Polymer-Based Additive Manufacturing Guidance for Aircraft Design and Certification

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Polymer-Based Additive Manufacturing Guidelines for Aircraft Design and Certification

- 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

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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)*

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 – 2/2019
TASK 3:
Establish statistical guidelines

3/2018 – 5/2019
TASK 4:
Transition
-Data and guidance to CMH-17
- Specifications to SAE
- Test methods to ASTM

COMPLETE

Current Focus of Project

America Makes - Project Overview

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- **Problem St**... ...l with application acceptable s... ...en used in aerospace v... ...nly high performance... ...tablish a complete da... ...nent applications... ...tured solution in a productior...

- **Objectives:** ...riate test matrix for process/... ...lts.

- **Project Ber**... ...ns; Framework for future ma... ...ss will be defined for members...

America Makes — Driven by NCDMM — NATIONAL CENTER FOR DEFENSE MANUFACTURING AND MACHINING

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

Database Released to the Institute and Its Membership Community to Enable the Widespread Use of ULTEM™ 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™ 9085 Type I Database for Fused Deposition Modeling® (FDM®) 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

rp+m rapid prototype + manufacturing — the new way to innovate — rpplusm.com

FEDERAL AVIATION ADMINISTRATION

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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…)

TASK 2: Qualification & Equivalency Overview

QUALIFICATION

BUILD

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

TEST

Qualification Testing at NIAR

Statistical Analysis

ANALYZE/PUBLISH

Baseline Qualification Database

ADDITIONAL BUILDS

Build #1
SDM

Build #2
Lockheed

Build #3
TBD

Build #4
TBD

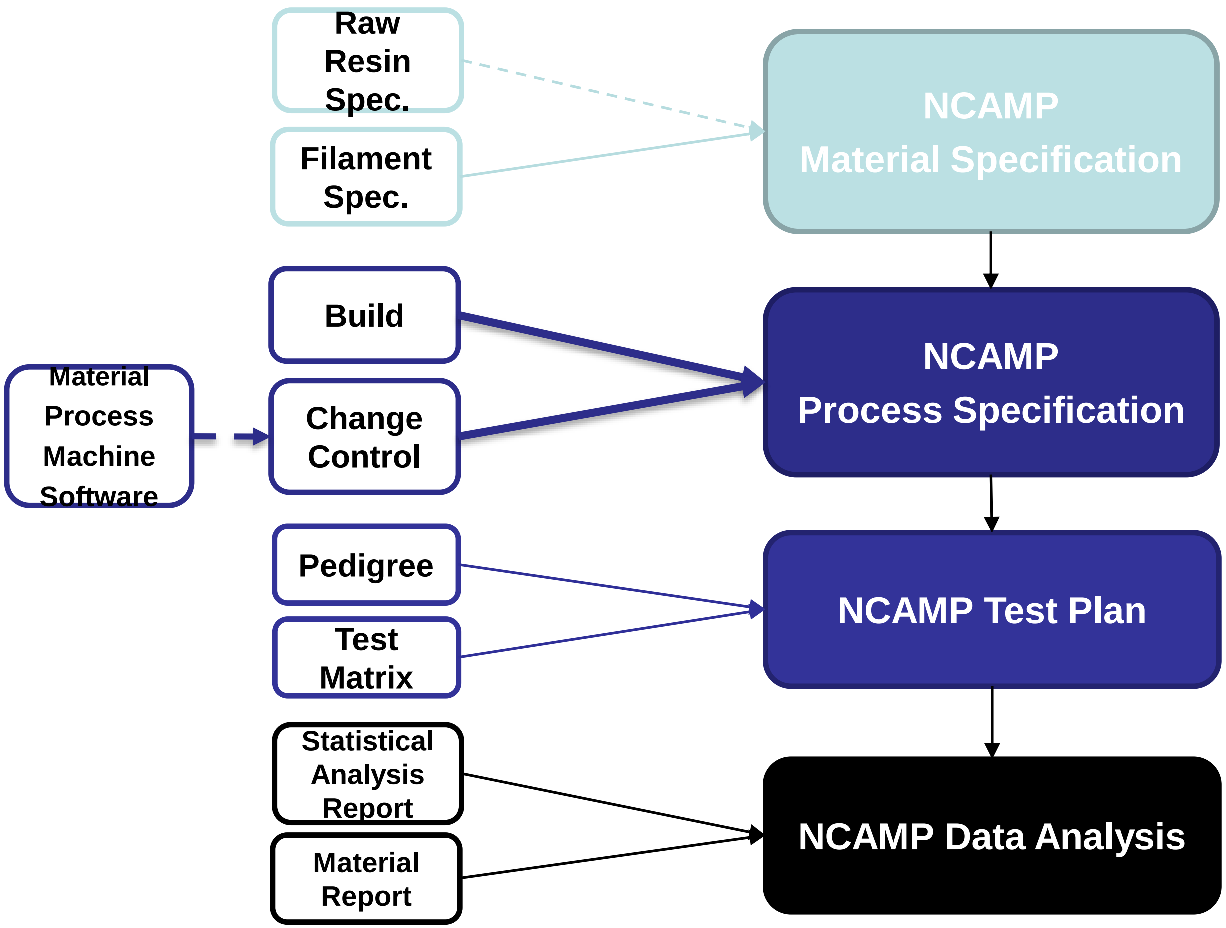
Equivalency/Additional Testing

* 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.

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

NCAMP DOCUMENTATION



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

Controlling the process is essential to success.

