Wichita State University

National Institute for Aviation Research

WHERE TEST PLANS BECOME RESULTS

Polymer-Based Additive Manufacturing Characterization and Qualification Guidelines for Aircraft Design and Certification

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Wichita State University
National Institute for Aviation Research
September, 2017

No restrictions on this briefing.

WSU-NIAR

NIAR Headquarters

Wichita State University
1845 Fairmount St, Wichita

Aircraft Structural Test & Evaluation Center

Kansas Coliseum
1229 E. 85th St N, Park City

National Center for Aviation Training

4004 N Webb Rd, Wichita

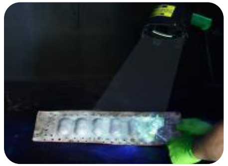
Electromagnetic Effects & Environmental Test Labs

Air Capital Flight Line
3501 S Oliver St, Wichita

NIAR LABORATORIES

Advanced Coatings

Aging Aircraft



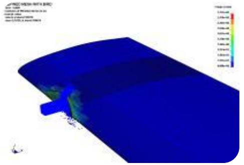
Ballistics/ Impact

CAD/CAM

CIBOR

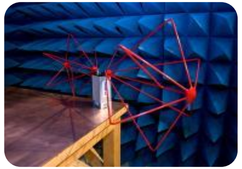
Composites

Computational Mechanics



Crash Dynamics

Electromagnetic Effects



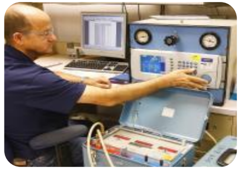
Environmental Test

Full-scale Structural Test

Human Factors

Mechanical Test

Metrology



NDT

Oil Analysis

Research Machine Shop

Reverse Engineering

Virtual Reality

Beech Wind Tunnel

NIAR ranks #1 in US Industry Funded Aero R&D

Referring to - National Science Foundation

AGENDA

- AM Design Allowables
- Polymer AM Program Overview
  - Major tasks/milestones/deliverables
  - Ties to CMH-17 and SAE
- Overview of NCAMP
- Observations and Lessons Learned
- New SAE Committee on Polymer AM
- Going Forward

AM Design Allowables

Design Allowable Development

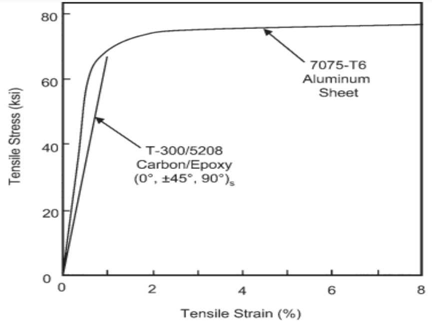
- Additive Manufacturing is quickly moving from development to production and thus highlighting the need for reliable design allowables

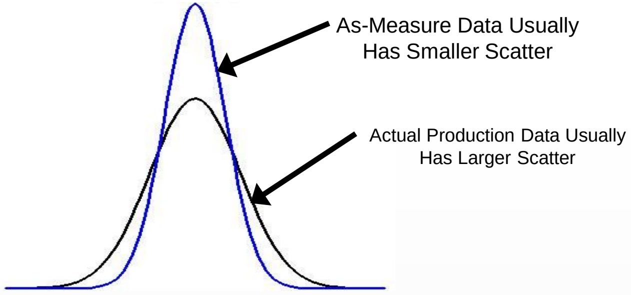
  - *Understanding the process for generating these allowables is as important as understanding the basic AM processes*

- *Disclaimer - Any reference to FAA and/or EASA policy is only this authors perspective any and formal guidance should come directly from the requisite Certification Office.*

Design Allowable Status

- Material behavior and variability varies widely between material types, processes and machines.
- Additively manufactured materials are relatively new and have not been extensively studied in terms of factors affecting variability.
- AM contains more process variables that can have an effect on process variability
- Experience with other process dependent materials, like composites, shows that we need to generate a substantial amount of data to properly characterize the behavior and create statistical guidance.





Source: Structural Composite Materials, F.C. Campbell

Little Standard Public Data Available

Transitions in Manufacturing

- Material Based - Conventional
  - Purchase stock material, cut, machine, bend form, etc,
  - Not much variation in material, good understanding how the process and the addition of design features affect part performance
    - Standard and well practiced QA
  - Companies invest in feature based design allowables - DRM
    - Bend, fillet radius, fastener spacing, splice joint configurations, standard extrusions, etc…
  - Scales easily to production and site to site.

- Process Based - AM
  - Little general understanding of the material and part to part variations
    - Process optimized to specific part
    - Little understanding of process changes
    - Subjective QA
    - Part is typically certified as a point design
  - Companies store lessons learned and try and extrapolate part knowledge to processes controls.
    - Little information on how design and build features affects material performance.
  - Processes difficult to scale and replicate

AM Shifts Sources of Variability

- Material Based → Process Based
  - Material is produced in large batches
  - Easy to verify and replicate
  - Process for making parts has little effect on the material variation

Process Based

- Makes parts - not material in small batches
- The batch is were most of the process variation is introduced
- More difficult to predict part performance.

AM Combines part and material variation

Polymer AM Program Overview

Technical Approach

- FAA sponsored program to 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.

