fiber direction and the other axis perpendicular to the principal fiber direction (the third axis is through the ply's thickness) (ASTM D 3878).

ply count, n—in laminated composite materials, the number of plies or lamina used to construct the composite (ASTM D 3878).

ply orientation, n—the acute angle (theta) including 90° between a reference direction and the ply principal axis. The ply orientation is positive if measured counterclockwise from the reference direction and negative if measured clockwise (ASTM D 3878).

ply principal axis, n—the ply coordinate axis that coincides with the direction of maximum in plane Young's modulus. For balance weave fabric, either warp or fill direction may be chosen (ASTM D 3878).

polymer, n—an organic material composed of molecules characterized by the repetition of one or more types of monomeric units (MIL-HDBK-17).

polymerization, n—a chemical reaction in which the molecules of a monomer(s) are linked together in repeating units to form larger molecules (ASTM D 907).

porosity, n—a condition of trapped pockets of air, gas, or vacuum within a solid material, usually expressed as a percentage of the total nonsolid volume to the total volume (solid plus nonsolid) of a unit quantity of material (MIL-HDBK-17).

porous TFE-coated cloth, n—a porous cloth coated with tetrafluoroethylene used in the bagging process that allows gasses or excess matrix materials to escape (flow) from a laminate during consolidation. It differs from perforated TFE in that it gives a textured surface to the laminate (ASTM D 5687).

prepreg, n—a ready to mold or cure fibrous reinforcement impregnated with a polymeric matrix. Its form may be sheet, tape, or tow. For thermosetting matrices, it has been partially cured to a controlled viscosity called B stage (ASTM D 3878 and MIL-HDBK-17).

prepreg areal weight (PAW), n—the weight per area of the prepreg composite material, expressed as pounds per square foot or the inverse square feet per pound. Used as a conversion factor to convert prepreg area to prepreg weight. See also fiber areal weight.

Discussion: Prepreg areal weight is a function of resin content and fiber areal weight:

$$PAW = \frac{FAW}{1 - RC}$$

Where:

PAW is prepreg areal weight (g/m^2)
FAW is fiber areal weight (g/m^2)
RC is resin weight content (fraction, e.g., 0.33)

To convert g/m^2 to lb/ft^2 multiply by 204.81 x 10^{-6}.

reinforcement, n—in a composite material, the discrete constituent of a composite material, either fiber or particle, which is contained within the continuous matrix (ASTM D 3878).

resin, n—a solid or pseudosolid organic material, often of high molecular weight, which exhibits a tendency to flow when subjected to stress, usually has a high softening or melting range, and usually fractures conchoidally (ASTM D 3878).

resin content (RC), n—see matrix content (ASTM D 3878).

sealant, n—a high-temperature material used to seal the edges of a vacuum bag to a base plate during consolidation (ASTM D 5687).

selvage, n—the woven edge portion of a fabric parallel to the warp (ASTM D 3878).

single yarn, n—an end in which each filament follows the same twist (ASTM D 3878).

stacking sequence, n—the arrangement of ply orientations and material components in a laminate specified with respect to some reference direction (ASTM D 3878).

staggered, adj—the description of ply placement where the joints are not positioned in the same in-plane location through some specified thickness of the laminate (ASTM D 5687).

tape, n—prepreg material (typically unidirectional material) equal to or less than 24 inches in width. Also see broadgoods.

textile, n—a general term applied to fibers and organized assemblies of fibers with sufficient integrity to retain the organization (ASTM D 3878).

thermoplastic, n—a plastic that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and that in the softened state can be shaped by flow into articles by molding or extrusion for example (ASTM D 883).

thermoset, n—a class of polymers that, when cured using heat, chemical, or other means, changes into a substantially infusible and insoluble material (ASTM D 3878).

tow, n—in fibrous composites, a continuous, ordered assembly of essentially parallel, collimated filaments, normally without twist and of continuous filaments (ASTM D 3878).