TASK 2: Qualification Methodology

NIAR | Wichita State University | National Institute for Aviation Research

AM MATERIAL LOT AND BATCH

SABIC RAW RESIN CERTIFIED BATCH 1 Spec: XXX	SABIC RAW RESIN CERTIFIED BATCH 2 Spec: XXX	SABIC RAW RESIN CERTIFIED BATCH 3 Spec: XXX
STRATASYS FILAMENT LOT (X – XX) SPEC: SSYS 300000-0001 Rev B	STRATASYS FILAMENT LOT (Y – YY) SPEC: SSYS 300000-0001 Rev B	STRATASYS FILAMENT LOT (Z – ZZ) SPEC: SSYS 300000-0001 Rev B

SPECIMEN MANUFACTURING

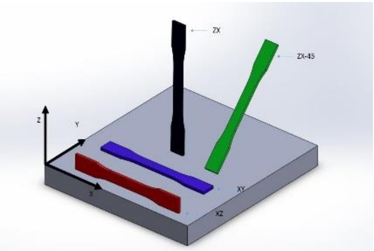
Machine 1	Machine 2	Machine 1	Machine 2	Machine 1	Machine 2
Lot 1	Lot 1	Lot 2	Lot 2	Lot 3	Lot 3
Single Build	Single Build	Single Build	Single Build	Single Build	Single Build

NO. SPECIMEN PER TEST METHOD AND ENVIROMENT

4 spec	4 spec	4 spec	4 spec	4 spec	4 spec

24 SPECIMENS TOTAL

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).



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Methodology repeated for each orientation

Test Matrix

QUALIFICATION TESTS	EQUIVALENCY
Tensile Strength	Tensile Strength
Compressive Strength	Compressive Strength
Flexural Strength	Flexural Strength
Shear	Shear
Open Hole Tension	Open Hole Tension
Filled Hole Tension	Open Hole Compression
Open Hole Compression	
Filled Hole Compression	
Single Shear Bearing Strength	

*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

Test Type and Direction	Property		Number of Batches x Number of Machines x Number of Coupons			
			Test Temperature/Moisture Condition			
		CTD	RTD	ETD1	RTW	ETW1
ASTM D638 (type 1) Tension X (2)	Strength and Modulus	3x2x4	3x2x4		1x2x4 (5)	3x2x4
ASTM D638 (type 1) Tension Y (2)	Strength and Modulus	3x2x4	3x2x4		1x2x4 (5)	3x2x4
ASTM D638 (type 1) Tension Z (2)	Strength and Modulus	3x2x4	3x2x4		1x2x4 (5)	3x2x4
ASTM D638 (type 1) Tension Z (45) (2)	Strength and Modulus	3x2x4	3x2x4		1x2x4 (5)	3x2x4
ASTM D695 modified (type 6.7.2) Compression X (1)(2)	Strength and Modulus	3x2x4	3x2x4	1x2x4	1x2x4 (5)	3x2x4
ASTM D695 modified (type 6.7.2) Compression Y (1)(2)	Strength and Modulus	3x2x4	3x2x4	1x2x4	1x2x4 (5)	3x2x4
ASTM D695 modified (type 6.7.2) Compression Z (1)(2)	Strength and Modulus	3x2x4	3x2x4	1x2x4	1x2x4 (5)	3x2x4
ASTM D695 modified (type 6.7.2) Compression Z (45) (1)(2)	Strength and Modulus	3x2x4	3x2x4	1x2x4	1x2x4 (5)	3x2x4
ASTM D790 Flex X (2)(6)	Strength and Modulus	3x2x4	3x2x4			3x2x4
ASTM D790 Flex Y (2)(6)	Strength and Modulus	3x2x4	3x2x4			3x2x4
ASTM D790 Flex Z (2)(6)	Strength and Modulus	3x2x4	3x2x4			3x2x4
ASTM D790 Flex Z (45) (2)(6)	Strength and Modulus	3x2x4	3x2x4			3x2x4
ASTM D5379 V-notch In-Plane Shear X (2)(3)(4)	Strength and Modulus	3x2x4	3x2x4		1x2x4 (5)	3x2x4

Note 1: Back-to-back strain gauges may be used on the first two specimens. If no buckling is observed, the

Table 4 FFF AM Material Mechanical Tests (Design Guidance Properties)

