Additive Manufacturing of Ultem Polymers and Composites

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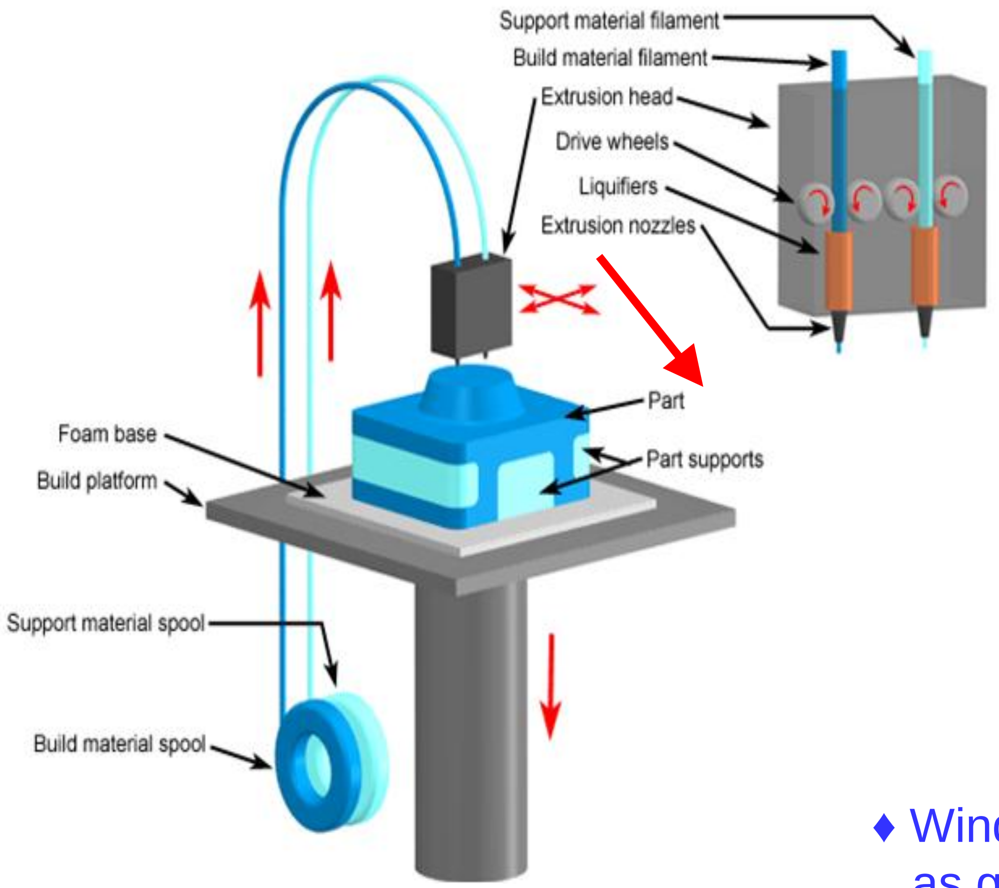
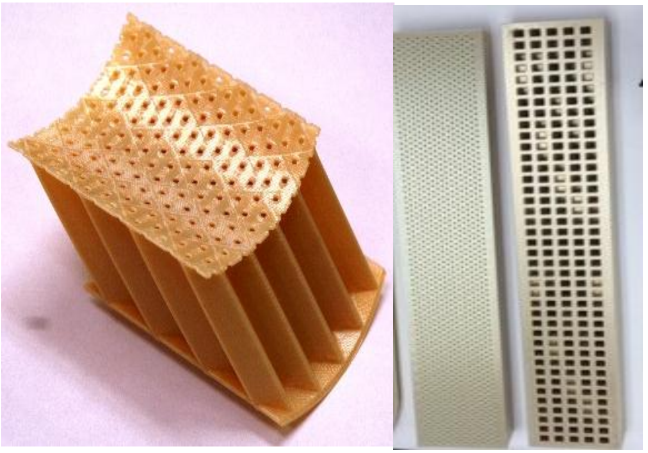
Fused Deposition Modeling (FDM): a polymer filament is melted and then deposited in successive layers to build a 3D component according to a computer-aided design (CAD) file

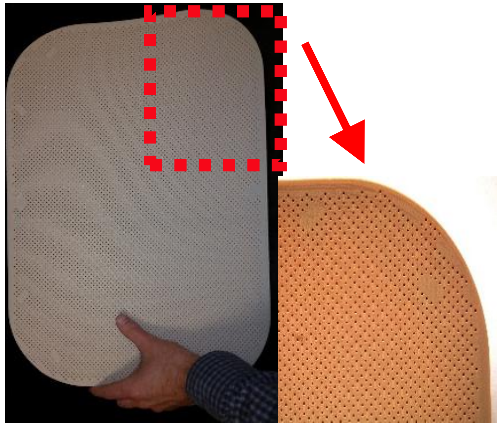


Advantages of Additive Manufacturing

- Quick turn around time for complex parts
- Shorten production and testing cycle
- Save money for low production volume parts