traveler, n—a coupon with the same nominal thickness and, preferably, width as the test specimen, made of the same material, and processed similarly to the specimen except usually without tabs or gages. The traveler is used to measure mass changes during environmental conditioning when it is impractical to measure these changes on the actual specimen (ASTM D 5687).

traveler panel, n—(aka witness panel) a panel that is subjected to the same conditions as a part or group of parts to allow destructive testing to verify processing.

unidirectional, n—any fiber-reinforced composite with all the fibers aligned in a single direction. Both prepreg material and consolidated laminates can be described as being unidirectional.

vacuum bag, n—a low gas permeable material used to enclose and seal the lay-up during a consolidation or debulking cycle (ASTM D 5687).

vacuum couple, n—the mechanical connection that seals the vacuum source to the lay-up during a consolidation or debulking cycle (ASTM D 5687).

vitrification, n—the point during polymerization where the Tg of the polymer rises above the temperature of cure.

void, n—any pocket of enclosed gas or air within a composite (ASTM D 3878).

void content, n—the volume percentage of voids in a composite (ASTM D 3878).

warp, n—(1) the yarn running lengthwise in a woven fabric; (2) a group of yarns in long lengths and approximately parallel, put on beams or warp reels for further textile processing including weaving, knitting, twisting, dyeing, and so forth (ASTM D 3878).

warp surface, n—the ply surface that shows the larger area of warp tows with respect to fill tows (ASTM D 3878).

warp surface nesting, v—process of laying up fabric plies in an alternating pattern where the warp surface is placed up and then for the next ply the warp surface is placed down, thus nesting the plies.

weave, v—interlaces, in a specific pattern, strands or yarns orientated in two or more directions in a planar textile process (ASTM D 3878).

woven fabric, n —a cloth constructed by a weaving process (ASTM D 3878).

yarn, n—in fibrous composites, a continuous, ordered assembly of essentially parallel, collimated filaments, normally with twist, and either discontinuous or continuous filaments (ASTM D 3878).

APPENDIX A—EXAMPLE PROCESS SPECIFICATION

The appendix contains an example process specification for the fabrication of carbon fiber-reinforced epoxy composite test laminates. The example specification is based on the format defined in MIL-STD-961 as shown below.

- 1.0 Scope
- 2.0 Applicable Documents
- 3.0 Requirements
  - 3.1 Personnel
  - 3.2 Required Materials
  - 3.3 Required Equipment
  - 3.4 Facilities
  - 3.5 Tooling
  - 3.6 Required Procedures
- 4.0 Quality Assurance
  - 4.1 Responsibility for Inspection
  - 4.2 Inspection
  - 4.3 Documentation
  - 4.4 Test Methods
- 5.0 Notes

It should be noted that this format is not the only acceptable format and is provided as an acceptable format widely used in industry. The format defined by SAE is also widely used within industry.

While the example specification contains specific requirements, it is not implied that the specified requirements are the only acceptable requirements for the fabrication of quality composite laminates. Many requirements are a function of the specific material being processed, e.g., cure temperature and time. The requirements do not identify objective values for many requirements in this example; however, the more requirements that include objective values, the better the control.

As a rule, composite laminate fabrication process specifications are not stand-alone documents. They will reference companion specifications for processes that warrant process specifications in their own right. An example process that warrants its own specification is nondestructive inspection. The example process specification contains references to companion (or sub tier) specifications, and since it is an example, the companion specifications do not exist.

Example Process Specification for the
Fabrication and Acceptance of Carbon Fiber Reinforced Epoxy Composite Test Laminates

1.0 SCOPE

1.1 This specification establishes the requirements and procedures for the fabrication and acceptance of carbon fiber reinforced composite test laminates. Laminates processed in accordance with this specification are used in the qualification of new materials, establishment of mechanical property equivalency, or batch acceptance.

