Additive Manufacturing Research Program at WSU-NIAR

Federal Aviation Administration

Presented by:

Rachael Andrulonis
Royal Lovingfoss
Brian Smith
Joel White

WSU-NIAR

Joint Centers of Excellence for Advanced Materials

NIAR

Wichita State University

National Institute for Aviation Research

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

CECAM center of excellence for composites and advanced materials

JAMS Technical Review

August 26, 2021

Agenda

- **Overview of NIAR AM JAMS Research and NCAMP Background –** Rachael Andrulonis, Royal Lovingfoss
- **Polymer Based Additive Manufacturing Guidelines for Aircraft Design and Certification –** Brian Smith, Rachael Andrulonis, Joel White
- **Joint Metal Additive Database Definition (JMADD) –** Joel White
- **Additional Additive Activities –** Rachael Andrulonis, Joel White

Introduction

- **Title**: Additive Manufacturing Guidelines for Aircraft Design and Certification
- **Project Participants**
    - John Tomblin – Executive Director
    - Royal Lovingfoss – NCAMP Director
    - Joel White – Engineering Manager
    - Rachael Andrulonis – Sr. Research Engineer
    - Brian Smith – Sr. Research Engineer
- **FAA Technical Monitor** – Danielle Stephens
- **Other FAA Personnel** – Cindy Ashforth (primary), Several others involved in various programs
- **Industry Partnerships/Other Collaborations** – Several through industry participants and Steering Committees
- Source of matching contribution for the current award – KART, Composites Lab, Industry Cost Share, America Makes

Overview of all Tasks

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National Institute for Aviation Research

	Qualification	Factors Effecting Qualification		Special Factors & Equivalencies
Task 16	Development of Qualification Program	Establish Industry/Gov't Steering Committee	Development of Statistical Guidelines	Guidelines and Recommendations
Task 18	Material Extrusion Qual Filled Thermoplastic	Processing Window Expanse	Fabricated v. Machined	Microstructure Scaling
Task 19	Powder Bed Fusion Qual Filled Thermoplastic	Machine & Material Variability	Test Methods	Material Extrusion Equivalency
		Scaling & Machining	Parameters Effects on FST	
Task 20	Powder Bed Fusion Qual EOS M290 | Ti-6Al-4V	Building Block	AM Roadmap	Powder Bed Fusion Equivalencies

Ti 6-4 – M290

Ti 6-4 Reuse

CCF Onyx + X7

CCF Onyx + X7

ULTEM9085 + Essentium 280i

HEXAM – P800

HEXAM Equiv.

Dynamic Testing

Machining

Dynamic Testing

Notching Methods

ULTEM9085 + F900mc

ULTEM9085 Equiv. x2

Micro-structure + Parameter Mapping

ULTEM9085 + F900

Test Methods
Handbook Development
SDO Support

FY16

FY18

FY19

FY20

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Technical Approach

Pre-Qualification

- Static & Dynamic Property Behaviors
- Effect of Defects
- Machine to Machine Variability
- Within Chamber Variability

Material Qualification

- Baseline Testing Applied to Increasingly Complicated Materials
- Expand Framework to Additional AM Technologies
- Perform Equivalencies to Demonstrate Framework

Factors Effecting Qualification

- Validate and Expand Processing Window
- FST Studies – Impact of Design
- Scaling – Specimen to Part Correlations
- Building Block – Application Specific Characterization

NCAMP Background

Presented by:

Royal Lovingfoss

WSU-NIAR

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August 26, 2021

Accelerated Insertion of Advanced Materials

focused on increasing the efficiency of advanced material implementation into new aircraft models while at the same time decreasing the cost of these materials

National Center for Advanced Materials Performance

Federal Aviation Administration

Memorandum

Date:	SEP 2 0 2010
To:	All Directorate Managers All Aircraft Certification Office Managers
From:	David W. Hempe, Manager, Aircraft Engineering Division, AIR-100
Prepared By:	Mark Freisthler, Aerospace Engineer, Transport Airplane Directorate, (ANM-115)
Supported By:	Robert Stegeman (ACE-111), Dale Hawkins (AIR-120) and Larry Ilcewicz (AIR 100).
Subject:	INFORMATION: Acceptance of Composite Specifications and Design Values Developed using the NCAMP Process
Memo No.:	AIR100-2010-120-003
Regulatory Reference:	§§23.603, 23.605 and 23.613 §§25.603, 25.605 and 25.613 §§27.603, 27.605 and 27.613 §§29.603, 29.605 and 29.613 §33.15 & §35.17

Summary

This policy memorandum provides clarification on the acceptability of material specifications and allowables developed by the National Center for Advanced Materials Performance (NCAMP) for composite materials. NCAMP has published a standard operating procedures document detailing the organization, methods and processes they will use to work with material suppliers, manufacturers, and regulatory bodies to develop composite material specifications and limited associated material allowables. These procedures are based on experience gained from the Advanced General Aviation Transport Experiment (AGATE) and NCAMP. Throughout this timeframe, AGATE and NCAMP have had a strong interface with the FAA, including the regulatory oversight

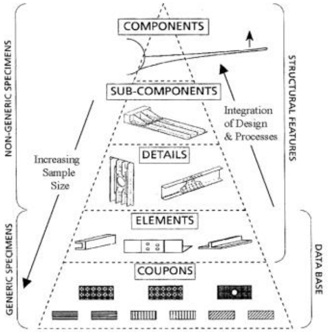
EASA	CERTIFICATION MEMORANDUM
	EASA CM No.: EASA CM - S – 004 Issue: 01 Issue Date: 14th of January 2014 Issued by: Structures section Approved by: Head of Certification Experts Department Regulatory Requirement(s): CS 2X.603, CS 2X.605, CS 2X.613, CS-E 70 and CS-P 170

Both the FAA and EASA accept composite specification and design values developed using the NCAMP process.

NCAMP works with the FAA, EASA, DoD and industry partners to qualify material systems and populate a shared materials database that can be viewed publicly.

What Will NCAMP Produce?

- **Industry-shared materials and process specifications**
- **Industry-shared material property data and allowables**
  - ✓ To fulfill some coupon level building block requirements

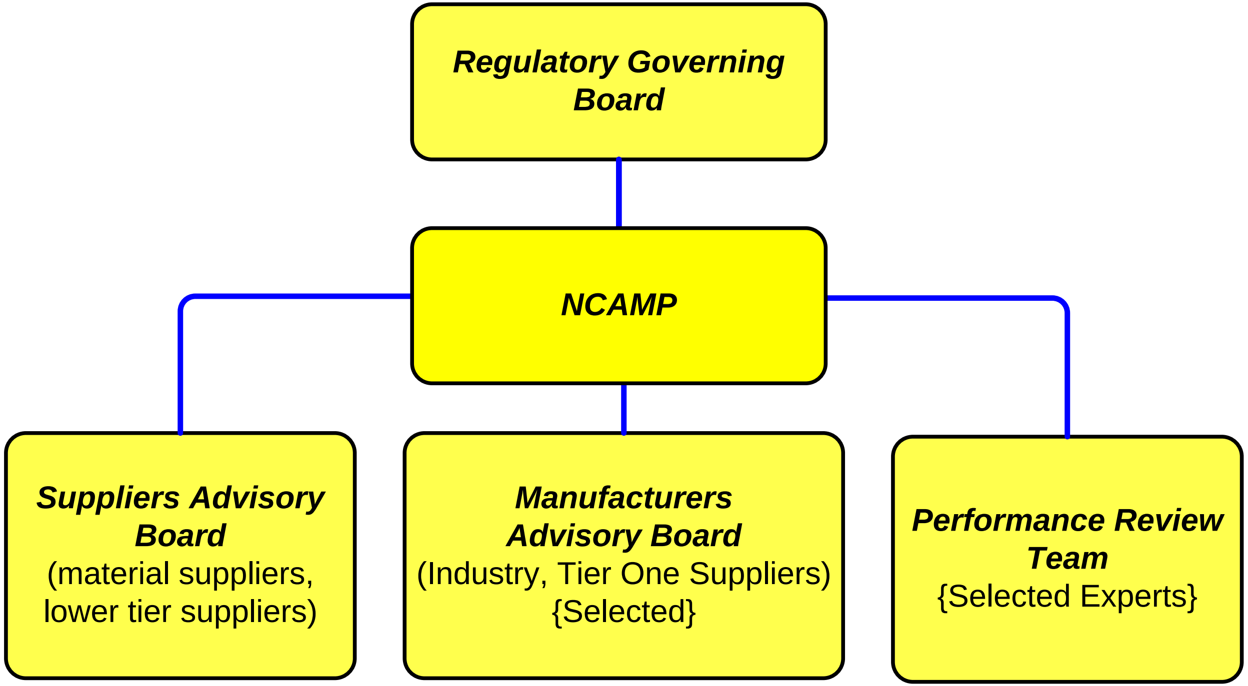


Most are available publicly

→ NCAMP NATIONAL CENTER for ADVANCED MATERIALS PERFORMANCE

Focuses on *basic* Advanced Material properties in support of higher level building blocks