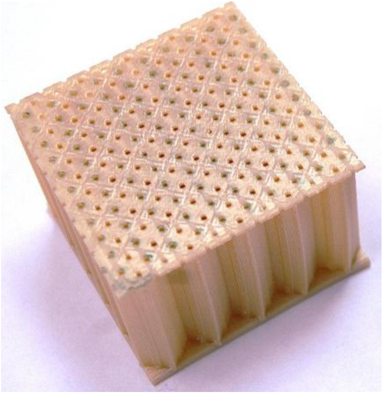
a) Acoustic liner & components
Ultem 9085
Modulate Sound Wave

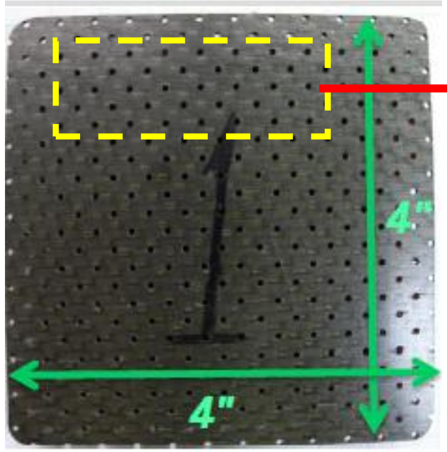


b) Perforated engine access door
Ultem 9085
Reduce Noise

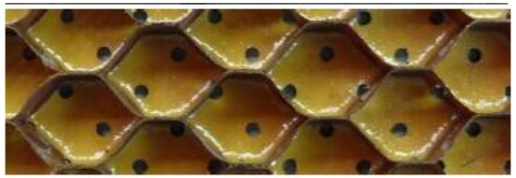
- ♦ Wind tunnel tests showed that FDM-printed acoustic liners performed as good as conventional liners (Honeycombs/facesheets)
- ♦ Unconventional acoustic liners by AM can modulate multiple frequencies

Fused Deposition Modeling Simplifies Acoustic Liner Fabrication

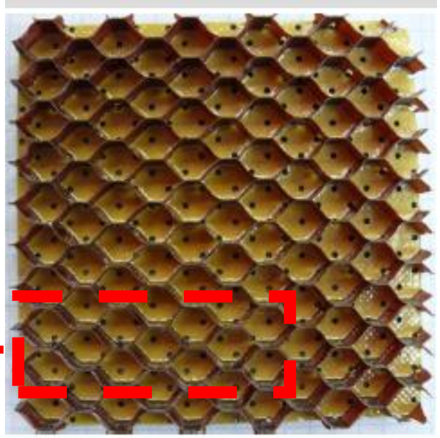




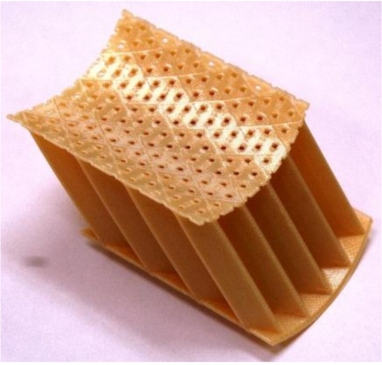
Perforated Facesheet



Bonded Structure



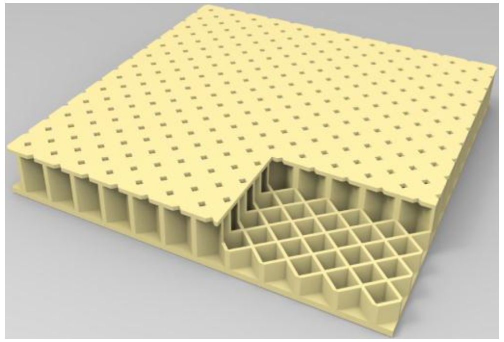
Honeycomb



Current manufacturing approach requires honeycomb, bonding and drilling

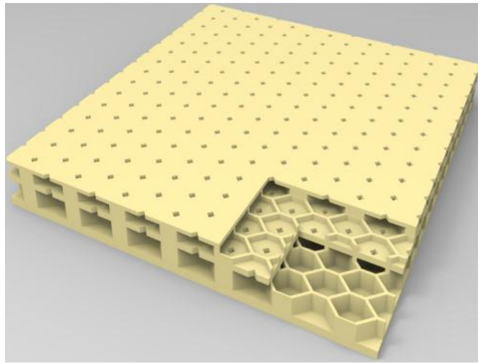
Integral facesheet/honeycomb structure is fabricated in one step using Fused Deposition Modeling