2.0 APPLICABLE DOCUMENTS

2.1 The following documents form a part of this specification to the extent specified.

ASTM D 792—Density and Specific Gravity (Relative Density) of Plastics by Displacement

ASTM D 3171—Constituent Content of Composite Materials

SACMA SRM 10—SACMA Recommended Method for Fiber Volume, percent Resin Volume and Calculated Average Cured Ply Thickness of Plied Laminates

SACMA SRM 18—SACMA Recommended Method for Glass Transition Temperature (Tg) Determination by DMA of Oriented Fiber—Resin Composites

3.0 REQUIREMENTS

3.1 Personnel

Fabrication of composite laminates shall be performed by qualified personnel who have passed both written and practical proficiency tests and possess the skills and job knowledge necessary to ensure acceptable workmanship.

3.2 Required Materials

This section lists the approved specific materials needed to perform the operations specified within this specification along with the specific trade names and sources.

3.2.1 Material Listing

a) Prepreg Test Material
b) Film Adhesive
c) Mold Release Agents—Bulk Liquid Wipe-On
d) Release Film—Nonporous Fluorinated Ethylene Propylene (FEP)
e) Release Film—Nonporous Teflon-Coated Glass Fabric

f) Release Fabric (Mold release coated)
g) Peel Ply—Nylon Fabric (uncoated)
h) Peel Ply—Polyester Fabric (uncoated)
i) Dam Materials—Sealant Tape
j) Dam Materials—Cork
k) Pressure Sensitive Tape—General Purpose
l) Pressure Sensitive Tape—Teflon Film
m) Pressure Sensitive Tape—Nonporous Teflon-Coated Glass Fabric
n) Pressure Sensitive Tape—Double Sided
o) Bleeder—Glass Fabric (style 120 and 7781)
p) Breather—Polyester Nonwoven
q) Nylon Vacuum Bag Film
r) Vacuum Bag Sealant Tape
s) Wiping Materials—Cotton Cloth Wipers
t) Wiping Materials—Cheesecloth, Cotton, Bleached
u) Wiping Materials—Paper and Synthetic Nonwoven Wipers
v) Synthetic Gloves
w) Barrier Hand Creams

3.2.2 Material Requirements

3.2.2.1 All prepreg and adhesive materials are required to have passed their applicable receiving inspection requirements as defined in the material specification and have been released for use.

3.2.2.2 Prepreg and adhesive materials that are frozen shall be warmed to ambient temperature for a minimum of two hours. Large rolls (in excess of 25 pounds) can require up to six hours to reach ambient temperature The materials are considered to be at ambient temperature when there are no traces of moisture or condensation on the outside of the polyethylene storage bag. During ply collation the prepreg and adhesive material shall be stored at ambient temperature in the environmentally controlled lay-up room in sealed polyethylene storage bags.

3.2.2.3 Splices are prohibited unless authorized by the requesting engineering documents.

3.2.2.4 Gaps between adjacent pieces of prepreg in the same layer and parallel to the fibers shall be kept to a minimum and shall not exceed 0.100 inches. Edge splice overlaps shall not exceed 0.030 inches. Edge splices of consecutive plies of the same orientation shall not be located directly over each other. They shall be staggered by at least 2.0 inches.

3.2.2.5 Prepreg plies containing defects shall be replaced.

3.2.2.6 Prepreg storage life and ambient exposure time shall be recorded and monitored to ensure compliance with the ambient working life requirements established in the applicable material specification.

3.2.2.7 Prepreg plies shall be handled in a manner to prevent damage.

3.2.2.8 Mold releases are not to be applied within the ply collation room or area.

3.3 Required Equipment

3.3.1 Equipment Listing

a) Vacuum source and supply (minimum of 22 inches of mercury)
b) Tool plate (also called base plate)
c) Caul Plate
d) Thermocouples
e) Reference bar (metal)
f) Cutting tools (knives or automated cutting system)
g) Work tables
h) Vacuum Ports—Through The Bag Fittings
i) Autoclave
j) Air Circulating Oven

3.3.1 Equipment Requirements

3.3.1.1 The autoclave shall be capable of holding the base plate with bagged lay-up. The autoclave shall be able to provide the required vacuum, pressure, and heat. The control system shall be calibrated on a defined schedule.