NCAMP Organizational Structure (Proven)



Benefits of NCAMP

- **To Material Suppliers**
  - Publication of key material properties
  - Non-proprietary industry material and process specifications
- **To Material Users**
  - Availability of published material properties suitable for:
    - Material selection
    - Initial sizing of structure
    - Initial design and analysis (additional testing may be required for product certification)
  - Reduced time and cost
- **To Government**
  - Reduced workload by eliminating redundant material qualification/allowables programs
  - Improved safety by leveraging industry experts

NCAMP Properties

- **Test Types**
  - Tension
  - Compression
  - Flex
  - Shear
  - Bearing
  - CAI
  - Notched/Un-notched
  - Others as needed

- **Test Conditions**
  - CTD (-65F)
  - RTD
  - ETW (Various)
  - ETD (Various)

- **Special Testing can also occur that can be kept proprietary or made public. Fatigue, Creep, Environmental conditions, etc.**

Currently Available NCAMP Databases

- AGATE (Contains many legacy materials)
- Cytec/Solvay 5215
- Cytec/Solvay 5250-5
- Cytec/Solvay 5320-1
- Cytec/Solvay EP2202
- Cytec/Solvay MTM45-1
- Hexcel 8552
- Newport NCT4708
- Tencate/Toray BT250E-6
- Tencate/Toray TC250
- Stratasys Ultem 9085
- Tencate/Toray TC1225 PAEK

*Polymer

Upcoming NCAMP Material Databases

- Teijin Tenax HTS45 E23 PEEK
- Powder Bed Fusion Filled Polymer Material PEEK
- Developing framework for metal AM (Titanium and Inconel)
- Axiom AX7800 5HS (CMC)
- Teijin Tenax IMS65P12 UD PEEK (chopped fiber)
- Solvay/Teijin EP2400/IMS65 E23 (VARTM/RTM)
- MarkForged Continuous Fiber Reinforced Polymer OFRA/CFRA

*Polymer

Polymer Based Additive Manufacturing Guidelines for Aircraft Design and Certification

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Polymer AM Research Activities

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Material Extrusion Qualification - Filled Thermoplastic

Markforged's AM Polymer Composite Material Onyx FR-A (OFRA) reinforced with Carbon Fiber FR-A (CFRA)

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Brian Smith

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Background

Motivation and Key Issues
- Material qualification for Markforged's Additively Manufactured Polymer Composite Material Onyx FR-A (OFRA) reinforced with Carbon Fiber FR-A (CFRA).

- Material performance capabilities for AM composite reinforced polymer material.

- An AM material with enhanced strength performance in specific loading scenarios.
- Potential Flame Retardant performance of a Nylon base polymer material with Carbon Fiber reinforcement.

Objective and Scope
- Expand the qualification framework for polymer AM materials.
- Generate material and process specifications.
- Generate full data set including statistically based B-Basis allowables for all qualification required test methods.

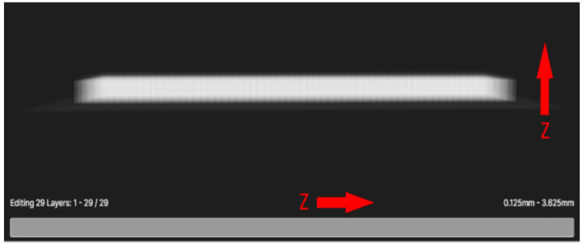
- Physical, mechanical, mechanical design guidance, fluid sensitivity, and nondestructive testing for all qualification required test methods.

Approach
- NCAMP material qualification methodology.
  - NTP AM-6754Q1
  - NPS 86754 Markforged Onyx-X7 Process Spec
  - NMS 754 Onyx FR-A
  - NMS 755 Carbon Fiber FR-A
  - NMS 754-1 (Slash Sheet)

Technical Information (Fiber Fill)

XY

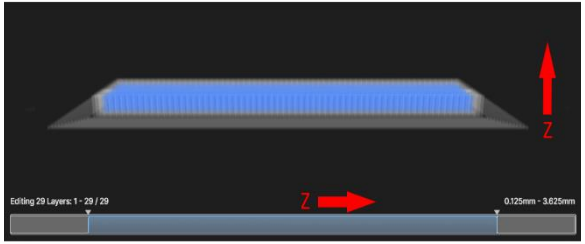
No Fiber (NF)

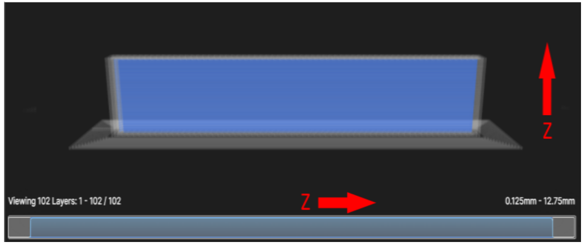


The blue areas throughout the part geometry in the figures show where CFRA reinforcement is planned for printing in each orientation.

XZ

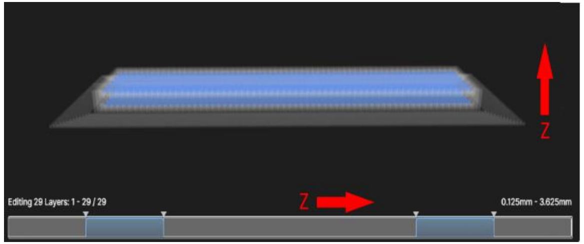
Full Fiber (FF)

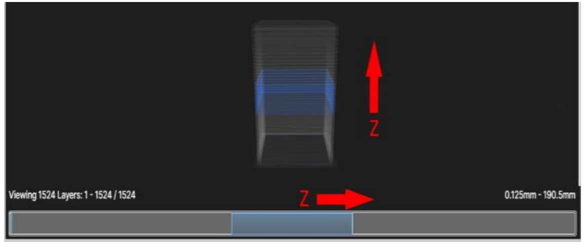




XZ

Partial Fiber (PF)





Technical Approach

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Develop a framework to advance AM materials into the aerospace industry.

Utilize the experience and framework of the NCAMP composite program as an example of process sensitive material characterization.

For more info on NCAMP:

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

Assess the validity with equivalency testing (additional machines)

May 2020 → **Q3 2021** → **Q2 2022** → **Q3 2022 – Q4 2022**

Establish Steering Committee → **Develop Qualification Framework (trials)** → Perform Qualification → Establish statistical guidelines → Transition
- Material property data
- Guidelines

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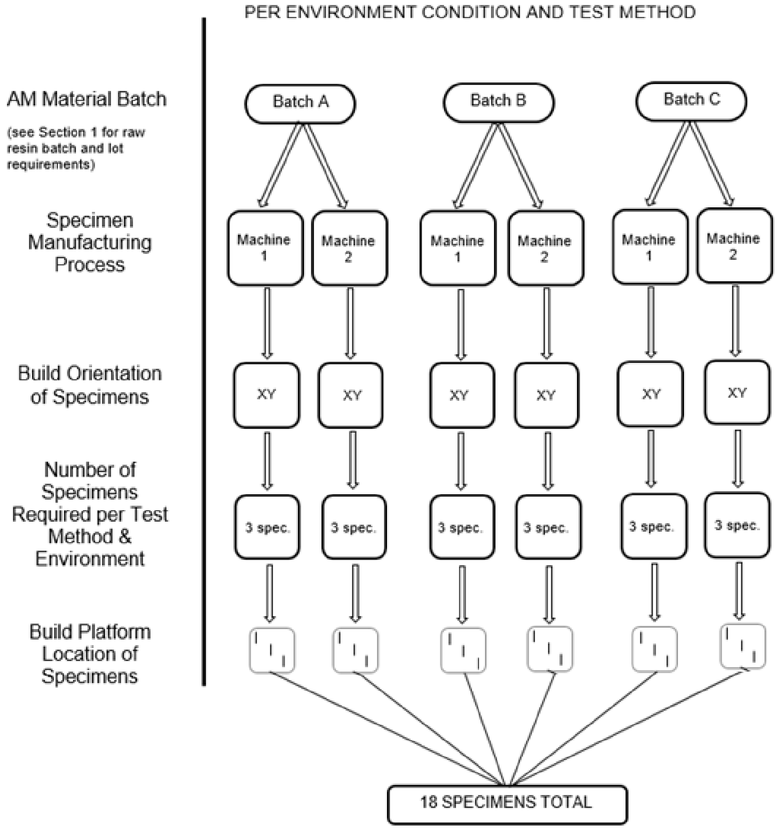
Qualification Methodology