200ºF Operating Temperature



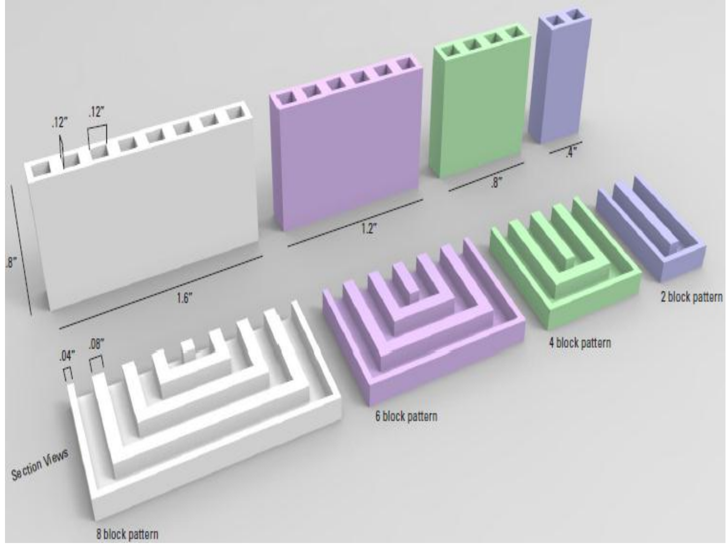
standard liner configuration

complex geometries

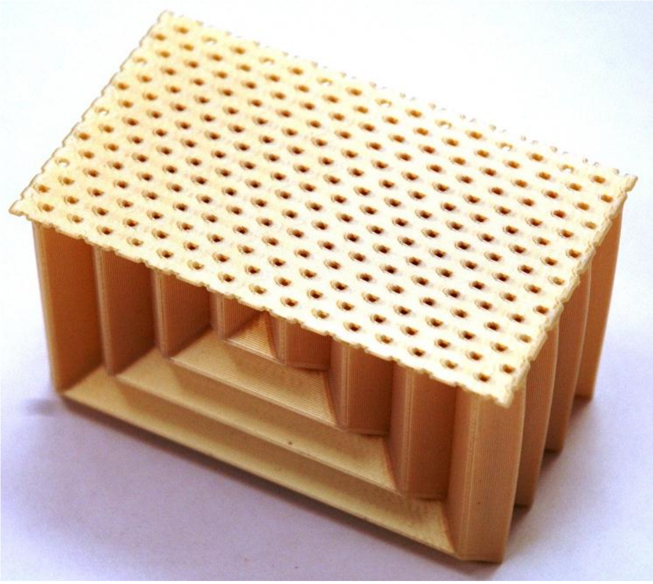


Fabricated with monolithic Ultem 9085 thermoplastic (T_g = 367^{o}F)

Fused Deposition Modeling Enables Fabrication of Advanced Acoustic Liner Concepts

