Polymer-Based Additive Manufacturing Guidance for Aircraft Design and Certification

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JAMS 2019 Technical Review
May 22 - 23, 2019
Motivation and Key Issues

- Additive Manufacturing is expanding at a high rate
- Process sensitive material (like composites) → Variability and repeatability are common issues not well understood
- Process control has shown to be an issue across all platform types
- Sources of variability are both material and process based
- No substantial database exists
The NCAMP Approach for Polymer AM

- Additive Manufacturing is quickly moving from development → production
  - Reliable design allowables are required
  - Process for generating allowables is critical
  - Working with industry and regulators provides a unique perspective on allowable development, status and issues.
- NCAMP is a proven process for allowables
- Equivalency aspect allows manufacturers to qualify installations

No existing public qualification of an additive material prior to this program.
Tasks

• Initial Qualification Program
  – Overview of materials, process
  – Test plan
  – Data generated
  – Statistics
  – Publication
  – Transition plans
  – Equivalency status

• Future Qualification Programs

• Related R&D efforts
  – Test method development
  – Scaling studies
  – Machine processing windows
Technical Approach

- **FAA Technical Monitor**: Ahmet Oztekin
- **FAA AVS Sponsor**: Cindy Ashforth

- Develop a framework to advance polymer-based additively manufactured materials into the aerospace industry.
- Utilize the experience and framework of the NCAMP composite program as an example of process sensitive material characterization.
- Assess the validity with equivalency testing.
- *Note: Program is in collaboration with America Makes (see objectives on following slide)*

**TASK 1:** Establish Steering Committee

**TASK 2A:** Develop Qualification Framework

**TASK 2B:** Validate framework with selected Polymer AM material

**TASK 3:** Establish statistical guidelines

**TASK 4:**
- Transition
- Data and guidance to CMH-17
- Specifications to SAE
- Test methods to ASTM

**Current Focus of Project**

9/2016 - 12/2016

11/2016 - 3/2017

3/2017 - 12/2018

10/2017 – 2/2019

3/2018 – 5/2019

COMPLETE
America Makes - Project Overview

- **Problem Statement:**
  ULTEM\textregistered 9085 is a polyetherimide high performance thermoplastic material with an acceptable strength-to-weight ratio and flame, smoke and toxicity (FST) rating. This material is often used in aerospace where a high strength thermoplastic material is needed. As this material is one of the only high performance thermoplastic materials available for Fused Deposition Modeling, it is important to establish a complete database of material properties to further enable use in various commercial and government applications. Such a database is a minimum requirement for deployment of an additively manufactured solution in a production environment.

- **Objectives:**
  1) Ensure Process Control and create documentation;
  2) Identity and publish appropriate test matrix for process/material combination;
  3) Fabricate test coupons;
  4) Complete testing and publish results.

- **Project Benefits:**
  Completed database to allow membership to exploit for commercial applications; Framework for future materials/processes will be completed and available to membership; Equivalency process will be defined for member to utilize outcomes in house.

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America Makes Announces Complete, Qualified Database of Material Properties for Fused Deposition Modeling\textregistered (FDM\textsuperscript{®}) Additive Manufacturing of ULTEM\textsuperscript{™} 9085 Resin

*Database Released to the Institute and Its Membership Community to Enable the Widespread Use of ULTEM\textsuperscript{™} 9085 Resin for Aerospace Interiors*

Youngstown, Ohio — February 6, 2019. America Makes proudly announces that Gold-level member, Rapid Prototype + Manufacturing LLC. (rp+m), has delivered a first of its kind, comprehensive UTLEM\textsuperscript{™} 9085 Type I Database for Fused Deposition Modeling\textregistered (FDM\textsuperscript{®}) Additive Manufacturing (AM) to America Makes and its membership community with the goal of furthering the use of the Type I certified material for aircraft interior components.