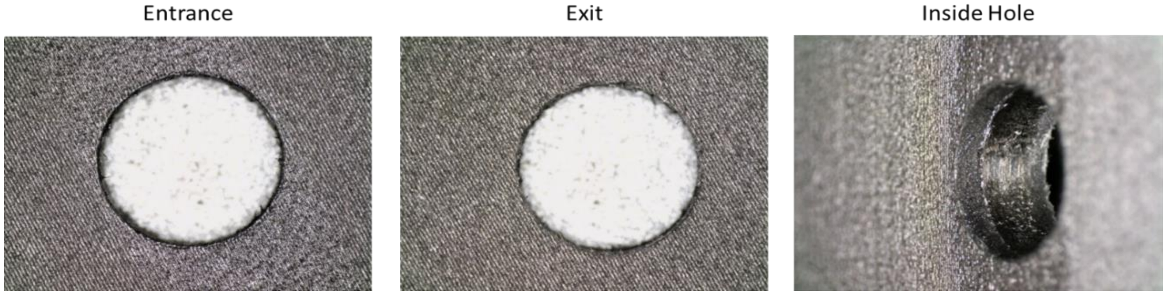


Status of Ongoing Effort

- Pre-Qualification fabrication and testing complete
  - Considerations from pre-qualification testing influenced the Process Specification and Test Plan.
    - Machining Trials
    - Elevated temperature studies and drying studies.
    - Mechanical testing and evaluation of required ASTM standard geometries.
- NCAMP documentation generated and published to NCAMP portal.
- NIAR has begun to receive Qualification samples from Markforged to begin submission for specimen processing and testing.

Summary of Findings

Conducted machining trial on Onyx FR-A reinforced with Carbon Fiber FR-A resulted in better hole consistency at both entrance and exit locations when compared to initial machined specimens.



Material drying requirement for dry test conditions was established from drying trials and determined to be 160°F for 7 days.

Maximum Operating Temperature (MOT) established from pre qualification studies, elevated temperature test conditions will utilize 160°F for the set temperature.

The qualification testing will be centered around Partial Fiber (PF) specimens with testing of Full Fiber (FF) specimens conducted for informational purposes.

Next Steps and Planned Work

Continue to receive specimens to satisfy all requirements within the test plan.

Perform qualification testing for all test requirements within:

- Physical Testing
- Mechanical Testing
- Mechanical Design Guidance Testing
- Fluid Sensitivity Testing
- Nondestructive Testing (X-Ray CT)

Establish Statistical Guidelines

Transition of material property data and guidelines

Material storage requirements to be determined during qualification testing.

- Results will be input into material specifications.

Expected Outcome

Qualification database & resultant specifications

Validation of NCAMP process with more complex AM material processes.

Acceptable performance variation in order to establish B-Basis allowables capable of successfully performing future equivalencies.

Technical Publications

ASTM test method guidance documentation

NCAMP reports and specifications

SAE standards development from NCAMP documentation

CMH-17 data and lessons learned

Powder Bed Fusion Qualification - Filled Thermoplastic

Hexcel AM – PEKK + Carbon Fiber

Presented by:

Rachael Andrulonis

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Background

- **Motivation and Key Issues**
  - Expand on the qualification framework established through the ULTEM program with a new process (laser powder bed fusion)
  - Additional considerations for new process that includes fiber
  - Equivalency approach for recycled material
- **Objective and Scope**
  - Collaborate with SMEs through a steering committee to conduct pre-qualification research to inform a robust qualification plan
  - Conduct a full qualification based on industry input
  - Generate property database and specifications
  - Transfer lessons learned to CMH-17
- **Approach**
  - Select a non-metallic AM material of interest that is process stable → HexAM
  - Previous data from America Makes program can be leveraged (no public specs generated and only available to America Makes members)
  - Engage industry SMEs throughout the process

Technical Approach

- **Develop a framework to advance powder bed fusion AM materials into the aerospace industry.**
- **Utilize the experience and framework of the NCAMP composite program as an example of process sensitive material characterization.**
  - For more info on NCAMP: https://www.wichita.edu/research/NIAR/Research/ncamp.php
- **Assess the validity with equivalency testing (additional machines, powder reuse)**

May 2020 → **Sept. 2021** → **July 2022** → **Fall 2022**

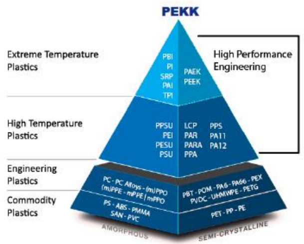
Establish Steering Committee → Develop Qualification Framework (trials) → **Perform Qualification** → Establish statistical guidelines → Transition - Material property data - Guidelines

2 Year Program (2020 – 2022)

HexAM Details

HexPEKK™

Polyetherketoneketone (PEKK)
- High performance thermoplastic
- Qualified from -300F to +300F
- FAR 25 (flammability) compliant



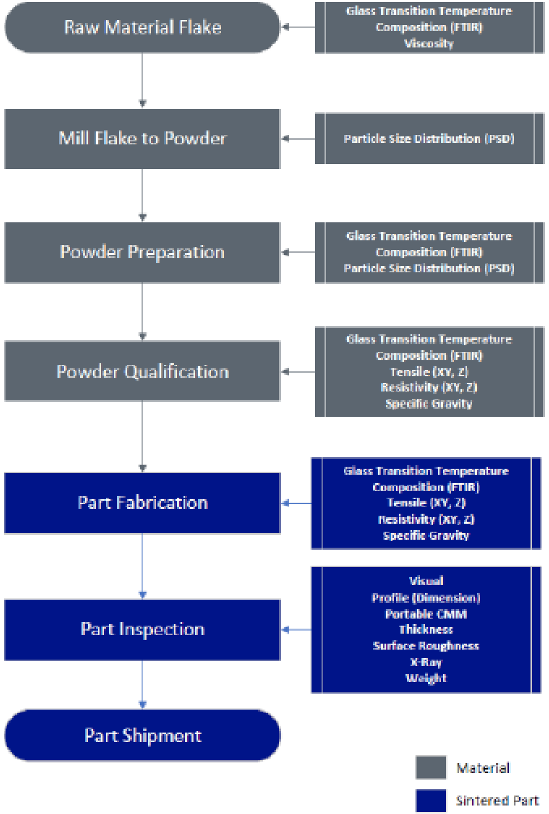
\+

Carbon Fiber
- Carbon fiber added to PEKK at the powder stage
- Results in a composite with industry leading mechanical properties
- Meets ESD requirements

Applications:
- Commercial Aircraft – optimized brackets, ducts, castings
- Manned Space
- Satellite
- Military Aircraft

- **Parts are excavated out of unsintered material ("Cake")**
- **HexAM™ process allows the Cake to be reclaimed, processed and run just like first use ("virgin") powder**
  - Equivalency for Cake and additional machines (Hexcel has 8)
- **No heat treat, support structure removal required**
- **Flightworthy hardware straight out of the machine**

Processing Information



PEKK Flake | PEKK Neat Powder | PEKK with Carbon Fiber

Current Work

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- **Pre-Qualification Efforts**
  - Steering Committee Meetings
  - Trial Test Matrix
  - Moisture conditioning evaluations
  - NDE (X-Ray CT) studies
  - Test method comparisons

- **Qualification Status**
  - Specifications drafted and reviewed by Steering Committee (Q2 2021)
  - Test matrix drafted and reviewed by Steering Committee (Q2 2021)
  - PCD Audit Complete (April 2021)
  - Documentation Review by AER - *Pending*

Trial Test Matrix Example

			RTA	ETA (180F)	ETW (180F)	ETD 2 (300F)	ETW 2 (300F)	ETD HT (450F)
Tension	ASTM D638 (DF-2) Tension XY	Strength and Modulus	3	3	3	3	3	3
	ASTM D638 (DF-2) Tension YX	Strength and Modulus	3					
	ASTM D638 (DF-2) Tension XZ	Strength and Modulus	3					
	ASTM D638 (DF-2) Tension ZX	Strength and Modulus	3			3		3
	ASTM D638 (DF-2) Tension Z45	Strength and Modulus	3					
	ASTM D638 (DF) Tension XY	Strength and Modulus	3		3	3		3
	ASTM D638 (DF) Tension YX	Strength and Modulus	3					
	ASTM D638 (DF) Tension XZ	Strength and Modulus	3					
	ASTM D638 (DF) Tension ZX	Strength and Modulus	3			3		3
	ASTM D638 (DF) Tension Z45	Strength and Modulus	3					
	ASTM D3039 Tension XY	Strength and Modulus	3		3	3		3
	ASTM D3039 Tension YX	Strength and Modulus	3					
	ASTM D3039 Tension XZ	Strength and Modulus	3					
	ASTM D3039 Tension ZX	Strength and Modulus	3			3		3
	ASTM D3039 Tension Z45	Strength and Modulus	3					