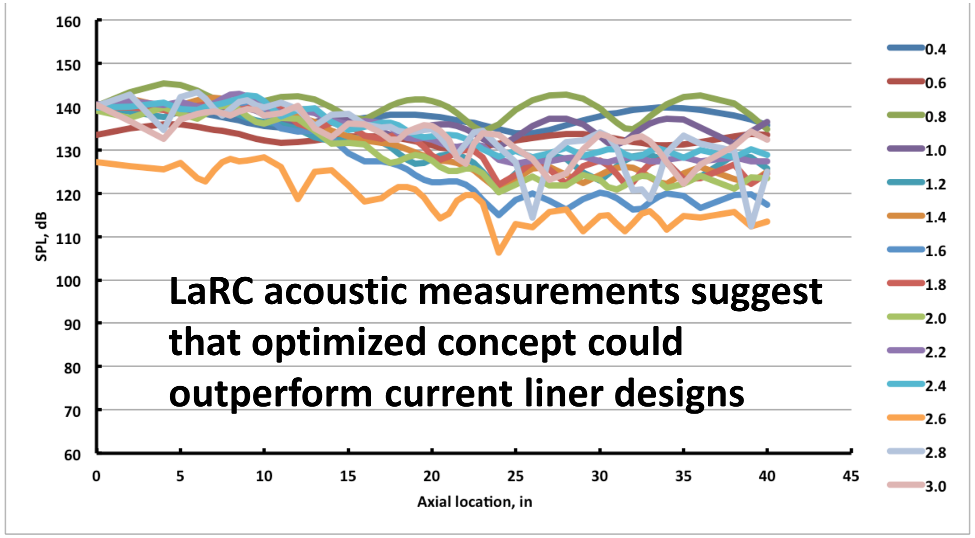


Acoustically-tuned passages provide broadband noise attenuation



FDM sample of advanced liner

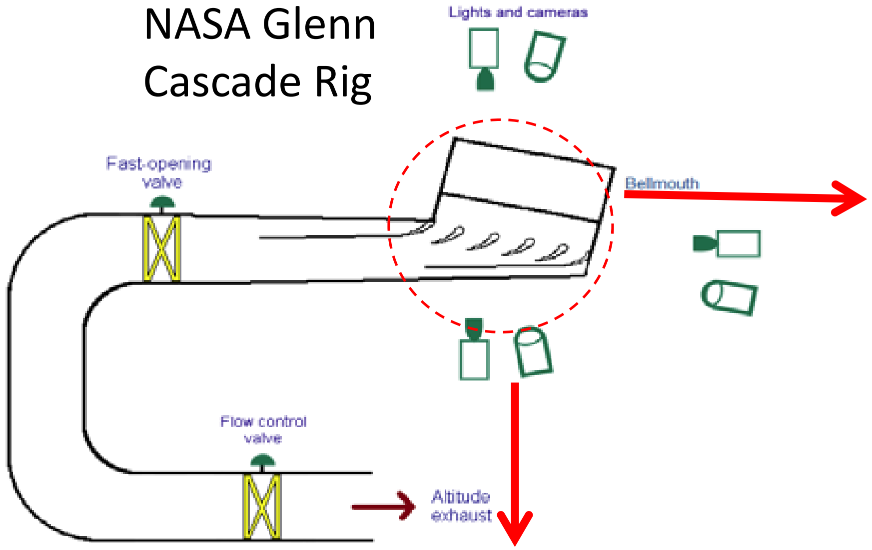
Fabricated 16x2 inch test article

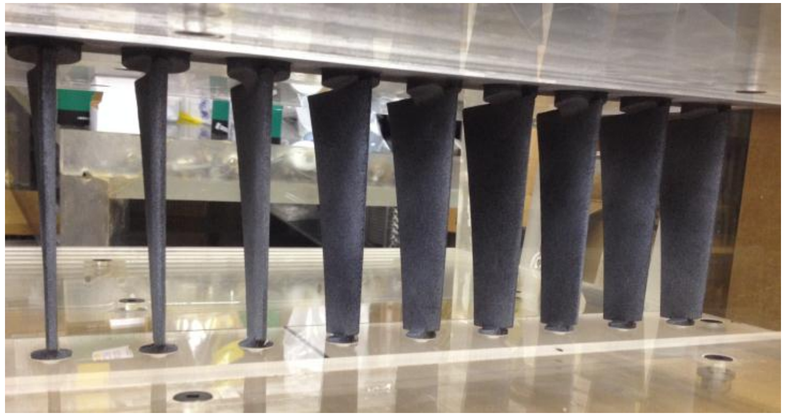


LaRC acoustic measurements suggest that optimized concept could outperform current liner designs

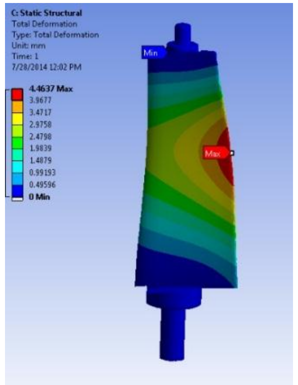
Structural Integrity of Inlet Guide Vane was evaluated under aerodynamic loading

NASA Glenn Cascade Rig

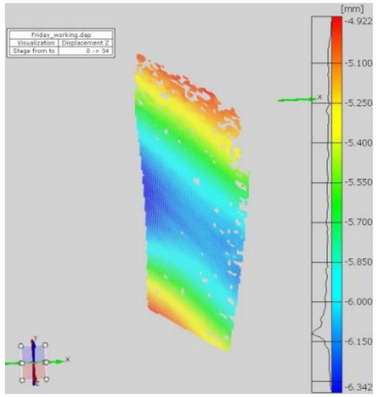




Vane Configuration in Cascade Rig



Stress Analysis



Deformation Measurements

Other FDM composites being evaluated:

Matrix (+C fiber)	Use Temperature (^{o}F)
Ultem 1000	350
Ultem 9085	275
ABS	200

Mechanical Properties of Ultems

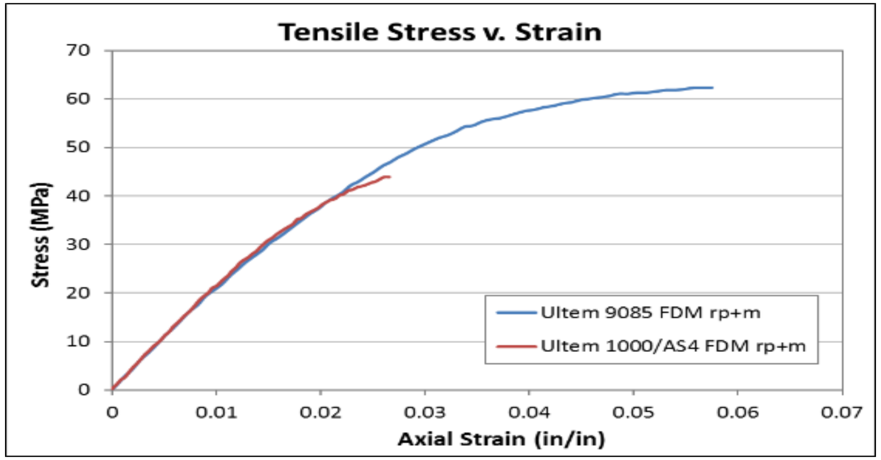
FDM Printing *vs* Injection Molding

Typical RT mechanical properties

Resin Type / Properties	Ultem 9085 Injection Molded (Sabic data)	Ultem 9085 FDM (Stratasys data) 0°	Ultem 9085 FDM rp+m (GRC tested) ±45°	Ultem 1000 Injection Molded (Sabic data)	Ultem 1000 + 10wt% AS4 FDM rp+m (GRC tested) 0° / ±45°
Tensile Strength (MPa)	83	72	62	110	50 / 44
Tensile Modulus (MPa)	3,432	2,200	2,090	3,579	2,860 / 2,092
Flexural Strength (MPa)	137	115	92	165	tbd
Flexural Modulus (MPa)	2,913	2,500	1,901	3,511	tbd
Compression Strength (MPa)	n/a	104	tbd	n/a	tbd
Compression Modulus (MPa)	n/a	1,930	1,890	n/a	tbd

♦ Ultem 9085 FDM prints contains about 5-8% voids.

Tensile properties of Ultem 9085 & C-filled Ultem 1000 as-received



♦ FDM-properties are inferior to Injection molding due to higher porosity:

- More Brittle
- lower elongation

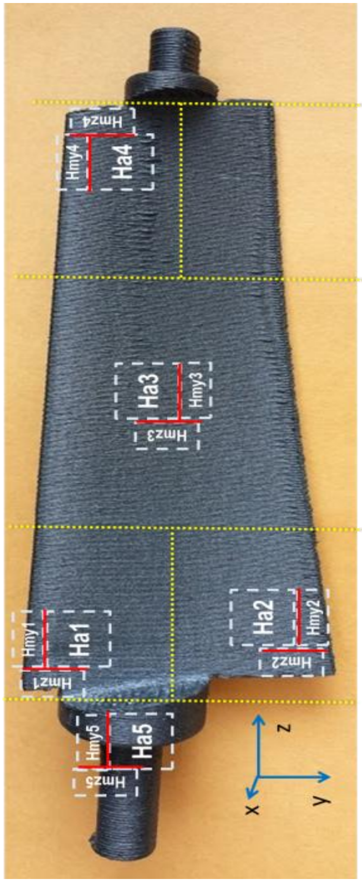
♦ FDM properties depend on:

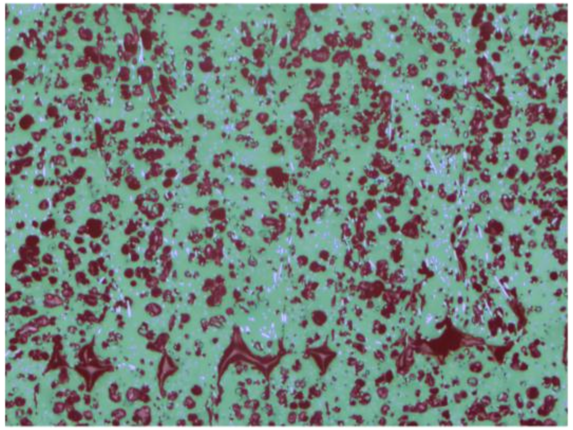
- built direction & raster angle
- thickness of the filaments
- tool path generation
- air gap between raster in the filled pattern

Engine Components by Fused Depostion Modeling

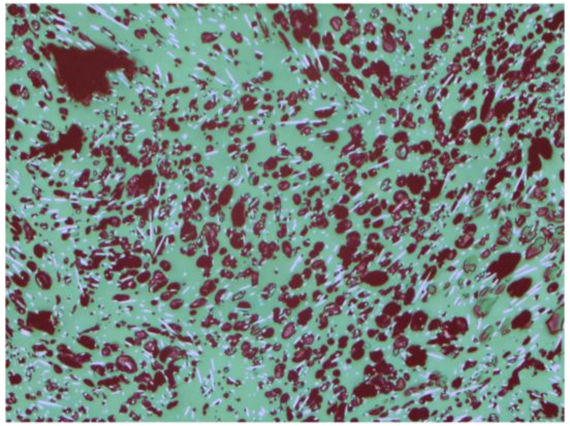
- ♦ **Quality evaluation of the first trial composite vanes made of Ultem 1000 + 10wt% C-fiber**
- ♦ **23-26% porosity (acid digestion) in Ultem 1000 composite vanes**
- ♦ **33% porosity determined by optical microscope images**