“The qualification of the ULTEM 9085 material and the establishment of the material properties database by the rp+m-led team are huge steps forward for AM, particularly...
Technical Approach and Methodology

- Demonstrate machine repeatability through process specification implementation.
- Quantify material variability through process.
- Quantify other design variables through process (environmental conditions, build location, build orientation, etc...)

CECAM

JAMS

AMTAS
TASK 2: Qualification & Equivalency Overview

QUALIFICATION

ULTEM 9085 Qualification Builds
3 Batches / 2 Machines at RP+M

Qualification Testing at NIAR

Build #1 SDM
Build #2 Lockheed
Build #3 TBD
Build #4 TBD

ADDITIONAL BUILDS

Equivalency/Additional Testing

NOTES

• All qualification and equivalency coupons to be built on Fortus 900 MC machines.

• Additional Builds
  • Phase 1 = Equivalency: Standard equivalency matrix, 1 lot only, will be same as one of the original lots for initial program
  • Phase 2 = Additional Testing: Tests not part of qualification database

* Outside of current project scope, but NIAR project deliverable will allow or equivalency process for future use by any party with the appropriate equipment and process.

TEST

Statistical Analysis

Baseline Qualification Database

ANALYZE/PUBLISH
Controlling the process is essential to success.

NCAMP DOCUMENTATION

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**STATUS**

- Final drafts of material and process specs - complete
- Build and Pack files included to reduce variation.
- Qual and Equiv. Test Plans finalized
- Site Inspections
  - Qual.: complete
  - Equiv.: complete
- Builds and tests complete for both Qual. And Equiv.
- Reports are complete and released
24 SPECIMENS TOTAL

Methodology repeated for each orientation

Notes:
- 2 Machines are required for qualification however 3 or more are recommended.
- Extra specimens should be tested for each property and temperature as “spares” to ensure desired quantity (min of 3 specimens).
**Test Matrix**

<table>
<thead>
<tr>
<th>QUALIFICATION TESTS</th>
<th>EQUIVALENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>Tensile Strength</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>Compressive Strength</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>Flexural Strength</td>
</tr>
<tr>
<td>Shear</td>
<td>Shear</td>
</tr>
<tr>
<td>Open Hole Tension</td>
<td>Open Hole Tension</td>
</tr>
<tr>
<td>Filled Hole Tension</td>
<td>Open Hole Compression</td>
</tr>
<tr>
<td>Open Hole Compression</td>
<td></td>
</tr>
<tr>
<td>Filled Hole Compression</td>
<td></td>
</tr>
<tr>
<td>Single Shear Bearing Strength</td>
<td></td>
</tr>
</tbody>
</table>

Tests performed at CTD, RTD, RTW, ETW conditions.

Trial studies were conducted to define shear and compression test methods with ISC input.
Table 3 FFF AM Material Mechanical Tests

<table>
<thead>
<tr>
<th>Test Type and Direction</th>
<th>Property</th>
<th>Number of Batches x Number of Machines x Number of Coupons</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM D638 (type 1) Tension X (2)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 1x2x4 (5) 3x2x4</td>
</tr>
<tr>
<td>ASTM D638 (type 1) Tension Y (2)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 1x2x4 (5) 3x2x4</td>
</tr>
<tr>
<td>ASTM D638 (type 1) Tension Z (2)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 1x2x4 (5) 3x2x4</td>
</tr>
<tr>
<td>ASTM D638 (type 1) Tension Z (45) (2)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 1x2x4 (5) 3x2x4</td>
</tr>
<tr>
<td>ASTM D695 modified (type 6.7.2) Compression X (1)(2)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 1x2x4 (5) 3x2x4</td>
</tr>
<tr>
<td>ASTM D695 modified (type 6.7.2) Compression Y (1)(2)</td>
<td>Strength and Modulus</td>
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<td>3x2x4 3x2x4 1x2x4 (5) 3x2x4</td>
</tr>
<tr>
<td>ASTM D695 modified (type 6.7.2) Compression Z (45) (1)(2)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 1x2x4 (5) 3x2x4</td>
</tr>
<tr>
<td>ASTM D790 Flex X (2)(6)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 3x2x4</td>
</tr>
<tr>
<td>ASTM D790 Flex Y (2)(6)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 3x2x4</td>
</tr>
<tr>
<td>ASTM D790 Flex Z (2)(6)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 3x2x4</td>
</tr>
<tr>
<td>ASTM D790 Flex Z (45) (2)(6)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 3x2x4</td>
</tr>
<tr>
<td>ASTM D5379 V-notch In-Plane Shear X (2)(3)(4)</td>
<td>Strength and Modulus</td>
<td>3x2x4 3x2x4 1x2x4 (5) 3x2x4</td>
</tr>
</tbody>
</table>