Test Type	Test Type (6)	Property	Number of Batches x Number of Machines x Number of Coupons		
			Test Temperature/Moisture Condition		
			CTD	RTD	ETW1
OHT	ASTM D5766 Open Hole Tension X (1)	Strength	3x2x4	3x2x4	3x2x4
OHT	ASTM D5766 Open Hole Tension Y (1)	Strength	3x2x4	3x2x4	3x2x4
OHT	ASTM D5766 Open Hole Tension Z (1)	Strength	3x2x4	3x2x4	3x2x4
OHT	ASTM D5766 Open Hole Tension Z (45) (1)	Strength	3x2x4	3x2x4	3x2x4
FHT	ASTM D6742 Filled Hole Tension X (2)	Strength	3x2x4	3x2x4	3x2x4
FHT	ASTM D6742 Filled Hole Tension Y (2)	Strength	3x2x4	3x2x4	3x2x4
FHT	ASTM D6742 Filled Hole Tension Z (2)	Strength	3x2x4	3x2x4	3x2x4
FHT	ASTM D6742 Filled Hole Tension Z (45) (2)	Strength	3x2x4	3x2x4	3x2x4
OHC	ASTM D6484 Open Hole Compression X (1,3)	Strength		3x2x4 (5)	3x2x4
OHC	ASTM D6484 Open Hole Compression Y (1,3)	Strength		3x2x4 (5)	3x2x4
OHC	ASTM D6484 Open Hole Compression Z (1,3)	Strength		3x2x4 (5)	3x2x4
OHC	ASTM D6484 Open Hole Compression Z (45) (1,3)	Strength		3x2x4 (5)	3x2x4
FHC	ASTM D6742 Filled Hole Compression X (2,3)	Strength		3x2x4	3x2x4
FHC	ASTM D6742 Filled Hole Compression Y (2,3)	Strength		3x2x4	3x2x4
FHC	ASTM D6742 Filled Hole Compression Z (2,3)	Strength		3x2x4	3x2x4
FHC	ASTM D6742 Filled Hole Compression Z (45) (2,3)	Strength		3x2x4	3x2x4
SSB	ASTM D5961 Single Shear Bearing X (4)	Strength & Deformation		3x2x4	3x2x4
SSB	ASTM D5961 Single Shear Bearing Y (4)	Strength & Deformation		3x2x4	3x2x4
SSB	ASTM D5961 Single Shear Bearing Z (4)	Strength & Deformation		3x2x4	3x2x4
SSB	ASTM D5961 Single Shear Bearing Z (45) (4)	Strength & Deformation		3x2x4	3x2x4

(1) Open hole configuration: 0.25" hole diameter, 1.5 inch width

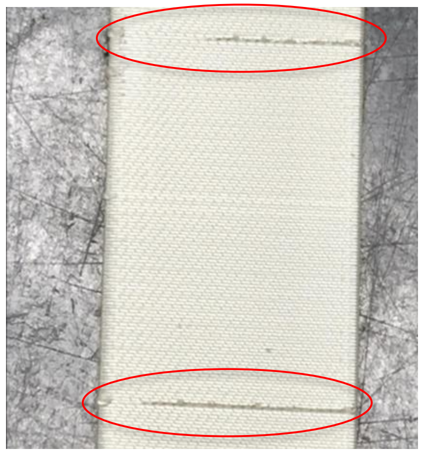
TASK 2: Qualification and Equivalency Printing

SubTask 1:	Audit of Material Specification (@ Stratasys Inc. filament facility), Process Specification, Process Control Documentation (@ Rapid Prototype and Manufacturing LLC)
Date:	March 28-30, 2017
Status:	Complete with minor corrective actions closed.
Outcomes:	Material specification passed quality audit. Process specification passed quality audit. Process Control Documentation passed quality audit. rp+m AS9100C QMS passed quality audit. Printing of qualification specimens began March 31, 2017.

TASK 2: Examples – Dispositioned versus Acceptable Specimens

Dispositioned

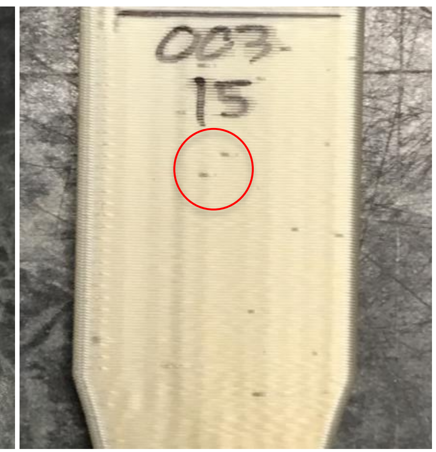
Embedded Support



Extrusion Lagging and Purge Blobs

Acceptable

Color Striation



Bubbles

***Sample dispositioning has occurred at all 3 printing locations throughout the coupon manufacturing process.**

TASK 2: Qualification and Equivalency Printing

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.*

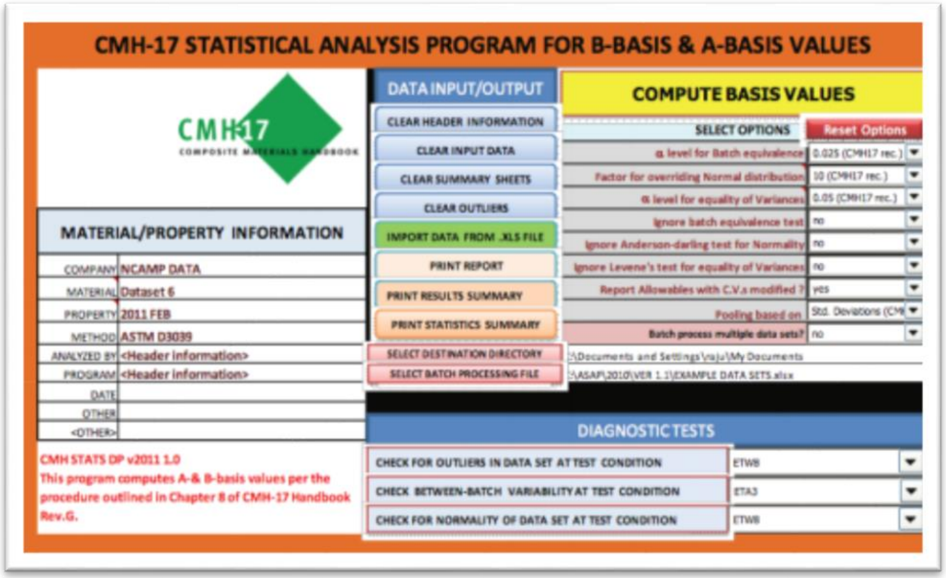
Equivalency Printing: (504 specimens each) - Complete