Sample ID	After drying					From Theor. Density			FWF wt%	FVF v%	porosity v%
	Balance	Pycnometer		Acid digestion							
	Mc, g	**Vc, cc**	**ρc, g/cc**	**Mf, g**	**Mm, g**	**Vf, cc**	**Vm, cc**	**Vp, cc**			
Ha1	0.7731	0.831	0.931	0.0712	0.702	0.0398	0.5527	0.2385	9%	5%	28.7%
Ha2	0.3977	0.374	1.063	0.0498	0.348	0.0278	0.2739	0.0722	13%	7%	19.3%
Ha3	0.9433	0.952	0.992	0.0894	0.854	0.0499	0.6724	0.2297	9%	5%	24.1%
Ha4	0.6676	0.734	0.911	0.0753	0.592	0.0421	0.4664	0.2256	11%	6%	30.7%
Ha5	1.1184	1.194	0.939	0.0627	1.056	0.0350	0.8313	0.3277	6%	3%	27.4%
Avg									***10%***	***5%***	***26%***
S.D.									***3%***	***2%***	***4%***
Va1	0.8706	0.929	0.938	n/a							
Va2	0.3349	0.347	0.966	0.0346	0.300	0.0193	0.2365	0.0912	10%	6%	26.3%
Va3	0.5443	0.492	1.112	0.0413	0.503	0.0231	0.3961	0.0729	8%	5%	14.8%
Va4	0.637	0.695	0.92	0.0632	0.574	0.0353	0.4518	0.2079	10%	5%	29.9%
Va5	1.2997	1.25	1.037	0.0833	1.216	0.0465	0.9578	0.2457	6%	4%	19.7%
Avg									***9%***	***5%***	***23%***
S.D.									***2%***	***1%***	***7%***





Optical Image of Horizontal Vanes

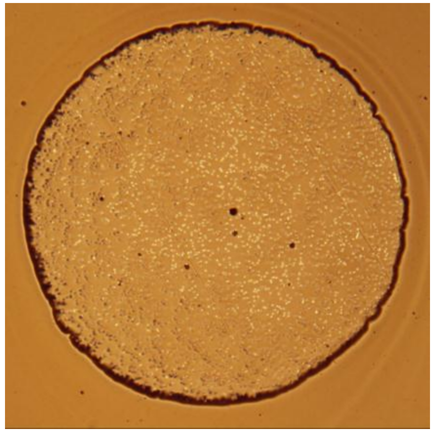


Optical Image of Vertical Vanes

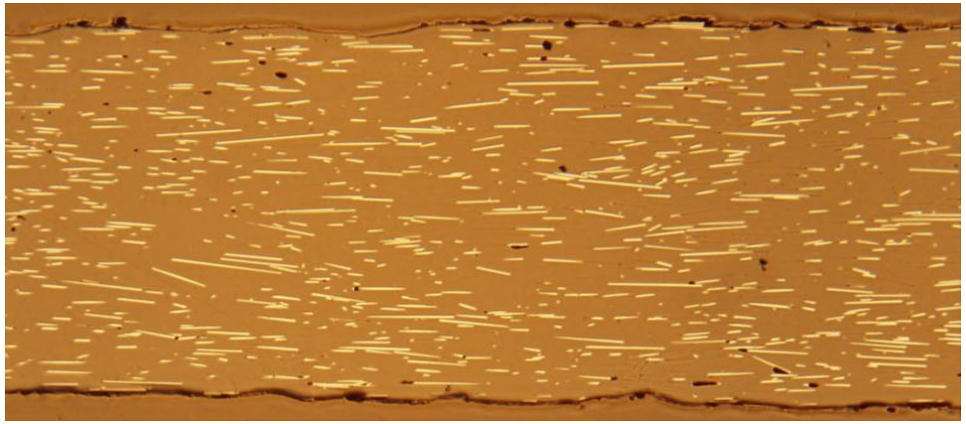
- ♦ **Fiber weight fraction, 10wt%, from the acid digestion consisted with the formulation**
- ♦ **No significant difference between the horizontal and vertical vanes in FVF and porosity**

Evaluation of As-received Fiber Filaments (Thick) and FDM-extruded Filaments at 420 ºC (Thin)

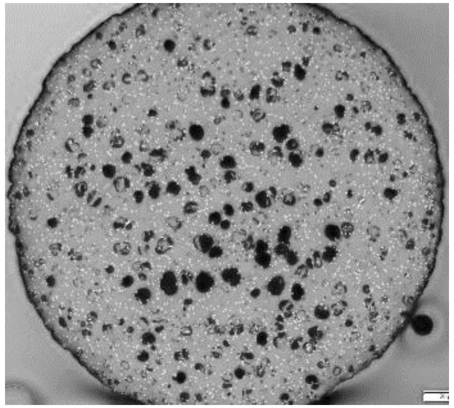
As-Received Ultem 1000 (Thick)