Note 1: Back-to-back strain gauges may be used on the first two specimens. If no buckling is observed, the
<table>
<thead>
<tr>
<th>Test Type</th>
<th>Test Type (6)</th>
<th>Property</th>
<th>Number of Batches x Number of Machines x Number of Coupons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Test Temperature/Moisture Condition</td>
</tr>
<tr>
<td>OHT</td>
<td>ASTM D5766 Open Hole Tension X (1)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>OHT</td>
<td>ASTM D5766 Open Hole Tension Y (1)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>OHT</td>
<td>ASTM D5766 Open Hole Tension Z (1)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>OHT</td>
<td>ASTM D5766 Open Hole Tension Z (45) (1)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>FHT</td>
<td>ASTM D6742 Filled Hole Tension X (2)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>FHT</td>
<td>ASTM D6742 Filled Hole Tension Y (2)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>FHT</td>
<td>ASTM D6742 Filled Hole Tension Z (2)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>FHT</td>
<td>ASTM D6742 Filled Hole Tension Z (45) (2)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>OHC</td>
<td>ASTM D6484 Open Hole Compression X (1,3)</td>
<td>Strength</td>
<td>3x2x4 (5)</td>
</tr>
<tr>
<td>OHC</td>
<td>ASTM D6484 Open Hole Compression Y (1,3)</td>
<td>Strength</td>
<td>3x2x4 (5)</td>
</tr>
<tr>
<td>OHC</td>
<td>ASTM D6484 Open Hole Compression Z (1,3)</td>
<td>Strength</td>
<td>3x2x4 (5)</td>
</tr>
<tr>
<td>OHC</td>
<td>ASTM D6484 Open Hole Compression Z (45) (1,3)</td>
<td>Strength</td>
<td>3x2x4 (5)</td>
</tr>
<tr>
<td>FHC</td>
<td>ASTM D6742 Filled Hole Compression X (2,3)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>FHC</td>
<td>ASTM D6742 Filled Hole Compression Y (2,3)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>FHC</td>
<td>ASTM D6742 Filled Hole Compression Z (2,3)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>FHC</td>
<td>ASTM D6742 Filled Hole Compression Z (45) (2,3)</td>
<td>Strength</td>
<td>3x2x4</td>
</tr>
<tr>
<td>SSB</td>
<td>ASTM D5961 Single Shear Bearing X (4)</td>
<td>Strength &amp; Deformation</td>
<td>3x2x4</td>
</tr>
<tr>
<td>SSB</td>
<td>ASTM D5961 Single Shear Bearing Y (4)</td>
<td>Strength &amp; Deformation</td>
<td>3x2x4</td>
</tr>
<tr>
<td>SSB</td>
<td>ASTM D5961 Single Shear Bearing Z (4)</td>
<td>Strength &amp; Deformation</td>
<td>3x2x4</td>
</tr>
<tr>
<td>SSB</td>
<td>ASTM D5961 Single Shear Bearing Z (45) (4)</td>
<td>Strength &amp; Deformation</td>
<td>3x2x4</td>
</tr>
</tbody>
</table>

(1) Open hole configuration: 0.25” hole diameter, 1.5 inch length
TASK 2: Qualification and Equivalency Printing


Date: March 28-30, 2017

Status: Complete with minor corrective actions closed.