9/2016 - 12/2016
TASK 1:
Establish Steering Committee

11/2016 - 3/2017
TASK 2A:
Develop Qualification Framework

3/2017 - 12/2018
TASK 2B:
Validate framework with selected Polymer AM material

10/2017 – 12/2018
TASK 3:
Establish statistical guidelines

3/2018 – 12/2018
TASK 4:
Transition
-Data and guidance to CMH-17
- Specifications to SAE

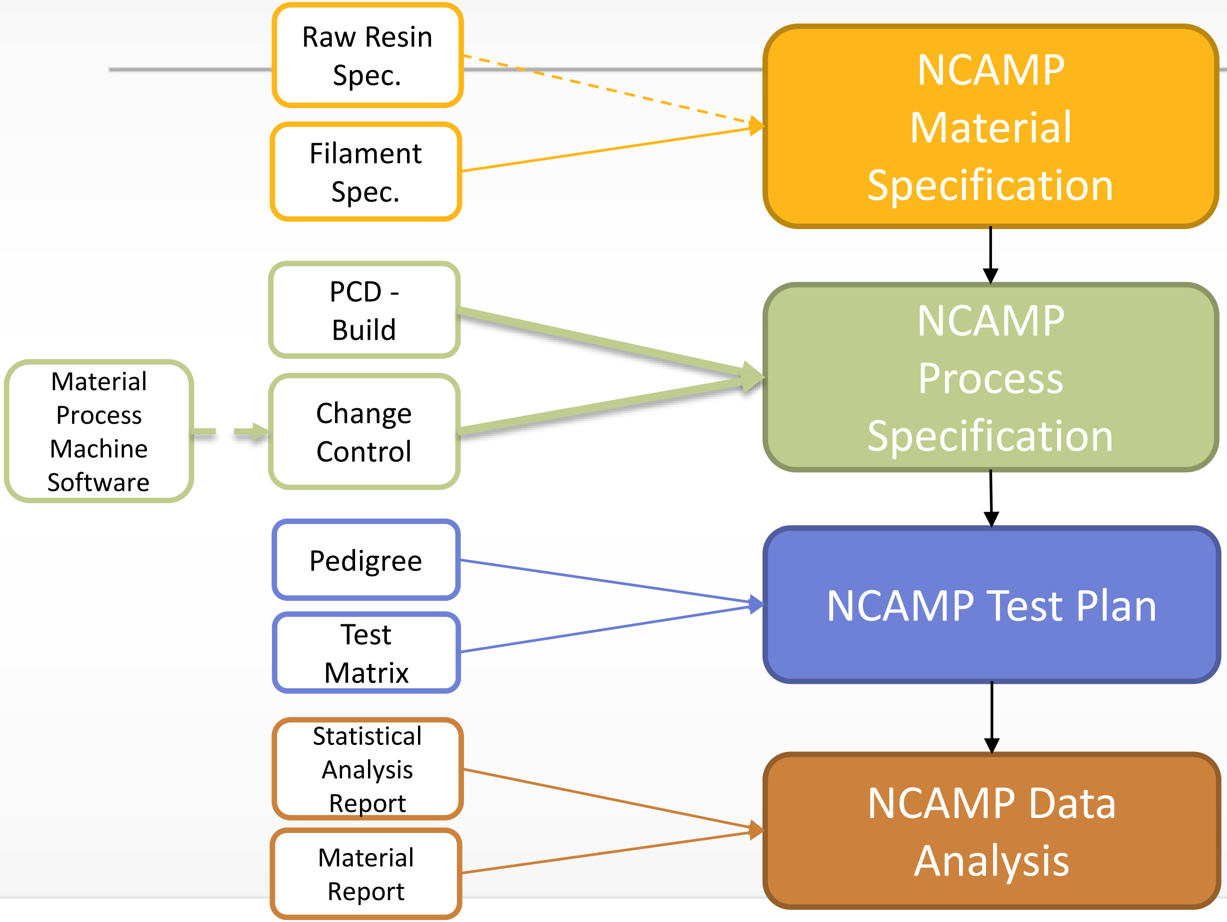
TASK 1: Steering Committee

- Kick off meeting August 2016 – in conjunction with CMH-17 PMC Meeting in St. Paul, MN
- 34 Members
- Monthly telecons and/or updates
- Reviews of test matrix and methods, build layout, test plan
- Input on program direction, AM expertise
- Agreed on first Material/Process (FDM – Ultem 9085)
- Web page - established
- Will continue coordination through end of program

TASK 2A: Qualification Framework

- Specifications
- Test Plan – Qualification and Equivalency
- Conformity Documentation
- Pedigree Template

NCAMP DOCUMENTATION STATUS



STATUS

- Final drafts of material and process specs are complete
- Build and Pack files included to reduce variation.

- Test Plan finalized
- Equivalency test plan being drafted
- Site Inspections – complete

Controlling the process is essential to success.

Material Specification

- **NMS 085** – Aerospace Filament Specification (ULTEM 9085)
- Released in draft form on March 22, 2017
- Establishes requirements for manufacturing of FDM filament
  - PCD
  - Material
  - Qualification – in process canister and filament material properties (test methods and acceptable values)
  - Storage, handling, traceability
- Slash Sheet – to include spec limits – will be drafted after qual data

Material Specification - BASE

NCAMP
NATIONAL CENTER for ADVANCED MATERIALS PERFORMANCE

Document No.: NMS 085, Revision -, March 22, 2017

NCAMP Material Specification
This specification is generated and maintained in accordance with NCAMP Standard Operating Procedures, NSP 100

Aerospace Filament Specification (ULTEM 9085)
(Stratasys - SSYS)

TABLE I – IN-PROCESS CANISTER MATERIAL PROPERTY REQUIREMENTS

Properties	Test Method	Unit	Class	Requirements
Pull force (7.1)	SSYS 106194-0000	lbs	I & II	Pull force spikes less than or equal to 1.75 lbs*
Moisture (7.3)	ASTM D7191	%	I & II	< or = 0.04%
Melt Flow (7.4)	ASTM D1238	g/10 min	I	6.5-11.0 g/10 min
		g/10 min	II	16.0-20.0 g/10 min

*Pull force spikes up to 3.75 lbs are acceptable provided they meet the following criteria: Length of spike above 1.75 lbs does not exceed 3 feet; length of spike above 2.75 lbs does not exceed 1 ft