3.3.1.2 The oven shall be capable of holding the base plate with bagged lay-up. The oven shall be able to provide the required vacuum and heat. The control system shall be calibrated on a defined schedule.

3.3.1.3 Ensure the cutting system blade is sharp and working correctly. The prepreg material should not be distorted when being cut. If the material is being distorted, then the cutting blade is to be replaced.

3.4 Facilities Control

3.4.1 Collation and bagging of the laminate shall be performed in a controlled environment in accordance with a company process specification.

3.4.2 Airborne particles are to be kept at a minimum within the controlled lay-up environment. Filters are to be used within the air circulation system and are to be replaced on a defined schedule that ensures they perform as required. The floor shall be sweep twice during a work shift. All work surfaces are to be dusted at the same time the floors are swept.

3.5 Tooling

3.5.1 Base plate and caul plates shall be either aluminum or steel with a roughness of 125 RMS or less. The base plate should have a minimum thickness of 0.25 inches and a maximum thickness of 0.50 inches with a flatness tolerance of 0.002 inches.

The caul plate should have a minimum thickness of 0.125 inches and a maximum thickness of 0.25 inches with a flatness tolerance of 0.002 inches.

3.5.2 Metal reference bar shall be either aluminum or steel with a thickness equal or greater than the composite lay-up.

3.6 Required Procedures

3.6.1 Process Instructions

3.6.1.1 A detailed sequential fabrication procedure shall be generated for the fabrication of each item. The fabrication procedure shall contain inspection buy-off sequences in accordance with Section 4.2. The fabrication procedures shall contain provisions for the recording of the following information: material batch number, material date of manufacture, material cumulative ambient out time at time of cure, date of collation and cure, general observations of the prepreg material handling characteristics, tool identification number, type and method of applying tool mold release, technician identity, and environmental conditions within the lay-up room during ply collation.

3.6.2 Tool Preparation

3.6.2.1 Mold release shall be applied to all new reference bars, base plates and caul plates. Reapply the mold release if during its use panels begin to stick. Apply the mold release in accordance with the manufactures instructions. Apply a light coating of air-dry release agent to the tools before each lay-up operation. This coating is to be uniform, smooth, and free of streaks. A solid FEP release film may be placed on the tool surface in lieu of applying the air-dry release agent. Inspect the tools for gouges and imperfections that could transfer to the composite laminate. Repair the defects before using the tool.

THIS PROCESS SHALL NOT BE PERFORMED WITHIN THE LAYUP ROOM.

3.6.3 Material Preparation

3.6.3.1 Cut the required plies using an automated digital numerically controlled ply cutting system or by hand using templates. Record the prepreg ambient out-time at the time of ply cutting. Identify each ply.

3.6.4 Lay-up Procedure

3.6.4.1 Collate the prepreg plies in the sequence and orientation as specified in the process instructions. Take care to align the ply orientation to the reference edge tool bar. Use templates, laser projection devises, or overlays to assist in the collation process. Proper ply orientation is essential to generating quality test data.

3.6.4.2 Smooth the ply by hand or with a squeegee or roller. Remove the backing paper (or poly as applicable). Retain the backing paper for ply count verification after collation. Visually inspect the ply for foreign objects. Remove any foreign objects. Notate on the process instructions completion of the ply collation.