**TASK 2: Examples – Dispositioned versus Acceptable Specimens**

Dispositioned

Acceptable

*Sample dispositioning has occurred at all 3 printing locations throughout the coupon manufacturing process.*
Qualification Specimens: (2846 specimens) - Complete

2 Major set backs (one on each machine) pushed back forecasted timeline considerably

- Issue #1: Machine 1 – tip and tip wipe setup errors
- Issue #2: Machine 4 – under filled specimens due to head output issues

Limited tests on re-built specimens are complete.

Equivalency Printing: (504 specimens each) - Complete

- Site 1: Stratasys Direct Manufacturing
- Site 2: Lockheed Martin MFC Orlando

Limited tests on re-built specimens are in progress.
Task 3: Development of statistical guidelines

GOAL: Understanding of how parameters interact and affect variability as well as final allowables.

- Establish qualification statistical requirements. The factors affecting variability will be assessed during this task.
- Establish equivalency requirements including specification minimums for acceptance.
- **Status – statistical analysis report is complete**
Statistical Analysis Approach

• CMH-17 Unstructured (no significant differences between batches, machines, production sites, etc.)
  – Normal distribution
  – Lognormal distribution
  – Weibull distribution
  – Non-parametric – no underlying distribution assumed

• CMH-17 Structured
  – ANOVA analysis with each machine-batch combination treated as separate group

• Modified CV (not yet evaluated with respect to AM)
  – Increases CV to a set percentage of the property mean
  – Included in the statistical analysis report

• Multivariate Generic Approach
  – This is a new approach and is not included in statistical analysis report
# Example Basis Values Table Using CMH-17 Methods

## Dogbone Tension (DT) Basis Values and Statistics - CTD Condition

<table>
<thead>
<tr>
<th></th>
<th>0.2% Offset Yield Strength</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std dev</td>
<td>0.710</td>
<td>0.499</td>
</tr>
<tr>
<td>Max</td>
<td>8.917</td>
<td>8.582</td>
</tr>
<tr>
<td>Batches</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Machines</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. Spec.</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

## Basis Values and Estimates

<table>
<thead>
<tr>
<th></th>
<th>Basis Values and Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B-Basis</td>
</tr>
<tr>
<td></td>
<td>5.398</td>
</tr>
<tr>
<td></td>
<td>6.868</td>
</tr>
<tr>
<td></td>
<td>5.149</td>
</tr>
<tr>
<td></td>
<td>6.066</td>
</tr>
<tr>
<td></td>
<td>6.046</td>
</tr>
<tr>
<td></td>
<td>11.733</td>
</tr>
<tr>
<td></td>
<td>11.879</td>
</tr>
<tr>
<td></td>
<td>8.648</td>
</tr>
<tr>
<td></td>
<td>9.374</td>
</tr>
</tbody>
</table>

## Modified CV Basis Values and Estimates

<table>
<thead>
<tr>
<th></th>
<th>Modified CV Basis Values and Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B-Basis</td>
</tr>
<tr>
<td></td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>6.007</td>
</tr>
<tr>
<td></td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>11.728</td>
</tr>
<tr>
<td></td>
<td>8.612</td>
</tr>
<tr>
<td></td>
<td>9.307</td>
</tr>
<tr>
<td></td>
<td>8.294</td>
</tr>
</tbody>
</table>
The Z45-axis dataset for batch A, machine 1 had unusually low values for both the 1% offset and the 0.2% offset in ETW1 condition.