TABLE II – IN-PROCESS FILAMENT MATERIAL PROPERTY REQUIREMENTS (SECTION 7.2)

Class	Diameter, Average (in)	99.73% of Diameter readings in range (in)	Diameter, min. (LSL) (in)	Diameter, max. (USL) (in)	Ovality, max. (in)	Diameter exceptions – local flaw, max. (in)*
I	0.07070 +/- 0.00040	0.0679 to 0.0735	0.0675	0.0739	0.0028	0.0739 diameter x 0.60 length
II	0.07070 +/- 0.00040	0.0679 to 0.0735	0.0675	0.0739	0.0028	0.0750 diameter x 0.150 length

* Exceptions shall be included in the calculations for diameter average and shall be included in the requirement that 99.73% of diameter reading fall within the given range.

8.4. MELT FLOW RATE

The melt flow rate (MFR) is determined with respect to ASTM D1238 using temperatures and loads defined in TABLE III. Material will have moisture content meeting limits defined in TABLE II prior to testing.

TABLE III – MELT FLOW INDEX TESTING PARAMETERS

Class	Mass (kg)	Dwell (s)	Cut time (s)	Number of Cuts	Time Reference (s)	Temp. (ºC)	MFI (g/10 min)
I	6.6	360	20	3	600	295	6.5 – 11.0

Process Specification

- **NPS 89085** – Polymer Additive Manufacturing Materials, Machine, Processing and Quality Requirements Specification for ULTEM 9085™ and Stratasys Inc. Fortus 900mc Machine
- Released in draft form on March 27, 2017
- Describes methods of fabricating test coupons using aerospace certified ULTEM 9085 on Fortus 900 MC Plus
- Established required processing for: constituent material, configuration of machine, operating software, machine calibration, machine and build parameters, acceptance criteria

Process Specification

NATIONAL CENTER for ADVANCED MATERIALS PERFORMANCE

Document No.: NPS 89085, Revision -, March 27, 2017

NCAMP Process Specification
This specification is generated and maintained in accordance with NCAMP Standard Operating Procedures, NSP 100

Polymer Additive Manufacturing Materials, Machine, Processing and Quality Requirements Specification for ULTEM 9085™ and Stratasys Inc. Fortus 900mc Machine

Appendix A: NCAMP Coupon Build information

The following information shall be utilized for any NCAMP material testing. Any deviation to the build definitions provided will result in non-conforming coupons which may not be acceptable. For a more complete definition of the test requirements please refer to the NCAMP test plan.

Table 11. .CMB Files for Coupon Fabrication

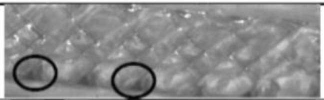
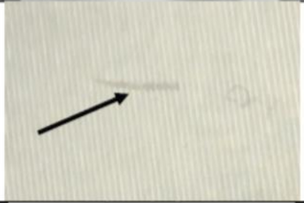
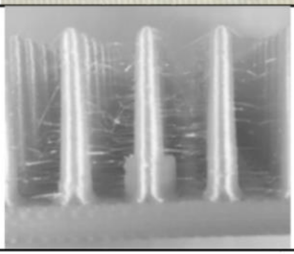
Test	Properties	Method	Type	ASTM F2921 Orientation	CMB Name
Tensile	Modulus, UTS, EAB, Poisson, Yield	ASTM D638	Type 1 T = 0.130"	XZ, XY, ZX, ZX-45	• D638_XY_T16A.cmb • D638_XZ_T16A.cmb • D638_ZX_T16A.cmb • D638_ZX45_T16A.cmb
Flex	Modulus, UFS	ASTM D790	NA	XZ, XY, ZX, ZX-45	• D790_XZ_T16A.cmb • D790_XY_T16A.cmb • D790_ZX_T16A.cmb • D790_ZX45_T16A.cmb

Table 2: Software Revisions

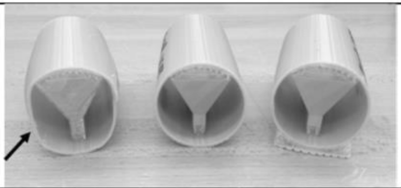
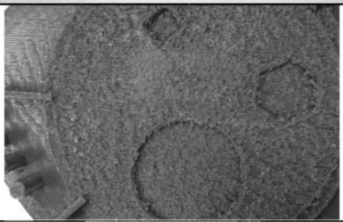
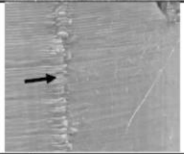
Number	Revision Description
Pre-Processing Software: Insight Version 11	Contains T16A for U9085 CG material on Fortus 900mc Plus in Modeler dropdown menu.
Controller Software Version: 3.20.2816.1	Contains the T16A upgrade with High Quality build mode. ActiveWipeTime returns non-4 digit number, InActiveWipeTime returns a value "0".

Note: The software for the Fortus 900 Plus machines are provided by Stratasys Inc.

Process Specification

Anomalies	Picture / Figure
Porosity	
Stairstepping	
Scratches	
Stringing	

Example of acceptable anomalies

Defects	Picture / Figure
Warpage	
Curl	
Overfill	
Heavy Seams	

Example of unacceptable anomalies

Test Plan

- **NTP AM-P-001** – Material Property Data Acquisition and Qualification Test Plan for NCAMP Project Number NPN 031701
- Released on March 7, 2017
- Test matrices intended to generate base level building block coupon data that are of common usefulness
- Includes information on specimen identification, raw resin physical tests, AM physical tests, AM mechanical property testing, process definition, inspection/conformance/witnessing, data reduction

TASK 2B:
Qualification Builds and Tests

QUALIFICATION

ADDITIONAL BUILDS

BUILD

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

TEST

Qualification Testing
at NIAR

Statistical Analysis

ANALYZE/PUBLISH

Baseline Qualification
Database

Equiv. #1
SDM

Equiv. #2
Lockheed

Build #3
TBD*

Build #4
TBD*

Equivalency/
Additional Testing

* NIAR project deliverable will allow for equivalency process for future use by any party with the appropriate equipment and process. Solicitations and funding sources for additional equivalencies are TBD.