Mechanical Properties - Tension

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			RTA		ETA (180F)		ETW (180F)		ETA 2 (250F)		ETA 2 (300F)		ETW 2 (300F)		ETA HT (450F)	
			Ultimate Strength [ksi]	Modulus [Msi]	Ultimate Strength [ksi]	Modulus [Msi]	Ultimate Strength [ksi]	Modulus [Msi]	Ultimate Strength [ksi]	Modulus [Msi]	Ultimate Strength [ksi]	Modulus [Msi]	Ultimate Strength [ksi]	Modulus [Msi]	Ultimate Strength [ksi]	Modulus [Msi]
ASTM D3039 Tension XY	Mean		15.795	0.973			12.899	0.931			6.712	0.728			2.836	0.086
	CV		1.729	0.847			0.909	1.037			5.088	7.414			2.447	5.991
ASTM D3039 Tension YX	Mean		15.289	0.851												
	CV		1.636	0.765												
ASTM D3039 Tension XZ	Mean		16.130	0.945												
	CV		1.023	2.105												
ASTM D3039 Tension ZX	Mean		9.425	0.763							4.818	0.543			1.754	0.054
	CV		5.109	1.162							2.542	3.895			5.683	6.461
ASTM D3039 Tension Z45	Mean		9.106	0.770												
	CV		1.446	0.595												
ASTM D638-DF Tension XY	Mean		14.728	0.788			12.144	0.737			6.086	0.457			2.351	
	CV		4.883	2.881			2.676	3.518			6.418	1.560			10.396	
ASTM D638-DF Tension YX	Mean		14.502	0.776												
	CV		0.596	4.560												
ASTM D638-DF Tension XZ	Mean		15.904	0.753												
	CV		1.914	3.221												
ASTM D638-DF Tension ZX	Mean		11.087	0.641							3.925	0.233			2.025	
	CV		4.045	1.111							4.522	16.298			5.332	
ASTM D638-DF Tension Z45	Mean		9.136	0.697												
	CV		7.879	1.375												
ASTM D638-DF2 Tension XY	Mean	XY	16.320	0.908	13.101	0.857	13.033	0.905	10.300	0.852	7.055083	0.762	4.881	0.322	2.598	0.085
	CV		2.896	10.662	1.450	0.923	0.930	2.943	4.367	2.880	1.820147	3.746	1.996	2.535	13.936	22.130
ASTM D638-DF2 Tension YX	Mean	YX	15.413	0.859												
	CV		4.976	2.011												
ASTM D638-DF2 Tension XZ	Mean	XZ	16.194	0.921												
	CV		1.656	0.764												
ASTM D638-DF2 Tension ZX	Mean	ZX	10.572	0.711							4.972	0.476			1.512	0.043
	CV		1.909	1.804							3.280	13.064			6.984	11.631
ASTM D638-DF2 Tension Z45	Mean	Z45	8.903	0.762												
	CV		7.760	2.376												

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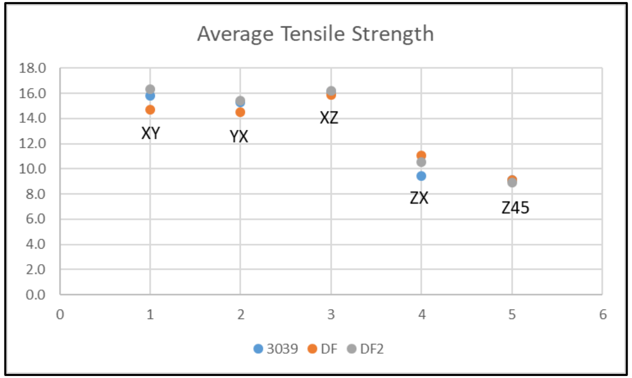
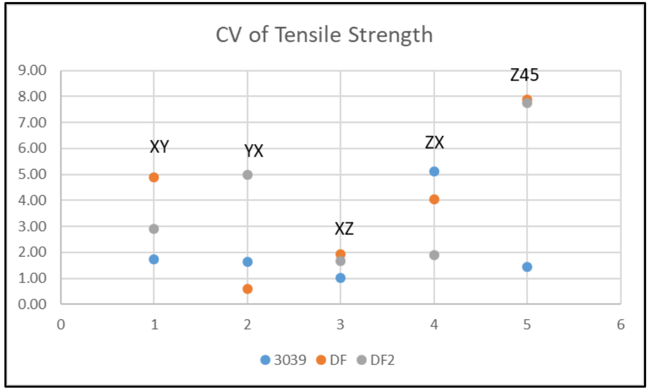
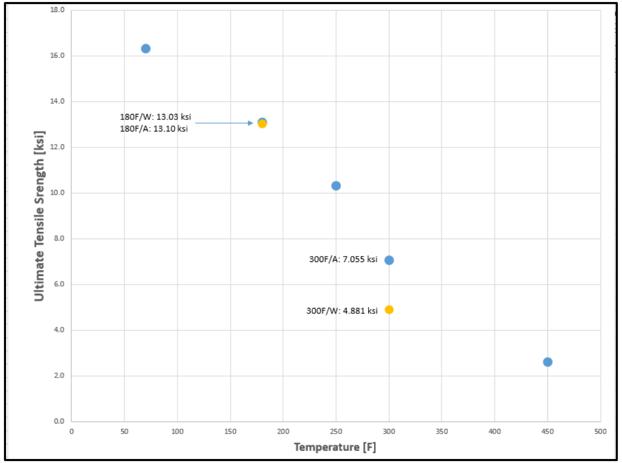
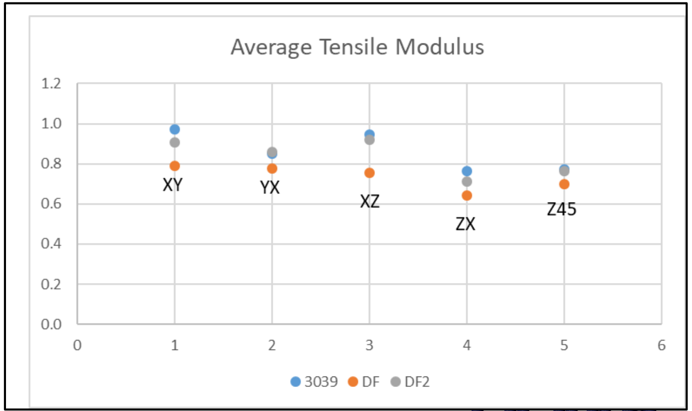
Tension Results









Documentation: Test Plan

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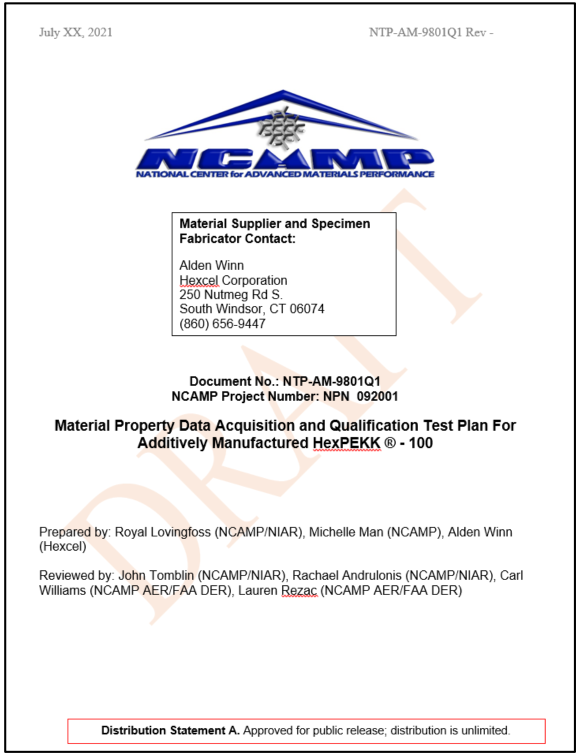

July XX, 2021 NTP-AM-9801Q1 Rev -

NATIONAL CENTER for ADVANCED MATERIALS PERFORMANCE

Material Supplier and Specimen Fabricator Contact:

Alden Winn
Hexcel Corporation
250 Nutmeg Rd S.
South Windsor, CT 06074
(860) 656-9447

Document No.: NTP-AM-9801Q1
NCAMP Project Number: NPN 092001

Material Property Data Acquisition and Qualification Test Plan For Additively Manufactured HexPEKK ® - 100

Prepared by: Royal Lovingfoss (NCAMP/NIAR), Michelle Man (NCAMP), Alden Winn (Hexcel)

Reviewed by: John Tomblin (NCAMP/NIAR), Rachael Andrulonis (NCAMP/NIAR), Carl Williams (NCAMP AER/FAA DER), Lauren Rezac (NCAMP AER/FAA DER)