Build specific differences/variations are being examined currently to understand driving factors to refine specification and inspection methods.
V-Notch In-Plane Shear
Specimen plots with outliers and basis values

Additively Manufactured Polymer Material / Stratasys ULTEM 9085
V-Notch In-Plane Shear (VIPS) X-axis Strength

Strength at 5% Strain

0.2% Offset Strength

CTD B-Basis (Normal)
RTD B-Basis (Lognormal)
RTW B-Estimate (Normal)
Flex Specimen plots with outliers and B-Basis values

- Flex strength shows example of orientation specific trends and behaviors consistent across all temperatures.
NCAMP Reports – Published on 4/17/2019

- ULTEM 9085 NMS 085 (NCAMP Material Base Specification)
- ULTEM 9085 NMS 085/1 (NCAMP Material Slash Specification)
- ULTEM 9085 NPS 89085 (NCAMP Process Specification)
- ULTEM 9085 Material Data Report
- ULTEM 9085 Qualification Statistical Analysis Report

https://www.wichita.edu/research/NIAR/Research/ultem9085.php
Task 4: Guidelines and Recommendations

GOAL: To provide guidance to industry for the collection of statistically meaningful critical data that designers need to utilize polymer-based additive manufacturing materials potentially including:

• Creation of a shared polymer AM database including test data, material and process specifications and statistical analysis methods.

• Development of handbook data and guidelines (i.e., CMH-17) – new Volume started in October 2018

• Coordinate with SAE to develop specifications from this program – Ongoing activity through the SAE AMS-AM non-metallic committee (AMS 7100 and 7101)

• Coordinate with ASTM and NIST on test method development and modification – ongoing and being coordinated through the ASTM Center of Excellence, F42, and D20

• Collaborate with other organizations as needed
The CMH-17 Organization

- **The Exec Committee**
  - Sets goals and priorities for the handbook
  - Establish knowledge transfer forum for evolving and mature handbook content

Each Executive Committee consists of Working and Task Group Chairs

- **Handbook Chairpersons**
  - PMC Executive Committee
  - CMC Executive Committee
  - MMC Executive Committee
  - AM Executive Committee

- **Secretariat**

- **Data Review**
  - John Tomblin, NIAR
  - Douglas Greenwood, FRC East (NAVAIR)

- **Design & Analysis**
  - Sung Park, NGC
  - Chris Woken, Stratasys

- **Materials & Processes**
  - Chris Holshouser, NIAR
  - Sam Cordner, NASA

- **Testing**
  - Royal Lovingfoss, NIAR
  - Brian Kitt, Spirit

- **Statistics**
  - Beth Clarkson, NIAR
  - Curt Davies, FAA

- **Guidelines**
  - TBD
SAE AMS-AM

Spec's

- FFF Process Specification 7100
- FFF Material Specification 7101

Slash Sheets

- FFF Process Specification 7100/1 Fortus MC-900+
- FFF Material Specification 7101/1 ULTEM 9085

Equals

General Specifications Defines Detailed Specification Requirements

NCAMP Dataset

= Equivalence Question

Allows for the Standardization of a Fixed Process

CECAM

AMTAS

Advanced Materials in Transport Aircraft Structures

JAMS

Joint Advanced Materials & Structures Center of Excellence

NIAR

National Institute for Aviation Research
ASTM (F42 and D20)

- Supporting ASTM F42 and D20 on mechanical test considerations
  - Rationale: The guide(s) will be used to augment the set of standards used for mechanical performance characterization of polymer AM materials so that process induced nuances can be accounted for prior to starting a qualification or testing program. Users consist of machine operators, printer OEMs, testing houses, ASTM sub-committee members, technology adopters/type-certification holders, and certification regulators.
- New guide will cover several test methods
- Best practices will be documented
- Selected test methods will be studied through a round robin test program
  - Alternative specimen geometries
  - Modified test fixtures
  - Machined vs As Printed specimens
  - Combinations of above
Looking forward

• Benefit to Aviation
  – First AM qualification database with M&P specs
  – Understanding of relevant considerations – how to qualify an AM process, parameters, sources of variability

• Future needs
  – Perform qualification on other AM materials, including filled/reinforced AM or other processes (PBF)
  – Machine Variability – parameter-structure-property mapping & machine type investigation
  – Building Block – coupon properties correlation to part performance
  – Demonstrate framework applicability to metallic AM