NOTES

- All qualification and equivalency coupons to be built on Fortus 900MC 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

America Makes

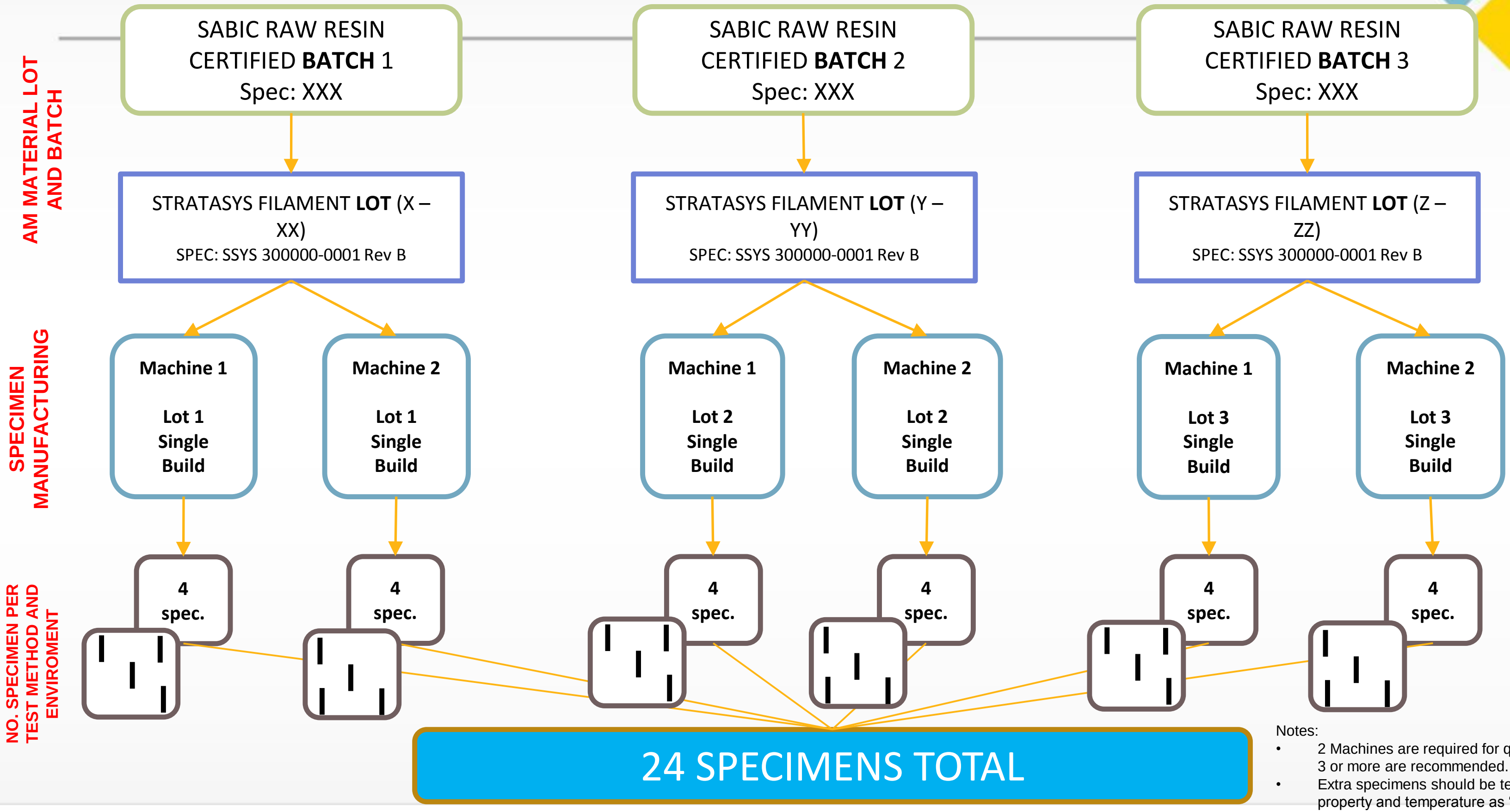
TASK 2B: Qualification Builds and Tests

- Detailed build plan with Stratasys and RP+M
  - Completed Detailed Audits
    - Stratasys & RP+M
- Specimen delivery is ongoing
- Job traveler information provided with each shipment
  - Delegated AR Inspectors
- Regular communication with all team members

Test Matrix Development

- Input from both Steering Committees, FAA, Stratasys, NIST, ASTM F42, other research
- Developed to meet CMH-17 data documentation and batch/specimen requirements for B-Basis allowables and “Complete Documentation”
- Screening tests were performed to work out major issues
  - Shear test methods
  - Compression failure modes
  - Machining of holes
  - Coupon measurement techniques