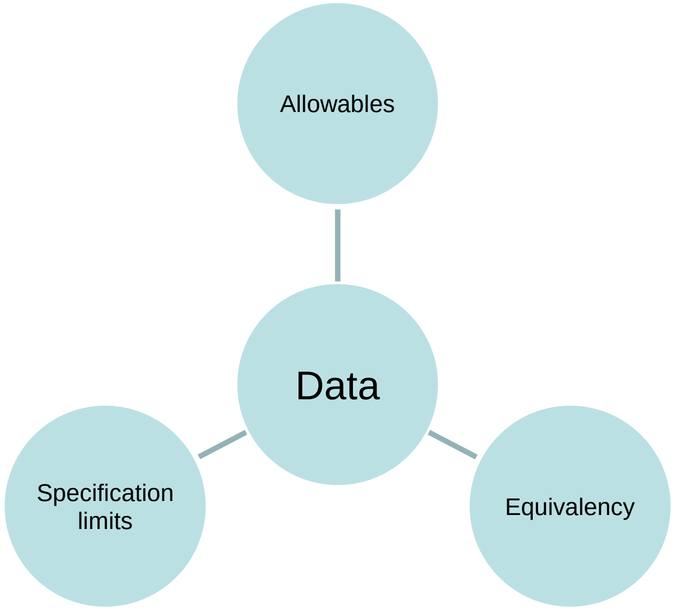
- Site 1: Stratasys Direct Manufacturing
- Site 2: Lockheed Martin MFC Orlando
- *Limited tests on re-built specimens are in progress*.

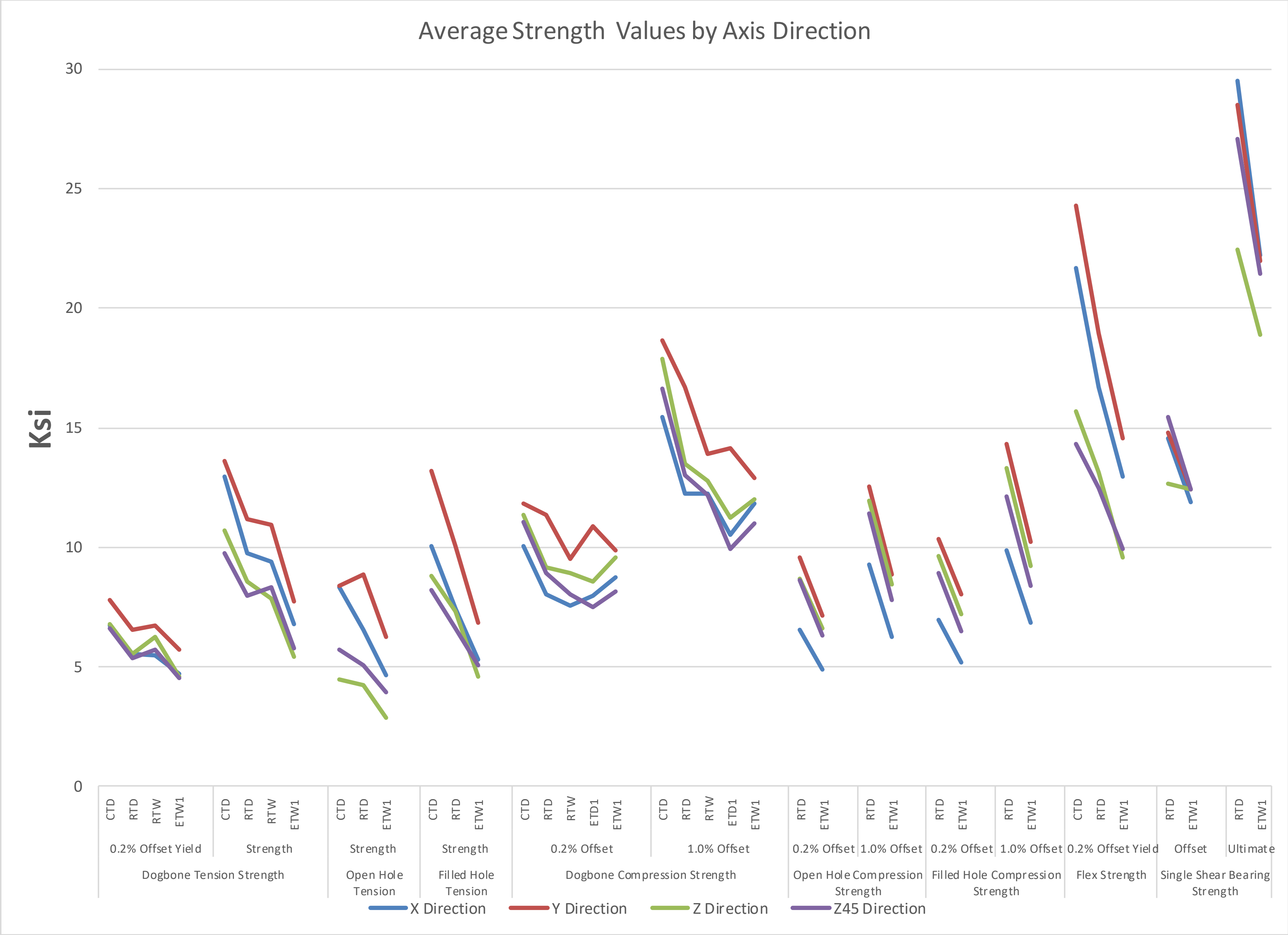
Task 3: Development of statistical guidelines