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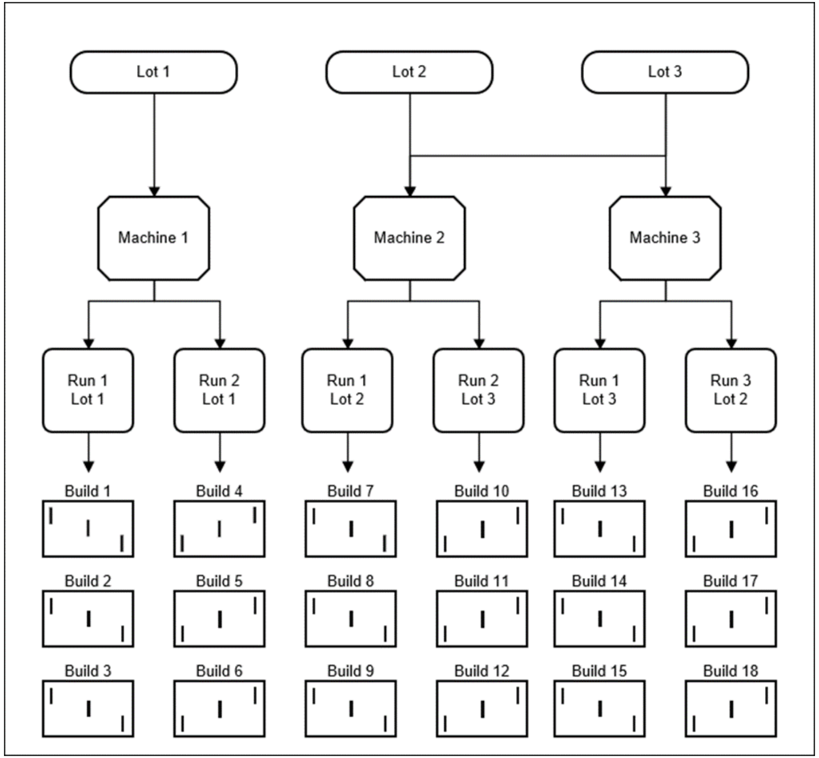

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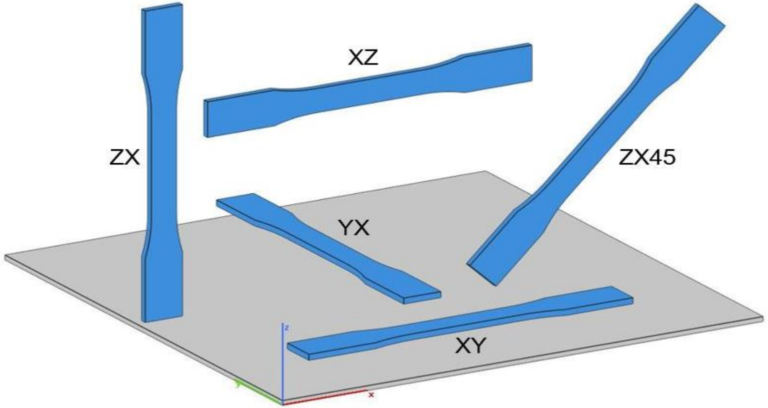
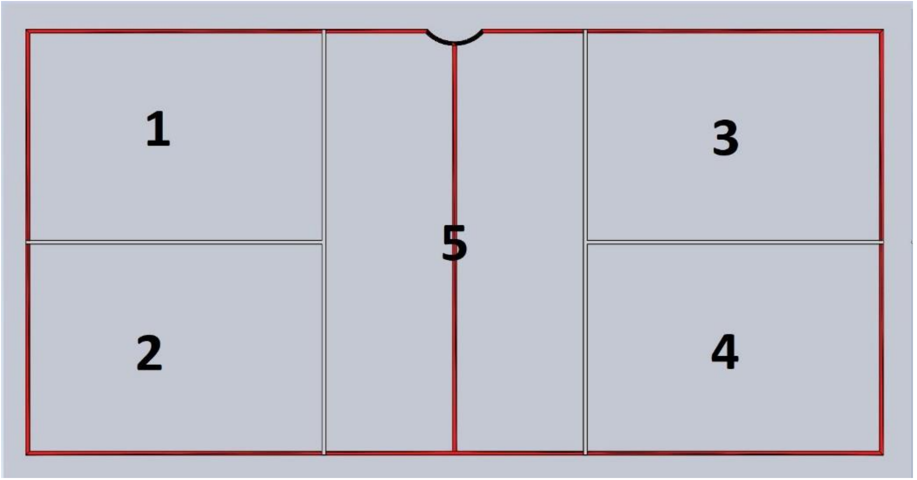
Documentation: Test Plan



Build Orientation Investigation



Build Location Investigation

Qualification Test Matrix

Test Type and Direction	Property	Number of Lots & Machines x Number of Runs x Number of Specimens				
		Test Temperature/Moisture Condition				
		CTA	RTA	180A	250A	250W
ASTM D638 (DF2) Tension XY	Strength and Modulus	3x2x3	3x2x3	1x2x3	3x2x3	3x2x3
ASTM D638 (DF2) Tension YX	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D638 (DF2) Tension XZ	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D638 (DF2) Tension ZX	Strength and Modulus	3x2x3	3x2x3	1x2x3	3x2x3	3x2x3
ASTM D638 (DF2) Tension Z45	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D695 Compression XY 1” right prism	Strength and Modulus	3x2x3	3x2x3	1x2x3	3x2x3	3x2x3
ASTM D695 Compression YX 1” right prism	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D695 Compression XZ 1” right prism	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D695 Compression ZX 1” right prism	Strength and Modulus	3x2x3	3x2x3	1x2x3	3x2x3	3x2x3
ASTM D695 Compression Z45 1” right prism	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D790 Flex (Proc. B) XY	Strength and Modulus	3x2x3	3x2x3	1x2x3	3x2x3	3x2x3
ASTM D790 Flex (Proc. B) YX	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D790 Flex (Proc. B) XZ	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D790 Flex (Proc. B) ZX	Strength and Modulus	3x2x3	3x2x3	1x2x3	3x2x3	3x2x3
ASTM D790 Flex (Proc. B) Z45	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D732 Shear XY	Strength and Modulus	3x2x3	3x2x3	1x2x3	3x2x3	3x2x3
ASTM D732 Shear YX	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D732 Shear XZ	Strength and Modulus	1x2x3	1x2x3			1x2x3
ASTM D732 Shear ZX	Strength and Modulus	3x2x3	3x2x3	1x2x3	3x2x3	3x2x3
ASTM D732 Shear Z45	Strength and Modulus	1x2x3	1x2x3			1x2x3

Qualification Test Matrix

Test Type	Property	Number of Lots & Machines x Number of Runs x Number of Specimens			
		Test Temperature/Moisture Condition			
		CTA	RTA	250/A	250W
ASTM D5766 Open Hole Tension XY	Strength	3x2x3	3x2x3	3x2x3	3x2x3
ASTM D5766 Open Hole Tension YX	Strength	1x2x3	1x2x3		1x2x3
ASTM D5766 Open Hole Tension XZ	Strength	1x2x3	1x2x3		1x2x3
ASTM D5766 Open Hole Tension ZX	Strength	3x2x3	3x2x3	3x2x3	3x2x3
ASTM D5766 Open Hole Tension ZX45	Strength	1x2x3	1x2x3		1x2x3
ASTM D6742 Filled Hole Tension XY	Strength	3x2x3	3x2x3	3x2x3	3x2x3
ASTM D6742 Filled Hole Tension YX	Strength	1x2x3	1x2x3		1x2x3
ASTM D6742 Filled Hole Tension XZ	Strength	1x2x3	1x2x3		1x2x3
ASTM D6742 Filled Hole Tension ZX	Strength	3x2x3	3x2x3	3x2x3	3x2x3
ASTM D6742 Filled Hole Tension ZX45	Strength	1x2x3	1x2x3		1x2x3
ASTM D6484 Open Hole Compression XY	Offset Strength		1x2x3		1x2x3
ASTM D6484 Open Hole Compression YX	Offset Strength		1x2x3		1x2x3
ASTM D6484 Open Hole Compression XZ	Offset Strength		1x2x3		1x2x3
ASTM D6484 Open Hole Compression ZX	Offset Strength		1x2x3		1x2x3
ASTM D6484 Open Hole Compression ZX45	Offset Strength		1x2x3		1x2x3
ASTM D6742 Filled Hole Compression XY	Offset Strength		1x2x3		1x2x3
ASTM D6742 Filled Hole Compression YX	Offset Strength		1x2x3		1x2x3
ASTM D6742 Filled Hole Compression XZ	Offset Strength		1x2x3		1x2x3
ASTM D6742 Filled Hole Compression ZX	Offset Strength		1x2x3		1x2x3
ASTM D6742 Filled Hole Compression ZX45	Offset Strength		1x2x3		1x2x3
ASTM D5961 Procedure C Bearing XY	Strength & Deformation		3x2x3	3x2x3	3x2x3
ASTM D5961 Procedure C Bearing YX	Strength & Deformation		1x2x3		1x2x3
ASTM D5961 Procedure C Bearing XZ	Strength & Deformation		1x2x3		1x2x3
ASTM D5961 Procedure C Bearing ZX	Strength & Deformation		3x2x3	3x2x3	3x2x3
ASTM D5961 Procedure C Bearing ZX45	Strength & Deformation		1x2x3		1x2x3