ULTEM 9085 QUALIFICATION PLAN



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

QUALIFICATION REQUIREMENTS	Req'd	TEST METHOD	Condition	Proposed Testing												TOTAL QTY
				DRY - Normal Conditioning ASTM D618-08 Procedure A									Wet - Moisture saturation reached at <.2% change in three consecutive			
			Test Temperature (^{o}F)	-65			RT			180			180			
Tensile Properties			FDM Machine Location	rp+m			rp+m			rp+m			rp+m			2216
Tensile Strength at Yield	X		Canister Lot Number	A	B	C	A	B	C	A	B	C	A	B	C	
Elongation at Break	X		Thickness (in)	0.140			0.140			0.140			0.140			
Young's Modulus	X	ASTM D638	Y-axis (Qty)	8	8	8	8	8	8				8	8	8	72
Ultimate Tensile Strength	X		X-axis (Qty)	8	8	8	8	8	8				8	8	8	72
Poisson Ratio	X		45 Z-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			Z-axis (Qty)	8	8	8	8	8	8				8	8	8	72
Flexural Properties																
Flexure Strength	X		FDM Machine Location	rp+m			rp+m			rp+m			rp+m			
Flexure Modulus	X		Canister Lot Number	A	B	C	A	B	C	A	B	C	A	B	C	
		ASTM D790	Y-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			X-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			45 Z-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			Z-axis (Qty)	8	8	8	8	8	8				8	8	8	72

Test Matrix

QUALIFICATION REQUIREMENTS	Req'd	TEST METHOD	Condition	Proposed Testing												TOTAL QTY
				DRY - Normal Conditioning ASTM D618-08 Procedure A									Wet - Moisture saturation reached at <.2% change in three consecutive			
			Test Temperature (^{o}F)	-65			RT			180			180			
Compressive Properties																
Compressive Strength	X	ASTM D695	FDM Machine Location	rp+m			rp+m			rp+m			rp+m			
Compressive Yield	X		Canister Lot Number	A	B	C	A	B	C	A	B	C	A	B	C	
Compressive Modulus	X		Y-axis (Qty)	8	8	8	8	8	8	8			8	8	8	80
			X-axis (Qty)	8	8	8	8	8	8	8			8	8	8	80
			45 Z-axis (Qty)	8	8	8	8	8	8	8			8	8	8	80
			Z-axis (Qty)	8	8	8	8	8	8	8			8	8	8	80
Shear Properties		ASTM D5379	FDM Machine Location	rp+m			rp+m			rp+m			rp+m			
150 Additional for fluid sensitivity			Canister Lot Number	A	B	C	A	B	C	A	B	C	A	B	C	
Shear Strength	X		Y-axis (Qty)													
Shear Modulus	X		X-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			45 Z-axis (Qty)													
			Z-axis (Qty)													

Test Matrix

QUALIFICATION REQUIREMENTS	Req'd	TEST METHOD		Proposed Testing												
			Condition	DRY - Normal Conditioning ASTM D618-08 Procedure A									Wet - Moisture saturation reached at <.2% change in three consecutive			TOTAL QTY
			Test Temperature (°F)	-65			RT			180			180			
Open Hole Tension		D5766	**FDM Machine Location**	rp+m			rp+m			rp+m			rp+m			
OHT Strength	X		**Canister Lot Number**	A	B	C	A	B	C	A	B	C	A	B	C	
			Y-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			X-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			45 Z-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			Z-axis (Qty)	8	8	8	8	8	8				8	8	8	72
Filled Hole Tension		D6742	**FDM Machine Location**	rp+m			rp+m			rp+m			rp+m			
FHT Strength	X		**Canister Lot Number**	A	B	C	A	B	C	A	B	C	A	B	C	
			Y-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			X-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			45 Z-axis (Qty)	8	8	8	8	8	8				8	8	8	72
			Z-axis (Qty)	8	8	8	8	8	8				8	8	8	72
Open Hole Compression		D6484	**FDM Machine Location**	rp+m			rp+m			rp+m			rp+m			
OHC Strength	X		**Canister Lot Number**	A	B	C	A	B	C	A	B	C	A	B	C	
			Y-axis (Qty)				8	8	8				8	8	8	48
			X-axis (Qty)				8	8	8				8	8	8	48
			45 Z-axis (Qty)				8	8	8				8	8	8	48
			Z-axis (Qty)				8	8	8				8	8	8	48

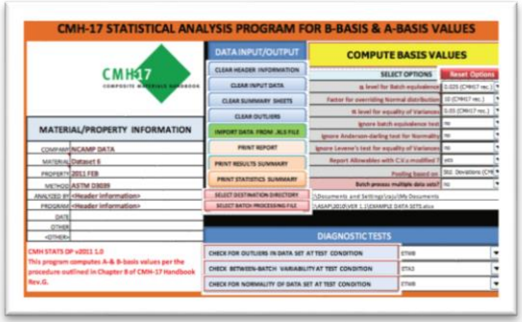
Test Matrix

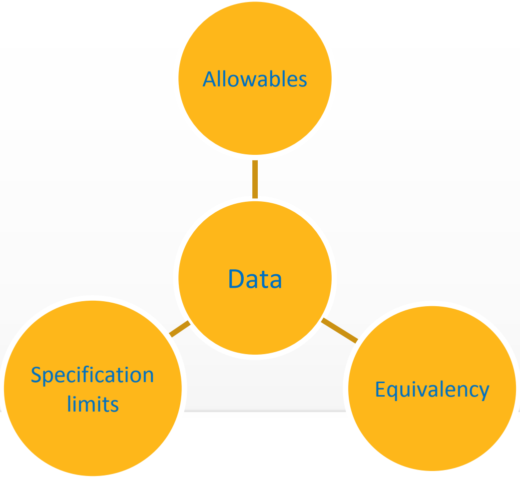
QUALIFICATION REQUIREMENTS	Req'd	TEST METHOD	Condition	Proposed Testing												TOTAL QTY
				DRY - Normal Conditioning ASTM D618-08 Procedure A									Wet - Moisture saturation reached at <.2% change in three consecutive			
			Test Temperature (°F)	-65			RT			180			180			
Filled Hole Compression		D6742	**FDM Machine Location**	rp+m			rp+m			rp+m			rp+m			
FHC Strength	X		**Canister Lot Number**	A	B	C	A	B	C	A	B	C	A	B	C	
			Y-axis (Qty)				8	8	8				8	8	8	48
			X-axis (Qty)				8	8	8				8	8	8	48
			45 Z-axis (Qty)				8	8	8				8	8	8	48
			Z-axis (Qty)				8	8	8				8	8	8	48
Single Shear Bearing		D5961	**FDM Machine Location**	rp+m			rp+m			rp+m			rp+m			
SSB Strength	X		**Canister Lot Number**	A	B	C	A	B	C	A	B	C	A	B	C	
SSB Deformation	X		**Y-axis (Qty)**				8	8	8				8	8	8	48
			X-axis (Qty)				8	8	8				8	8	8	48
			45 Z-axis (Qty)				8	8	8				8	8	8	48
			Z-axis (Qty)				8	8	8				8	8	8	48
IZOD Impact (unnotched specimens)		D256	**FDM Machine Location**	rp+m			rp+m			rp+m			rp+m			
Impact Resistance	X		**Canister Lot Number**	A	B	C	A	B	C	A	B	C	A	B	C	
			Y-axis (Qty)				8	8	8							24
			X-axis (Qty)				8	8	8							24
			45 Z-axis (Qty)				8	8	8							24
			Z-axis (Qty)				8	8	8							24