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***







Average Strength Values by Axis Direction
Ksi
30
25
20
15
10
5
0
CTD
RTD
RTW
ETW1
0.2% Offset Yield
Strength
Dogbone Tension Strength
Open Hole Tension
Filled Hole Tension
ETD1
0.2% Offset
1.0% Offset
Dogbone Compression Strength
Open Hole Compression Strength
Filled Hole Compression Strength
Flex Strength
Offset
Ultimate
Single Shear Bearing Strength
X Direction
Y Direction
Z Direction
Z45 Direction

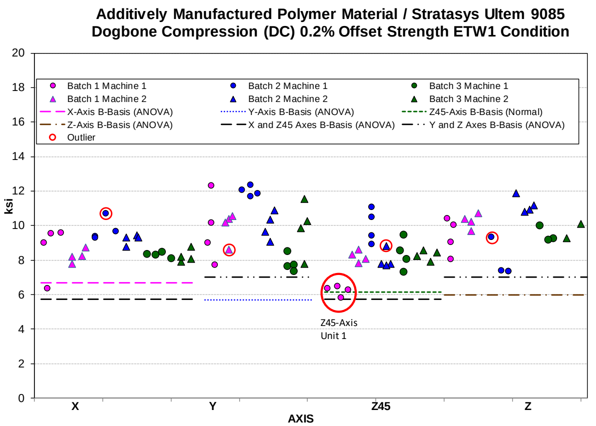
Statistical Analysis Approach

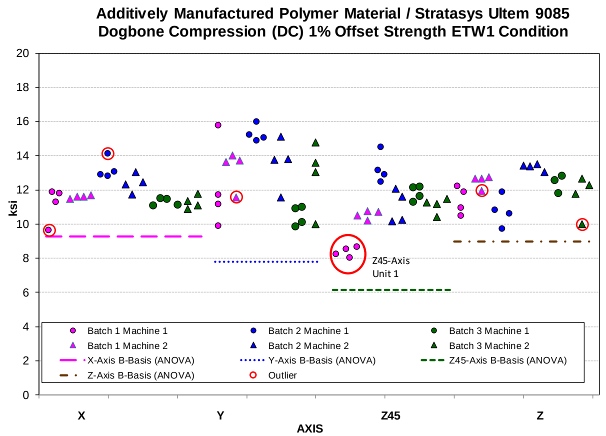
- CMH-17 Unstructured (no significant differences between batches, machines, production sites, etc.)
  - Normal distribution
  - Lognormal distribution
  - Weibull distribution
  - Non-parametric – no underlying distribution assumed
- CMH-17 Structured
  - ANOVA analysis with each machine-batch combination 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

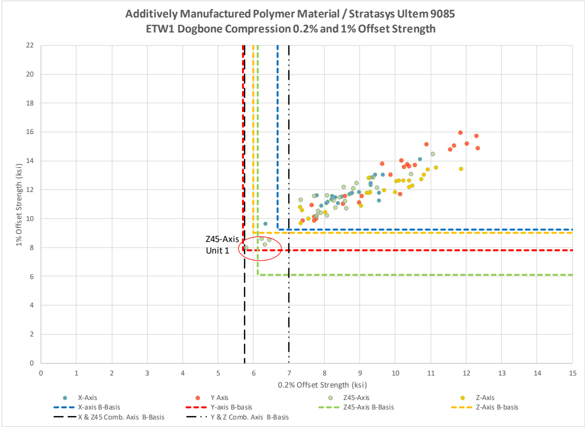
Example Basis Values Table Using CMH-17 Methods

Dogbone Tension (DT) Basis Values and Statistics - CTD Condition									
	0.2% Offset Yield Strength					Strength			
Axis	X-Axis	Y-Axis	Z45-Axis	Z-Axis	X, Z45 & Z Axes	X-Axis	Y-Axis	Z45-Axis	Z-Axis
Mean	6.714	7.792	6.606	6.804	6.708	12.965	13.594	9.768	10.720
Stdev	0.710	0.499	0.549	0.398	0.565	0.665	0.926	0.466	0.667
CV	10.582	6.407	8.314	5.855	8.424	5.131	6.814	4.773	6.225
Mod CV	10.582	7.204	8.314	6.927	8.424	6.565	7.407	6.386	7.112
Min	5.557	6.762	5.837	6.194	5.557	11.465	11.584	8.848	8.730
Max	8.917	8.582	7.780	7.512	8.917	14.501	15.050	10.877	11.880
Batches	3	3	3	3	3	3	3	3	3
Machines	2	2	2	2	2	2	2	2	2
No. Spec.	24	24	24	24	72	24	24	24	24
Basis Values and Estimates									
B-Basis	5.398	6.868	5.149	6.066	5.642	11.733	11.879	8.648	9.374
A-Estimate	4.455	6.205	4.139	5.537	4.866	10.849	10.649	7.866	8.025
Method	Normal	Normal	ANOVA	Normal	ANOVA	Normal	Normal	ANOVA	Weibull
Modified CV Basis Values and Estimates									
B-Basis	NA	6.752	NA	5.931	NA	11.387	11.728	8.612	9.307
A-Estimate		6.007		5.305		10.257	10.391	7.784	8.294
Method		Normal		Normal		Normal	Normal	Normal	Normal