Next Steps

- **Next steps and planned work**
  - Finalize and post test plan to the NCAMP Portal
  - Complete necessary NCAMP conformity steps
  - Start qualification builds at Hexcel
  - Start testing at NIAR
  - Assess equivalency options and discuss with Steering Committee
- **Expected outcome**
  - Expanded qualification framework and guidance for polymer powder bed fusion
  - Database and associated specifications
  - Data for CMH-17 submittal (Data Review and Statistics Working Group evaluation)
  - Test Method and Specification Guidance documentation

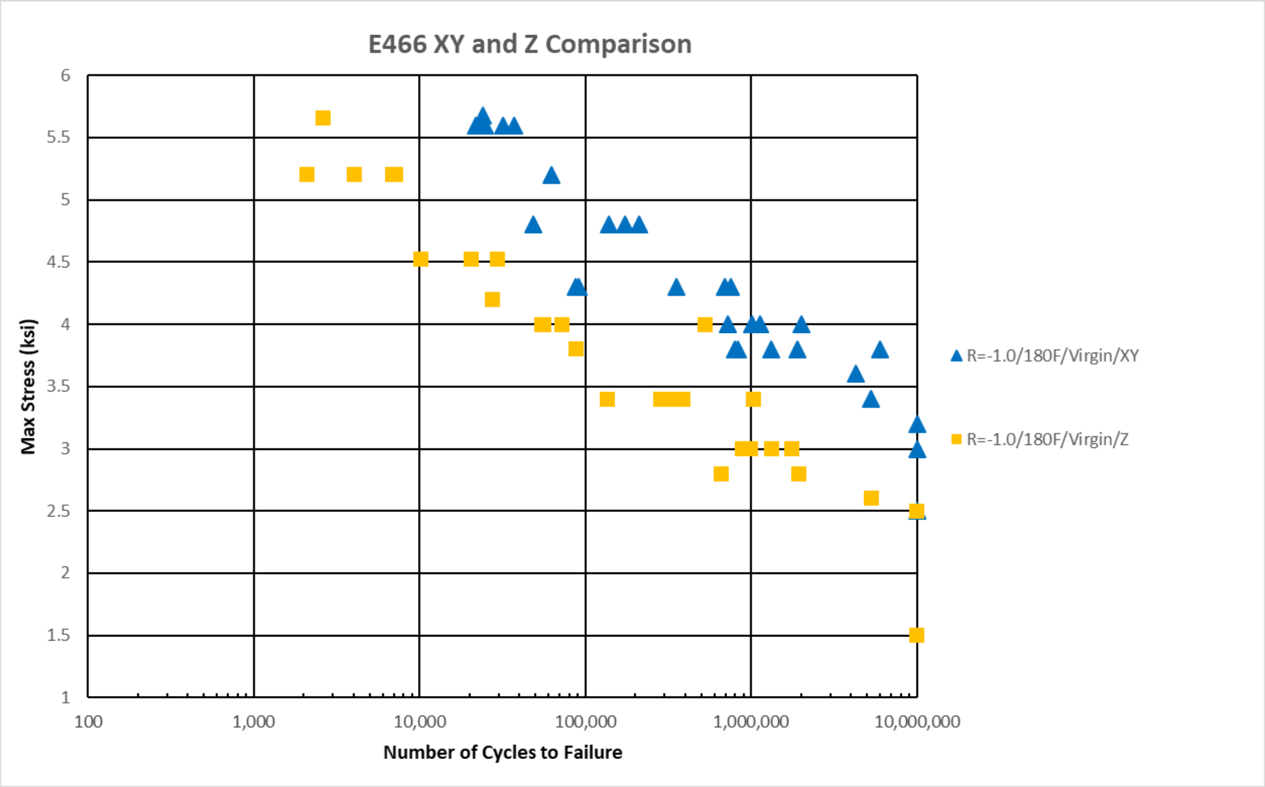
Factors Affecting Qualification: Application Testing

- **Fatigue Testing on HexAM material planned**
  - Can be published in CMH-17 along with qualification data

Status:

- **Trial Coupons tested (static and fatigue)**
  - All gage failures
  - Some alignment issues and roundness issues
  - Processing changes to achieve better alignment
- **Test Plan**
  - Input from Steering Committee, industry (Northrop Grumman) and DoD POCs
  - Initial static tests were performed to determine stress level
  - Several iterations of fatigue testing in both XY and Z directions (Traditional Design Curves – Load Controlled (R=-1), High Cycle Fatigue)
- **Expected completion by end of 2021**

Fatigue Results To Date



Technical Publications

- NCAMP reports (material and statistics)
- NCAMP material and process specifications
- SAE specification development
- CMH-17 data (qualification) and lessons learned
- Guidance documentation on specification development

Other Polymer AM Activities

	Qualification	Factors Effecting Qualification		Special Factors & Equivalencies
Task 16	Development of Qualification Program	Establish Industry/Gov't Steering Committee	Development of Statistical Guidelines	Guidelines and Recommendations
Task 18	Material Extrusion Qual Filled Thermoplastic	Processing Window Expanse	Fabricated v. Machined	Microstructure Scaling
Task 19	Powder Bed Fusion Qual Filled Thermoplastic	Machine & Material Variability	Test Methods	Material Extrusion Equivalency
		Scaling & Machining	Parameters Effects on FST	
Task 20	Powder Bed Fusion Qual EOS M290 | Ti-6Al-4V	Building Block	AM Roadmap	Powder Bed Fusion Equivalencies

Post-ULTEM qualification guidelines

- **Status**
  - CMH-17 AM Volume created with working groups established
  - On-going support of SAE AMS-AM on the development of ULTEM specifications
  - On-going support of ASTM F42, D20, and ASTM AM COE

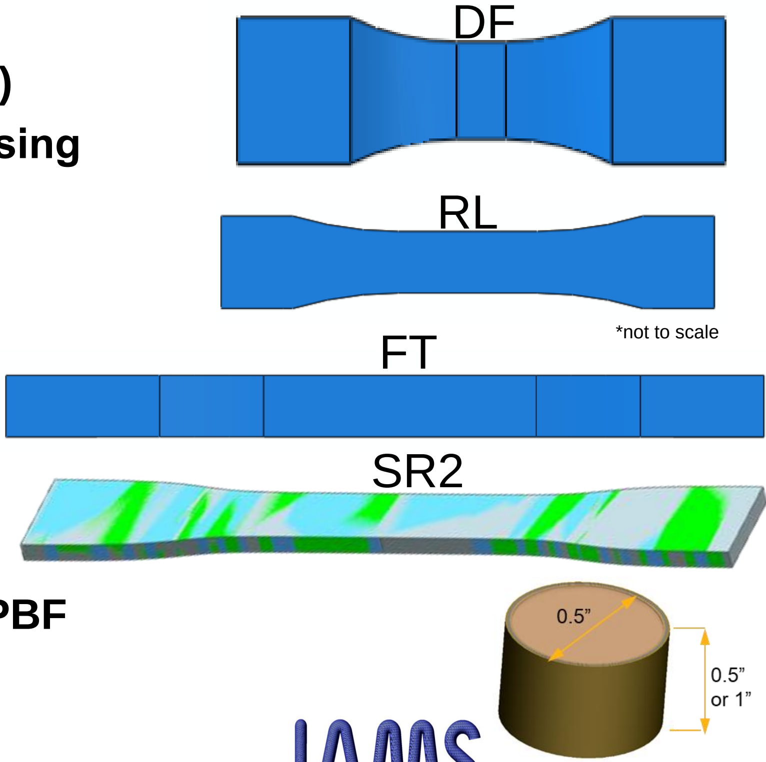
- **Deliverables**
  - Charters for all CMH-17 AM Work Groups
  - AMS 7100 & AMS 7101 Published
  - New work items created for testing guidance and alternative geometries for Tension & Compression

Test Methods

- **Objectives**
  - The goal of this study is to develop guidelines for best practices on test methods for polymer AM materials.
  - Determine how different specimen thicknesses effect micro-structure for as-printed and as-printed + machined testing.
  - Learnings from as-printed vs. machining as well as thickness studies will be part of an additional guidance document through the ASTM AM CoE.