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.





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:

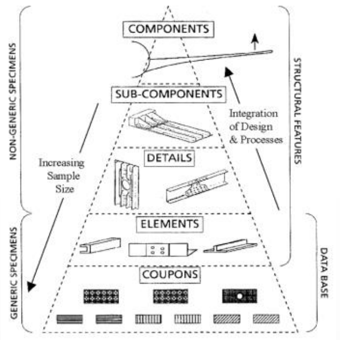
- Creation of a shared polymer AM database including test data, material and process specifications and statistical analysis methods.
- Development of handbook data and guidance (i.e., CMH-17).
- Coordinate with SAE to develop specifications from this program.

Overview of NCAMP

What Does NCAMP Produce?

- Industry-shared materials and process specifications
- Industry-shared material property data and allowables
  - ✓ May fulfill some coupon level building block requirement

Most are available publicly



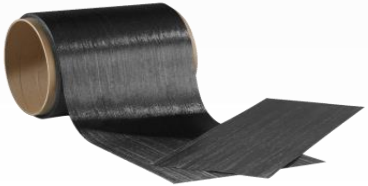
→

NCAMP
NATIONAL CENTER for ADVANCED MATERIALS PERFORMANCE

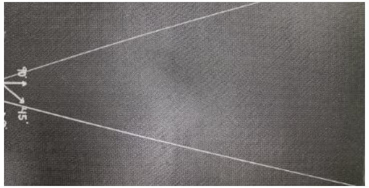
Focuses on *basic* lamina & laminate properties in support of higher level building blocks

http://www.niar.wichita.edu/coe/ncamp.asp

Equivalency Process Overview



Prepreg from
Material Supplier



Composite Panel
Fabricated by
Equivalency
Companies

Specimens Machined
by NCAMP

Specimens Tested by
NCAMP

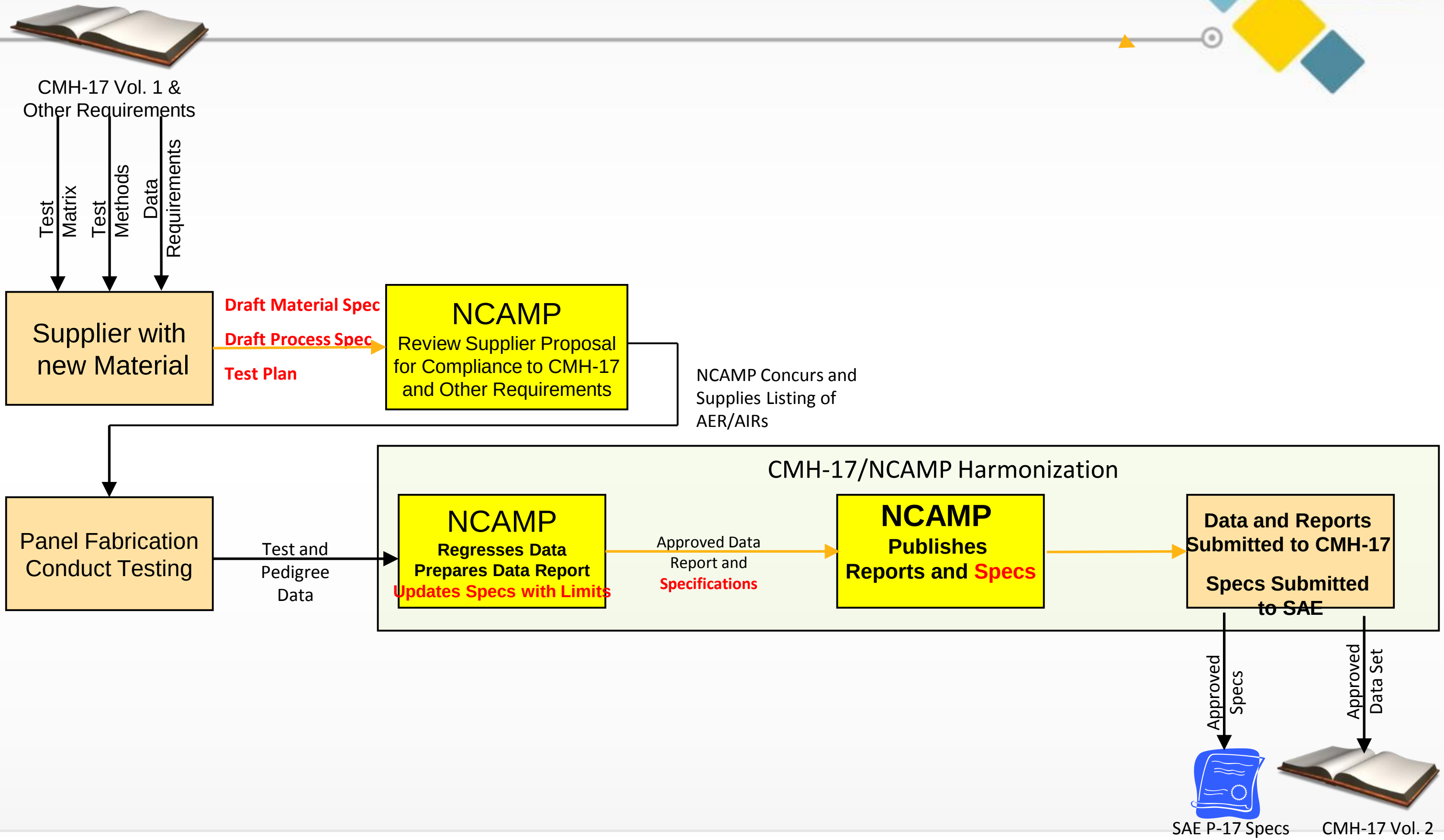
If Equivalency is demonstrated, Qualification's data may be used in certified aircrafts such as:

- Materials and Processes Specifications
- Material Property data and Allowables

NCAMP and CMH-17 Integration

- NCAMP processes and procedures are integrated with CMH-17
  - NCAMP procedures for development of composite material properties will be coordinated with Vol. 1 procedures
  - Data generated following NCAMP procedures will be forwarded to CMH-17 committee for publication in Vol. 2
  - CMH-17 Vol. 3 will provide guidance to potential data users of Vol. 2 data

Typical Data Flow



Observations and Lessons

Observations and Lessons so far…

- Companies slow to include AM in production processes – DVT vs production
- Need for machine maintenance plans
  - How do you know that the machine is capable of producing conforming material? What causes bad builds?
- Configuration control is bigger than we thought … and needs control
  - Machine maintenance and hardware/software
  - Build and pack files, orientation, location
  - Operators & training vs best practice
  - Calibration
- Don't assume ~~everyone~~ anyone knows the definitions
- Need to remove subjective nature of QA – What constitutes a good part
  - Definitions, limits, methods all need definition
  - Some processes have unique features, and defects to consider
  - What does the witness coupon provide and how is it used?
- Material Control Matters
  - Not all material is equal or is stable

Aerospace OEM's farther along in a TC/PC approach to AM.

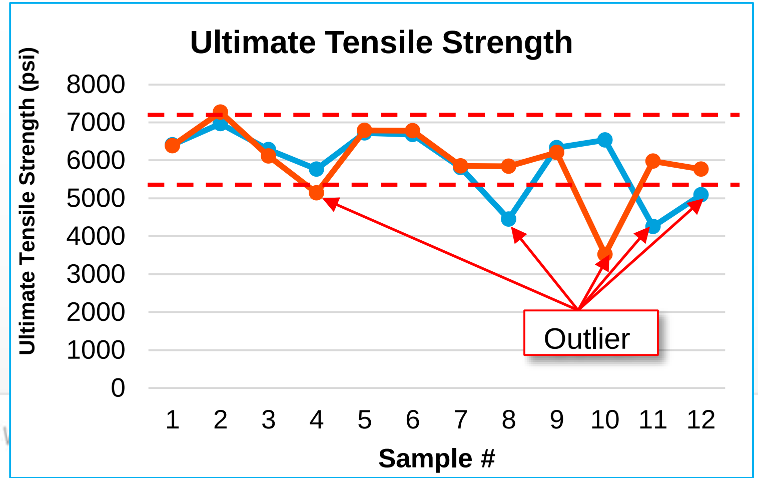
Process Induced Defects

- America Makes Project 3003 - Develop Material Allowables for the FDM Process and Ultem 9085
  - Understood to be a Mature Process widely utilized by industry
  - First Phase of testing revealed large variability in the results
  - Extensive root cause test and analysis found process induced defects
  - Required hardware and software upgrades to remedy

Many Process Changes Incorporated Need to Address Variability.

Defect Characterization

- Defects categorized into 11 different types via fractography
- Defects occur in every batch (12 samples)
- Burnt material (T1) appeared in ~40% of the lowest performers and was found to be the driving defect in 80% of those samples
- Burnt material also produced the highest and most consistent knockdown in UTS out of all other defects

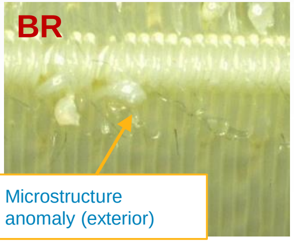


Defect Type	Description
T1	Burnt material
T2	Microstructure anomaly (exterior)
T3	Microstructure anomaly (interior)
T4	Poor Interlayer adhesion (contour)
T5	Poor interlayer adhesion (raster)
T6	Poor contact area (contour)
T7	Poor contact area (raster)
T8	Voids
T9	Bead width variation (contour)
T10	Bead width variation (raster)
T11	Abnormal porosity