Dogbone Compression Z45-axis ETW plots showing outliers and basis values

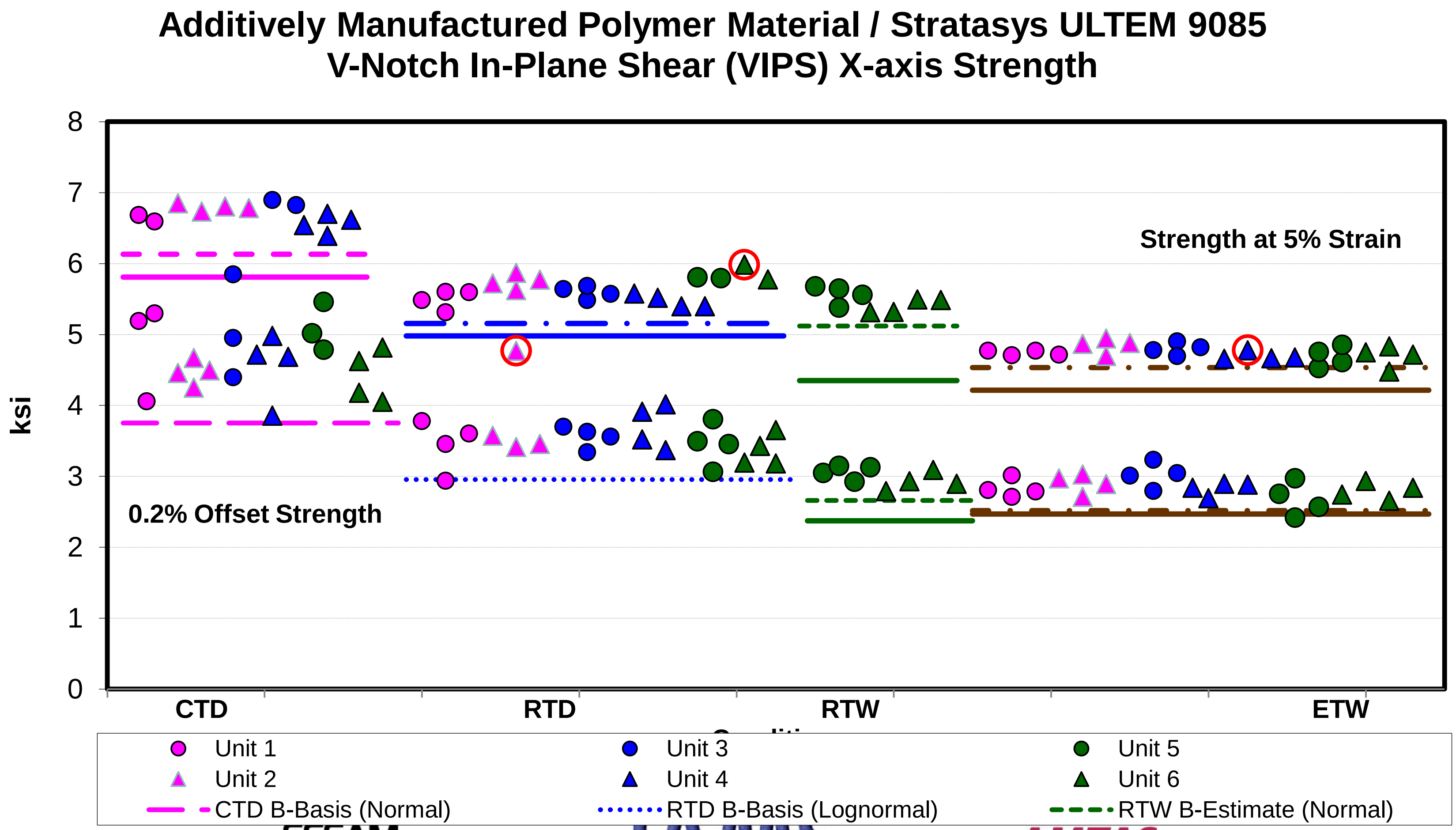






- ➢ The Z45-axis dataset for batch A, machine 1 had unusually low values for both the 1% offset and the 0.2% offset in ETW1 condition.
- ➢ Build specific differences/variations are being examined currently to understand driving factors to refine specification and inspection methods