3.6.4.3 Continue with collation of the remaining plies. Take care to not trap air between subsequent plies by tacking the ply at one edge then working the ply down towards the opposite edge. Vacuum debulk the laminate stack every 4 plies. Debulk the prepreg as follows:

a) Place a layer of porous release material over the prepreg plies. Extend the layer beyond the boundaries of the laminate.

b) Place at least one layer of dry glass cloth or synthetic breather over the porous release material. Extend to the vacuum ports.

c) Place a nylon vacuum bag, sealed with vacuum bag sealant tape, over the laminate. A vacuum-debulking box may be used in lieu of the nylon vacuum bag.

d) Apply vacuum (22 to 29 inches of mercury) to the laminate for a maximum of ten minutes.

e) Remove vacuum debulking materials and continue ply collation.

3.6.4.4 After the last ply has been collated, place a glass yarn (string) along the edges of the laminate (except for the edge with the reference bar). Extend the glass yarn far enough to reach the area between where the edge dam will be located and the vacuum bag sealant tape.

3.6.4.5 Place the edge dam around the three remaining edges of the ply stack-up. Make sure the dam is in contact with the ply stack-up edge. Place one layer of FEP release film over the laminate. Extend the film beyond the dams. Seal the release film to the top of the edge dam.

3.6.4.6 Apply the caul plate on top of the release film. The caul plate should fit inside the edge dams.

3.6.4.7 Place dry fiberglass cloth or synthetic breather over the caul plate. Extend the breather material to just inside where the vacuum bag sealant tape will be located. Make sure the breather material covers the glass yarn from 3.5.4.4.

3.6.4.8 Prepare two dry fiberglass cloth vacuum port pads for inclusion into the bagging material stack-up. The vacuum port pads should be roughly 4 by 4 inches and four to six plies thick. Place the two vacuum pad ports on top of the breather material at opposite corners of the base plate. Place the bottom portion of the vacuum port on the port pads.

3.6.4.9 Place vacuum bag sealant tape around the periphery of the lay-up. Do not remove the paper release layer from the sealant tape at this time.

3.6.4.10 Place a nylon vacuum bag over the top of the entire lay-up. Extend the bag beyond the perimeter of the vacuum bag sealant tape. Tack the bag to top of the vacuum bag sealant tape on one side of the lay-up. Pull the bag tight and seal to the top of the remaining vacuum bag sealant tape sealing the vacuum bag on all four sides.

3.6.4.11 Attach the upper portion of the vacuum port to the lower portion by cutting a hole through the bagging film directly over the bottom portion at both locations. Attach a static vacuum gage at one of the ports and a vacuum line to the other vacuum port and slowly evacuate the bagged lay-up, making sure there are no wrinkles in the bagging film. Once the vacuum stabilizes at a minimum of 20 inches of mercury, perform a leak check.

3.6.4.12 Perform the leak check as follows:

a) Pull 20 to 29 inches of mercury vacuum,

b) Isolate the system, wait two minutes and record the initial vacuum level,

c) Wait two additional minutes and record the change (drop) in vacuum,

d) Acceptable leakage rate is less than 1.0 inches of mercury two minutes,

e) If the leakage rate is 1.0 inches of mercury or greater in two minutes, locate the leak and repair as required,

f) Repeat the leak check, until the acceptable leakage rate is achieved.

3.6.4.13 Transport the bagged assembly to the autoclave for cure.

3.6.5 Cure Procedure

3.6.5.1 Autoclave cure the panel as follows:

a) Place bagged assembly in the autoclave.

b) Hook up thermocouples and vacuum lines. Remove the static gage and hook up both vacuum ports. One line will be an active line, while the second line will function as the static line.

c) Pull 20 to 29 inches of mercury on the bagged assembly.

d) Perform the leak check of 3.6.4.12.

e) Increase the autoclave pressure to 80 ±5 psi. When the pressure reaches 25 psi, vent the vacuum to atmosphere.

f) When the pressure reaches 75 psi, increase the temperature to 350° ±10°F at 1° to 5°F per minute. Begin the hold when the coldest thermocouple reaches 340°F. Hold at 350° ±10°F for 120 to 140 minutes based on the coldest thermocouple in the autoclave run.

g) At the end of the hold at 350° ±10°F for 120 to 140 minutes, cool to 150°F in no less than 35 minutes.

h) Remove the assembly from the autoclave for unbagging.