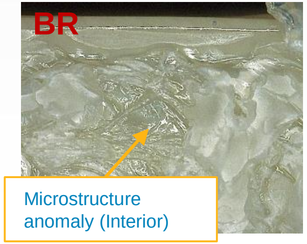
Defect Characterization: Defect Types

T1

T2

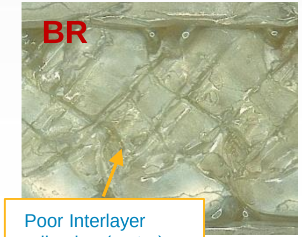


T3

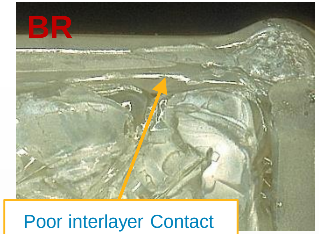


T4

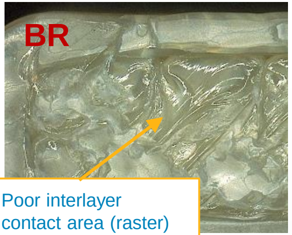
T5



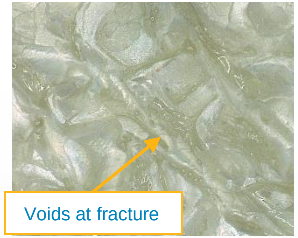
T6



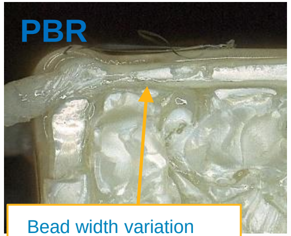
T7



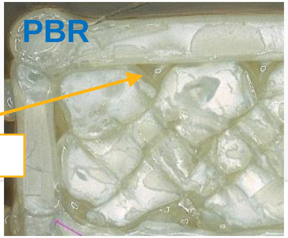
T8



T9



T10



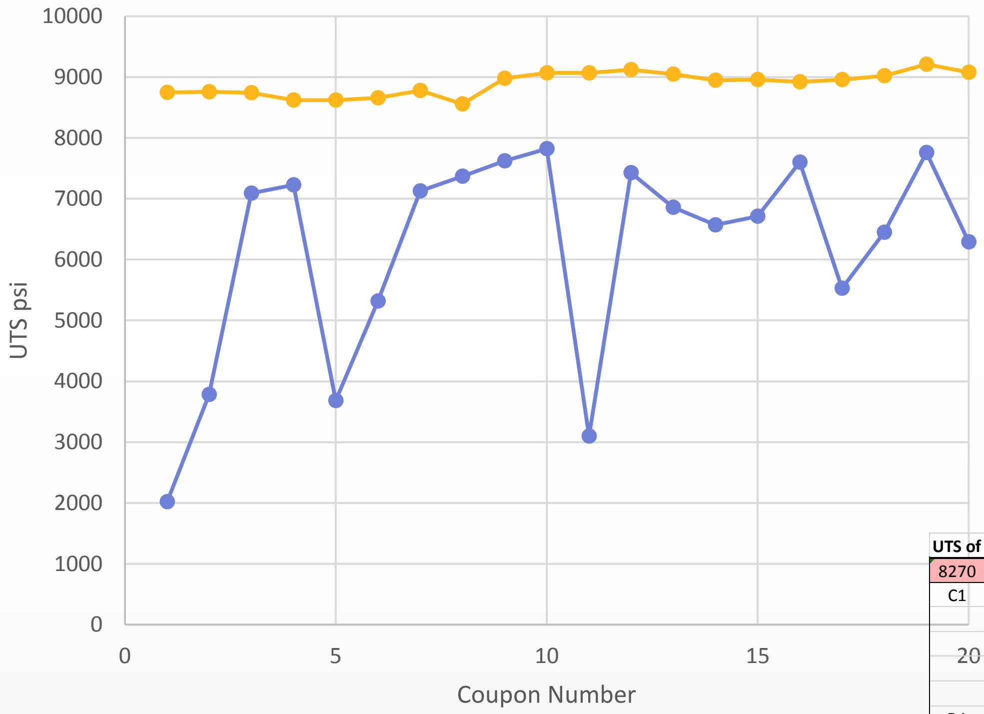
T11

BR: Build Up related

PBR: Potential Build Up related

Strength data – Todays Standard T16 vs T16A

Standard T16 and T16A Tip – 10/5/2016



Average	8894
STDEV	192
COV	2
Min	8560
Max	9210

T16A

Average	6168
STDEV	1717
COV	28
Min	2020
Max	7820

T16

UTS of Upright Coupons

8270	8100	8515	8490					8420	8430	8340	8295
C1	C2	C3	C4					A1	A2	A3	A4
				8530	8355	8475	8310				
				B1	B2	B3	B4				
D1	D2	D3	D4					E1	E2	E3	E4
8455	8515	8530	8380					8680	8585	8480	8200

Test Considerations

- Cannot print a coupon
  - Near net shape and final machining required
- Need to understand how build features will affect the coupon
  - Some print routines will provide a boundary and fill
  - What defines a material property vs a build feature – EG: Holes
  - Need to capture process variability and not build features in test
- Some materials and build features affect failure modes
  - Develop consistent standards
- Surface finish affects fatigue characteristics
  - Most other testing is not a significant item
- Need to understand the limits of the data produced to parts they represent
  - EG: Limits on thicknesses?
- Post processing matters
  - Sequence and process needs exact definition.
  - Understand physical limits

SAE AMS AM – POLYMER Committee

- Committee Created Under Additive Manufacturing Umbrella (Metallics and Polymer)
- Stratasys Sponsoring first Specifications
  - FDM Process - ULTEM 9085 and 1010 Materials
    - Material and Process Specifications
      - AMS 7100 & AMS7001
    - Drafts due this month for committee review
  - Discuss specifications at face-to-face in Chandler AZ (Oct 16-17)
  - Plan on Formal Ballot in December
  - Ensure Path for data similar to composites (CMH-17, SAE)

Going Forward

- Developing test methods and framework for AM material allowables is important. Test methods and build features need to be understood.
  - Need clear definition of material property vs design features
  - Controlling variation requires descriptive and prescriptive specifications
  - Specification Limits, how they are generated and how they are used needs definition, development and discussion.
  - Equivalency is a good thing to control process variation

Thank you...

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