Test Methods:
Alternative Geometries

- Tension
- D638 Type 1 – baseline (based on ULTEM Qual.)
- Double flared sub-scale – Boeing's most promising result
- Reduced length - Second Boeing candidate, consistent with Airbus specimens
- Flat size, Thicker grip – ME friendly
- LMCO – Streamline Radius
- Compression
- D695 modified 6.7.2 – baseline
- D695 Type 6.2 (cylinder) – commonly used for PBF
- D695 Type 6.1 (prism) – 0.5"x0.5"x (1"or 2")



Test Methods:
D638 Conclusions

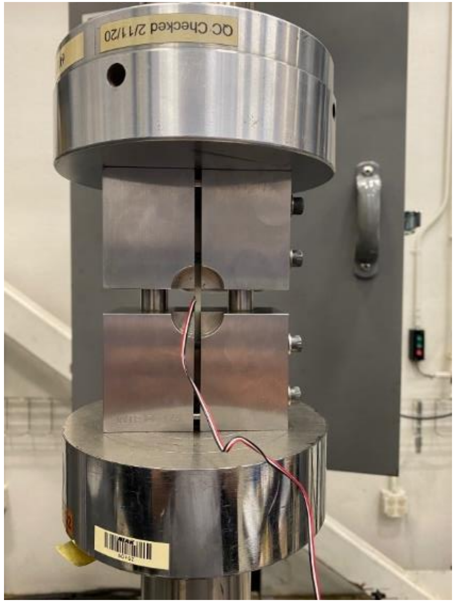
- **As-printed Specimen evaluation for Material Extrusion**
  - Leading candidate alternatives look good for D638
  - Machining specimens still working through approach and testing
  - Non-ME technologies remain on hold (some volunteers ID'd)

	Geometry	Printability	Failure Mechanism	CoV
Tension Testing (As-Printed)	Double Flare, Sub Scale (DF)	●	●	◕
	Full size, thick grip (FT)	◑	◑	◕
	Reduced Length (RL)	●	◕	◔
	D638 Type 1 (T1)	◑	◕	●
	Streamline Radius 2 (SR2)	◑	◔	◑

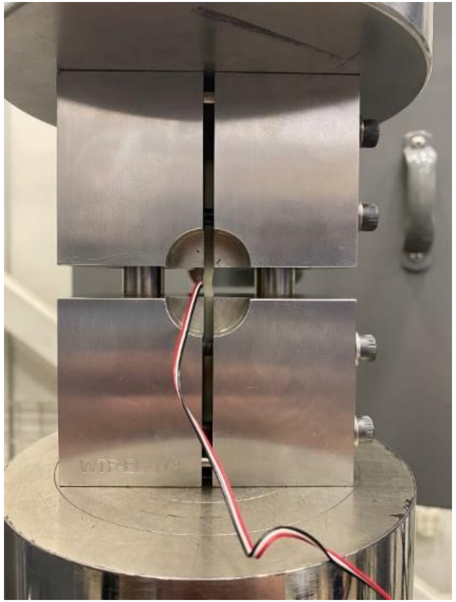
Compression Studies Ongoing

NIAR® WICHITA STATE UNIVERSITY NATIONAL INSTITUTE FOR AVIATION RESEARCH

D695 fabrication by RP+M
D6641 Testing studies ongoing at NIAR



Pre-test

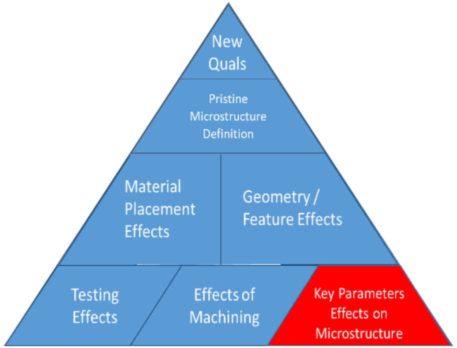


Post-test buckling

JAMS Joint Centers of Excellence for Advanced Materials

FY18 Structure Property Mapping

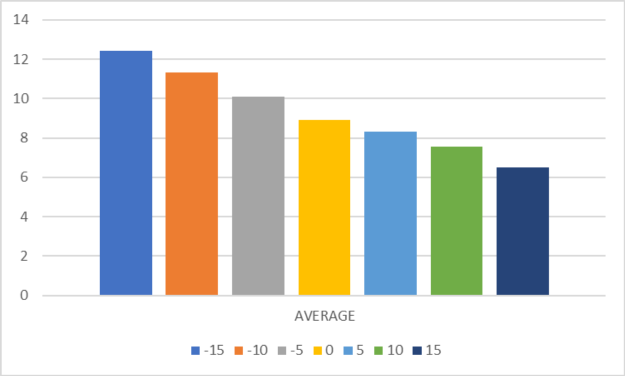
- **Objective**
  - Theory: consistent micro-structure will allow for different machines to achieve the same mechanical performance.
  - First step in determining possibility of expanding machines and even platforms.
  - Process parameters and input variables were tightly controlled and limited during the U9085 qualification but need to be correlated back to a micro-structure definition to prove that the full-range of operating conditions could be opened up on the F900/900mc
- **Overview**
  - Literature review completed on weight of influence by parameter
  - Test & Fab Matrix and Test Plan: vary 8 HIGH to MED impact variables
  - 720 Specimens printed and tested – D638 tensile



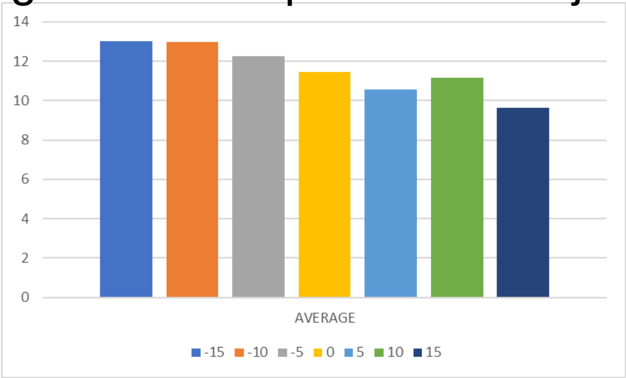
Structure Property Mapping: Interesting Results

- Air gap settings (adjacent rasters, contour and rasters, and contour to contour) were the only parameters that had significant trends
- Parameter changes didn't decrease CoV only overall performance

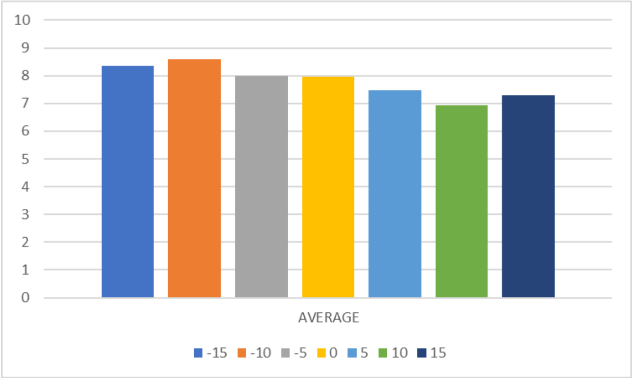
Tensile Strength vs Air Gap between adjacent rasters



XY



XZ



ZX

All values in ksi
Modifications were 0.000X"

FY18 Machining Studies

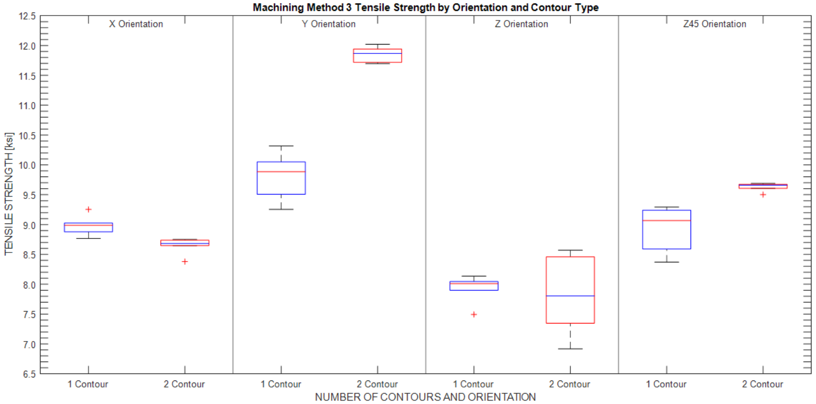
- **Objective**
  - Determine methods of machining/grinding/finishing that do not introduce surface defects and flaws altering the behavior of the material and determine if the micro-structure can be upheld after machining.
- **Overview**
  - Best practices and literature review on machining FFF completed
  - Three machine techniques explored with 1 and 2 contours
  - Printing and Testing completed; key results on next slide