V-Notch In-Plane Shear
Specimen plots with outliers and basis values



Flex Specimen plots with outliers and B-Basis values

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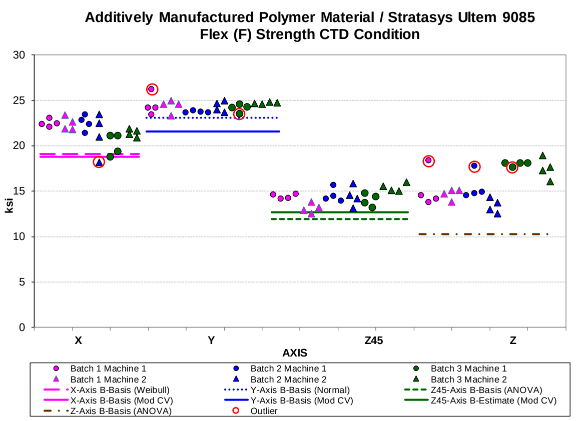
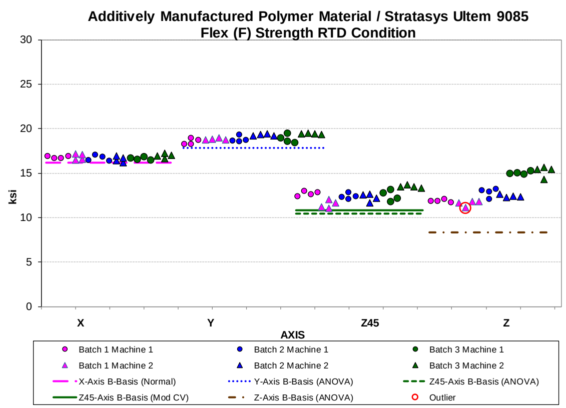
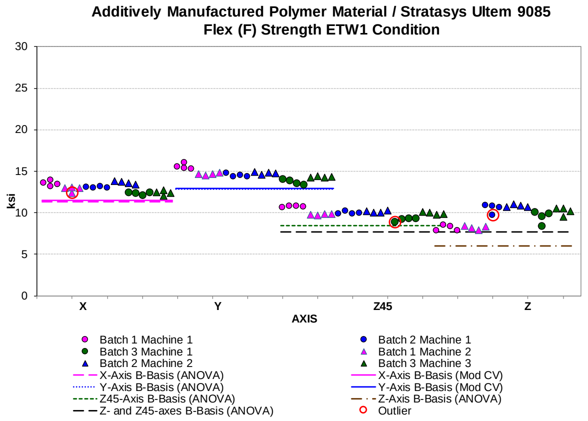
CTD



RTD



ETW1



- Flex strength shows example of orientation specific trends and behaviors consistent across all temperatures.

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NCAMP Reports –*Published on 4/17/2019*

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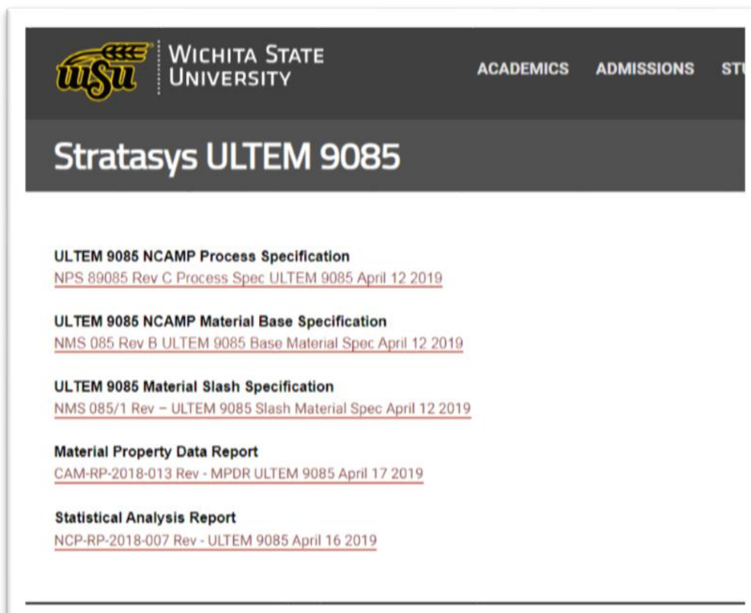
- **ULTEM 9085 NMS 085 (NCAMP Material Base Specification)**
- **ULTEM 9085 NMS 085/1 (NCAMP Material Slash Specification)**
- **ULTEM 9085 NPS 89085 (NCAMP Process Specification)**
- **ULTEM 9085 Material Data Report**
- **ULTEM 9085 Qualification Statistical Analysis Report**



https://www.wichita.edu/research/NIAR/Research/ultem9085.php

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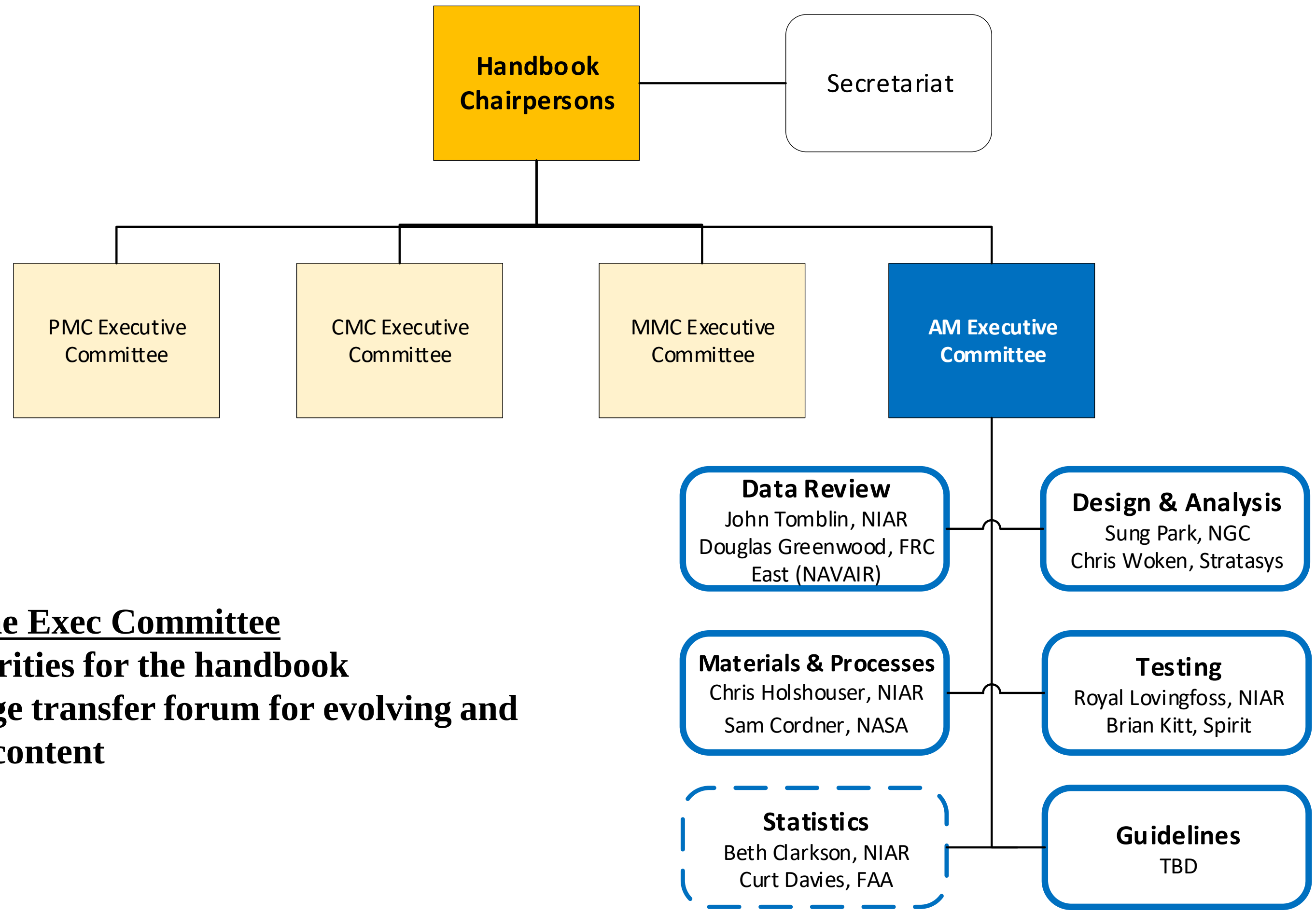
Task 4: Guidelines and Recommendations