3.6.5.2 Record the following information:

a) Cure serial number
b) Autoclave identification
c) Material (material specification and product name)
d) Batch and roll number
e) Cure date

3.6.6 Panel Identification

3.6.6.1 Identify each panel with its unique identification number.

3.6.7 Inspection

3.6.7.1 Inspect each panel as defined in Table 1.

Table 1 - Panel Inspection Requirements

Inspection Test	Sample Size	Number of Samples	Test Method
Cured Per Ply Thickness	Entire Panel	10 locations	4.4.1
Glass Transition Temperature	0.50 by 2.0 in.	Two	4.4.2
Resin Content	0.5 by 0.5 in.	Three	4.4.3
Density	0.5 by 0.5 in.	Three	4.4.4

3.6.7.2 Inspection requirements shall be as defined in the applicable material specification. Panels failing to meet the applicable requirements shall not be tested.

3.6.7.2 Nondestructively inspect each panel by Through Transmission Ultrasonics (TTU) in accordance with company procedures.

3.6.8 Machining

3.6.8.1 Machine the panel into test specimens as specified in the Engineering documentation.

4.0 QUALITY ASSURANCE

4.1 Responsibility for Inspection

The Quality Assurance Organization has the responsibility to ensure that the quality requirements specified in this specification are met. Quality Assurance shall verify that the fabrication of the composite is performed by qualified technicians.

4.2 Inspection

Quality Assurance shall perform the necessary inspections to verify the following procedures are performed in compliance with this specification.

4.2.1 Monitoring Procedures—Equipment

4.2.1.1 Quality Assurance shall survey ovens, autoclaves, freezers, and nondestructive inspection equipment monthly to assure proper calibration procedures have been performed.

4.2.1 Monitoring Procedures—Materials

4.2.2.1 Quality Assurance shall verify that the following requirements are met:

a) Only properly qualified prepreg materials are used in the fabrication

b) The plies are collated in the orientation specified in the engineering requirements document,

c) Splices and gaps within a ply are in accordance with 3.2.2.3 and 3.2.2.4,

d) The prepreg material is warmed to room temperature prior to the opening of the storage container in accordance with 3.2.2.2

e) The lay-up does not contain any visible foreign material contamination, and

f) The material ambient out-time is recorded in accordance with 3.2.2.6.

4.2.3 Monitoring Procedures—Facilities

4.2.3.1 Quality Assurance shall verify that the lay-up room is in accordance with 3.4.

4.2.4 Monitoring Procedures—Tooling

4.2.1.1 Quality Assurance shall verify that the tooling complies with the requirements of 3.5.

4.3 Documentation

4.3.1 Quality Assurance shall monitor and maintain records on the following information.

a) Prepreg batch and roll number
b) Prepreg cumulative freezer storage life and cumulative ambient out-time
c) Cure cycle information of 3.6.5.2
d) Inspection results of 3.6.7

4.4 Test Methods

4.4.1 Cured Per Ply Thickness—Determine cured per ply thickness in accordance with SACMA SRM 10.

4.4.2 Glass Transition Temperature—Determine glass transition temperature in accordance with SACMA SRM 18.

4.4.3 Resin Content—Determine laminate resin content in accordance with ASTM D 3171.

4.4.4 Density—Determine laminate density in accordance with ASTM D 792.

5.0 NOTES

None.

APPENDIX B—TYPICAL PROCESSING PARAMETER TOLERANCES

Parameter	Typical Application	Tolerance
temperature	cure temperature	±10°F
pressure	autoclave pressure during cure cycle	±5 psig
time	length of cure	-0, + 15 minutes
vacuum	vacuum level during cure cycle	±2 inches of Hg
angle	ply orientation	±2°