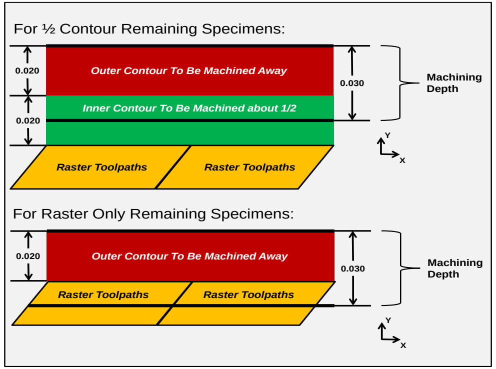
Machining Study Results

DIAMOND TOOL 140/175 GRIT
SURFACE ROUGHNESS : ≥32 Micro

DIAMOND TOOL 500 GRIT
SURFACE ROUGHNESS : ≥32 Micro

PCD DIAMOND TOOL
SURFACE ROUGHNESS : ≥32 Micro



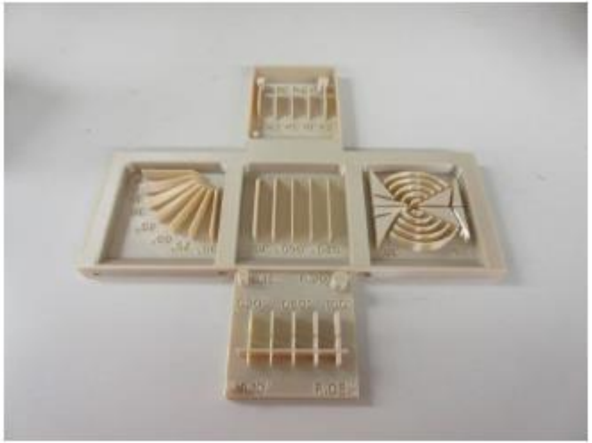


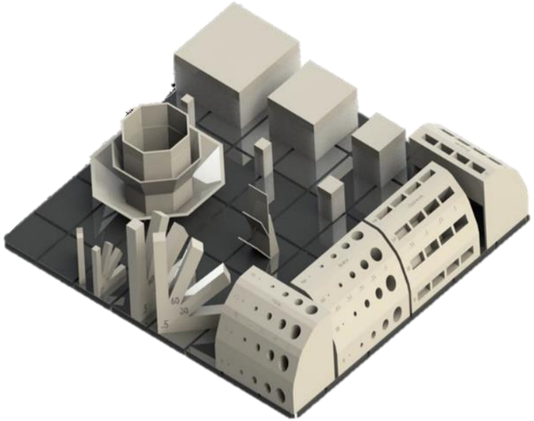
Scaling Studies (Part Feature)

- **Objective**
  - Perform building blocks for initial feature-level testing.
  - This study addressed how initial raster angle, specimen thickness, and contour thickness impacts tensile strength.
- **Overview**
  - 108 specimens fabricated at three different cross-sectional areas (ASTM D638)
  - Gage widths of 0.5” and 0.75” for Type 1 and Type 3 specimens
  - Two thicknesses (0.13” and 0.28”), Type 3 0.300” thick
  - As-fabricated and contour removed by machining
  - Raster angle from 0° to 40°
  - An increase in cross sectional area for XY specimens leads to decrease in tensile strength (all else held constant)
  - As-machined tensile strength reduced compared to as-fab

Feature-Full Geometries

Established “calibration” or challenge parts created from multiple previous America Makes efforts and industry partners





Machine Type Variability

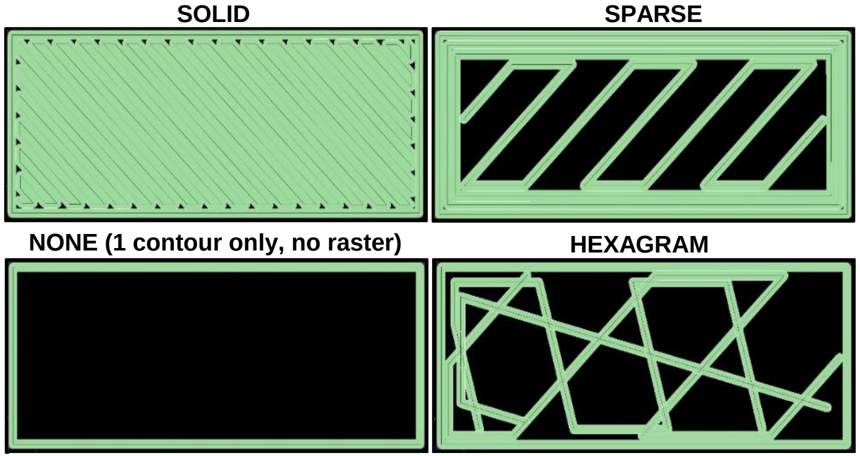
- **Objective**
  - Investigate variability associated with machine type: Will changing the machine (model or manufacturer) affect final mechanical property allowables if the resulting micro-structures are the same? This could be performed initially comparing the ULTEM 9085 database generated on a Fortus 900MC to other FDM machines (ie. Fortus 450 or F900) that are widely used in industry.
- **Status**
  - Gated by microstructure definitions
  - Discussions underway with SSYS and FAA representatives to determine machine architectures

FY19 Scaling Studies – Effect on FST

- **Objective**
  - To assess select processing parameters (such as density, build strategy, insight parameters) on the final FST (fire, smoke, toxicity) properties for the existing ULTEM 9085 database.
  - Study the effects of optimization and skinning as well as regular part deviations from the toolpath layup strategies
- **Status**
  - Literature review completed on processing parameters and process inputs effect on FST for FFF
  - All testing completed
  - Thermoplastic property comparison research completed
  - Final report under internal review

FST: Project Details & Results

- This study seeks to evaluate the effect of material extrusion pre-processes parameters on additively manufactured ULTEM 9085 CG FST properties.
- This study intends to determine the effect of varying specimen thickness and infill pattern on flammability and to develop an understanding of worst-case FST properties due to a possible fabrication failure for additively manufactured thermoplastic interiors.
- The goal of the study to determine the fire-retardancy of ULTEM 9085 specimens with minimum thickness and to research if there exists a combination of thicknesses and infill patterns that complies with industry specifications.



Infill style used in builds


Pre (left) and post-test (right) vertical burn test specimens

FY19: Test Methods

- **Objectives**
  - The goal of this study is to develop guidelines for best practices on test methods for polymer AM materials.
  - Determine how different specimen thicknesses effect micro-structure for as-printed and as-printed + machined testing.

Fabrication → *Contour Measurement* → *Machining (Milling)* → *Dimensioning* → *Testing*

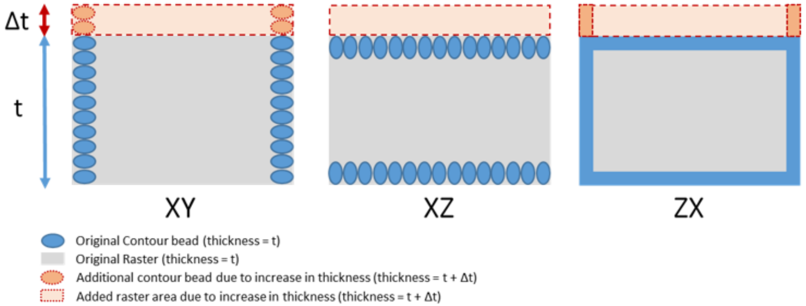
  - Learnings from as-printed vs. machining as well as thickness studies will be part of an additional guidance document through the ASTM AM CoE.

- **Investigation of specimen quality and test repeatability for as fabricated and machined specimens of Type 1, Type 3, and Dual Flange (DF) specimen**

- **Status**
  - Project work complete. Final report under review.

Test Methods: Project Details & Results

- This study intends to determine the effect of varying specimen thickness, five geometries, and two finish types on the UTS (Ultimate Tensile Strength).
- The results discovered that thicker XZ specimens had lower UTS than thinner ones as thinner coupons have a higher amount of contours on a given cross-section area in a gauge section.
- For as-fabricated specimen tensile testing the use of Type 1 geometry is recommend based on the low dispersion in data.
- The use of Type 3 geometry is recommended for as-machined coupon testing as Type 3 has the largest dimensions which allow the machine shop to fix the coupon position on a machine resulting in more accurate machining and an increase in surface quality.
- On the contrary, in an application where both surface quality and consistent tensile strength are required, the use of Type 4 and DF are not recommended due to the small dimensions.



Comparison of a cross-section area diagrams in a gauge section and effect of increased thickness in XY, XZ, and ZX

Pre-test and post-test specimens

Metal AM Activity

	Qualification	Factors Effecting Qualification		Special Factors & Equivalencies
Task 16	Development of Qualification Program	Establish Industry/Gov't Steering Committee	Development of Statistical Guidelines	Guidelines and Recommendations
Task 18	Material Extrusion Qual Filled Thermoplastic	Processing Window Expanse	Fabricated v. Machined	Microstructure Scaling
Task 19	Powder Bed Fusion Qual Filled Thermoplastic	Machine & Material Variability	Test Methods	Material Extrusion Equivalency
		Scaling & Machining	Parameters Effects on FST	
Task 20	Powder Bed Fusion Qual EOS M290 | Ti-6Al-4V	Building Block	AM Roadmap	Powder Bed Fusion Equivalencies