0% Porosity

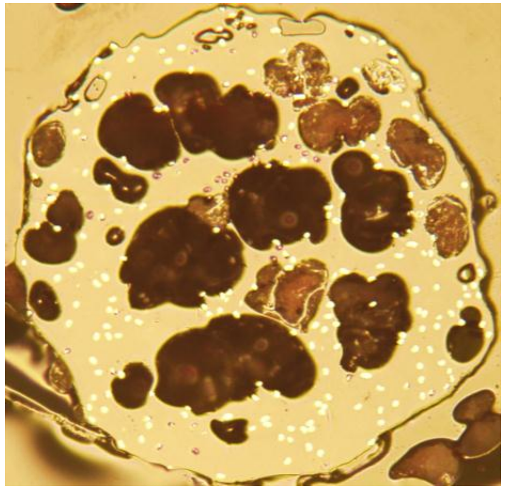


Chopped fibers aligned along the filament axis as expected from extrusion



15% Porosity

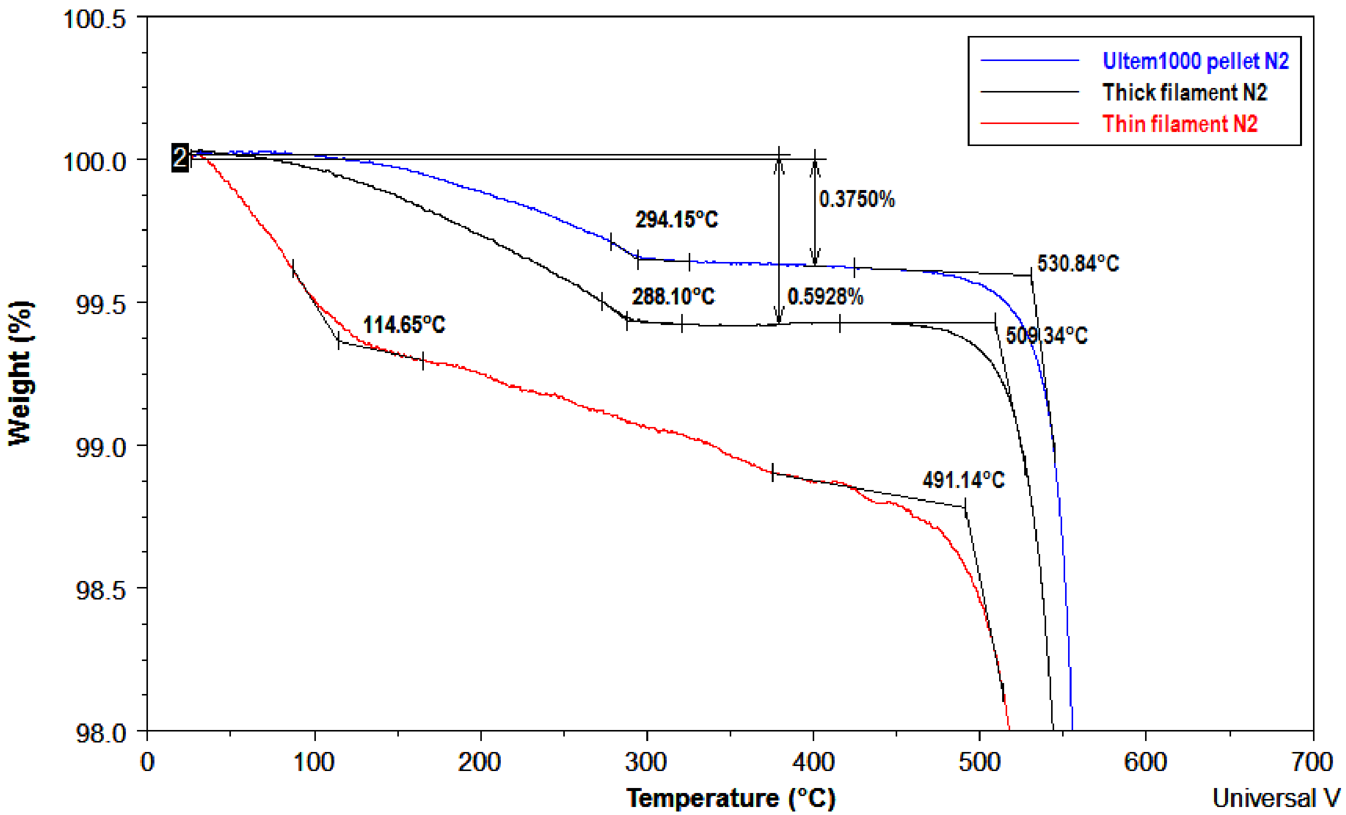
FDM-extruded at 420°C (Thin)