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

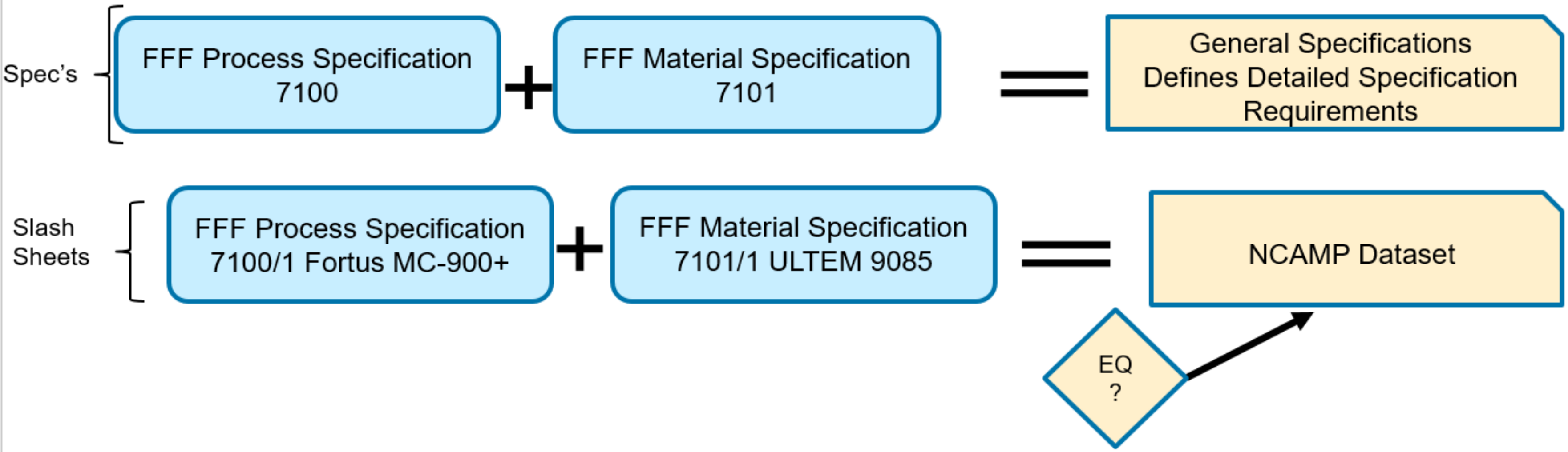
Each Executive Committee consists of Working and Task Group Chairs



The Exec Committee

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

SAE AMS-AM



Allows for the Standardization of a Fixed Process

ASTM (F42 and D20)

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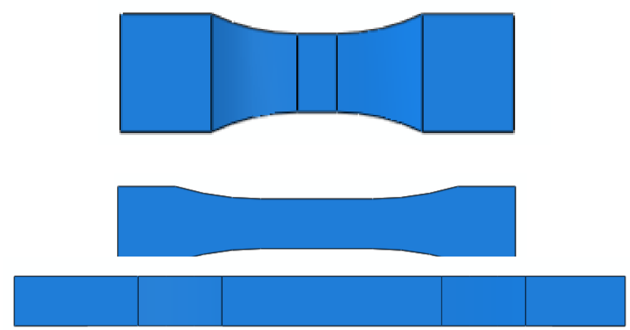
- Supporting ASTM F42 and D20 on mechanical test considerations
- ASTM WK66029: *New Guide for Mechanical Testing of Polymer Additively Manufactured Materials*
  - Rationale: The guide(s) will be used to augment the set of standards used for mechanical performance characterization of polymer AM materials 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



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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

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