Ultem 1000 thin filament extruded at 420°C exhibited ~30% porosity

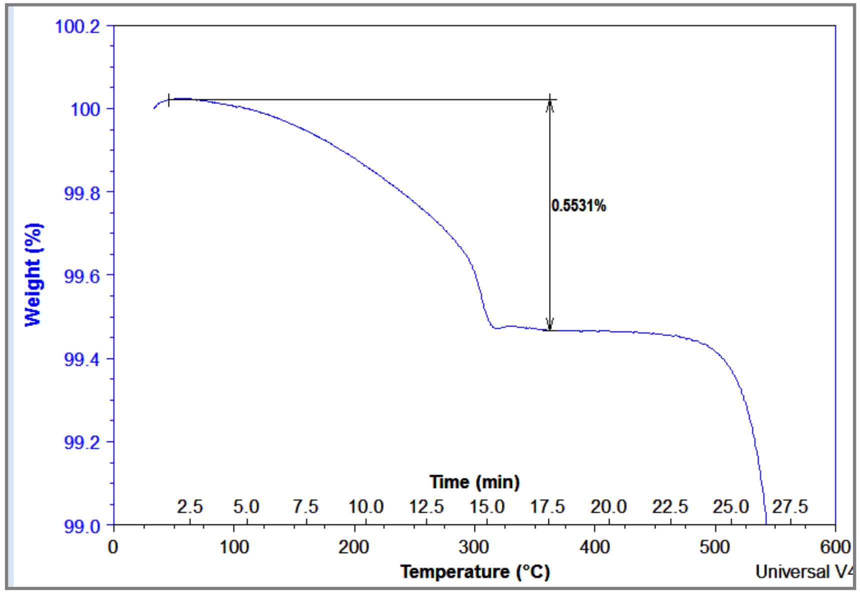
Sample ID	After drying					From Theor. Density			FWF, wt%	FVF, v%	porosity, v%
	Balance	Pycnometer		Acid digestion							
	Mc, g	Vc, cc	ρc, g/cc	Mf, g	Mm, g	Vf, cc	Vm, cc	Vp, cc			
Filament, thick	0.2753	0.2084	1.3209	0.0254	0.250	0.014	0.1968	-0.003	**9%**	**7%**	**-1.2%**
Filament, thin 1	0.0582	0.0645	0.9029	0.0054	0.053	0.003	0.0416	0.02	**9%**	**5%**	**30.9%**
thin 2	0.0583	0.0653	0.8924	0.0054	0.053	0.003	0.0417	0.021	**9%**	**5%**	**31.6%**

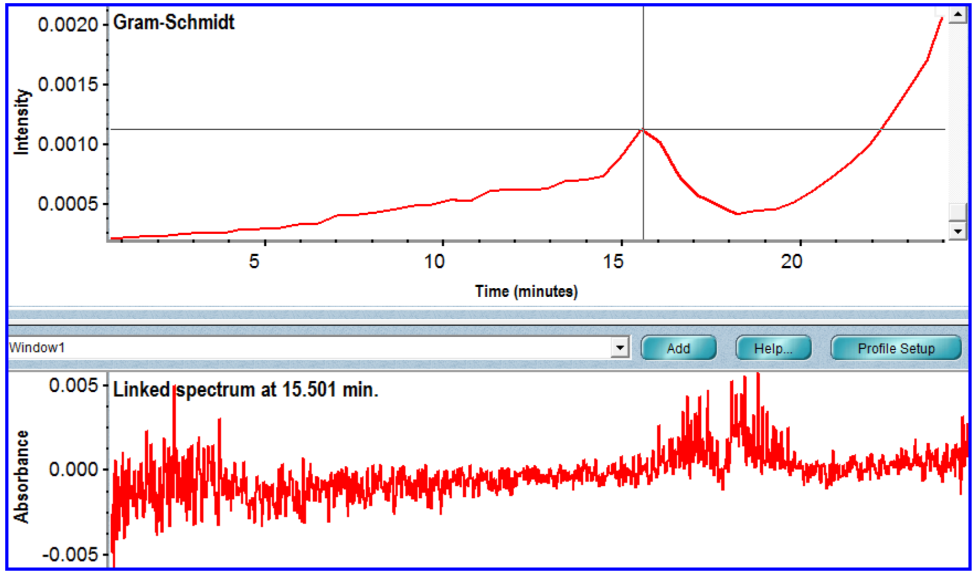
- Void formation mechanisms of the currently printed Ultem 1000 + 10wt% C-fiber composite?
  - Evaluated the filament feedstock: As-received (Thick) vs. exposed to 420 °C thru printer inlet (Thin)

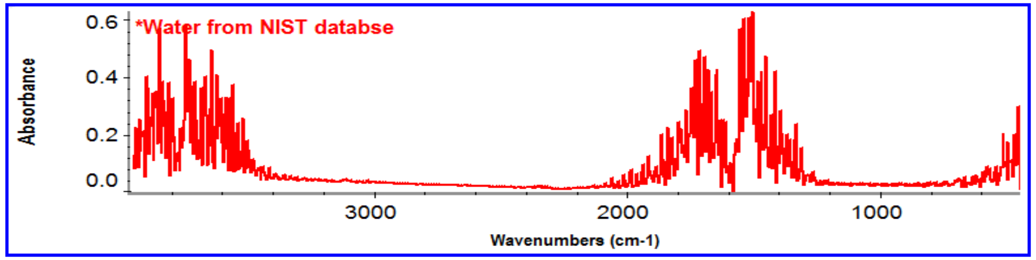


- ✓ TGA curves show changes in material behavior from pellet, to extruded filament, and to 420 °C exposed filament, i.e., thermal degradation onset temperature decreased gradually and weight loss pattern changed

- Void formation mechanisms of the currently printed Ultem 1000 + 10wt% AS4 C-fiber composite?
  – Evaluated the filament feedstock: As-received (Thick) vs. exposed to 420 °C thru printer inlet (thin)



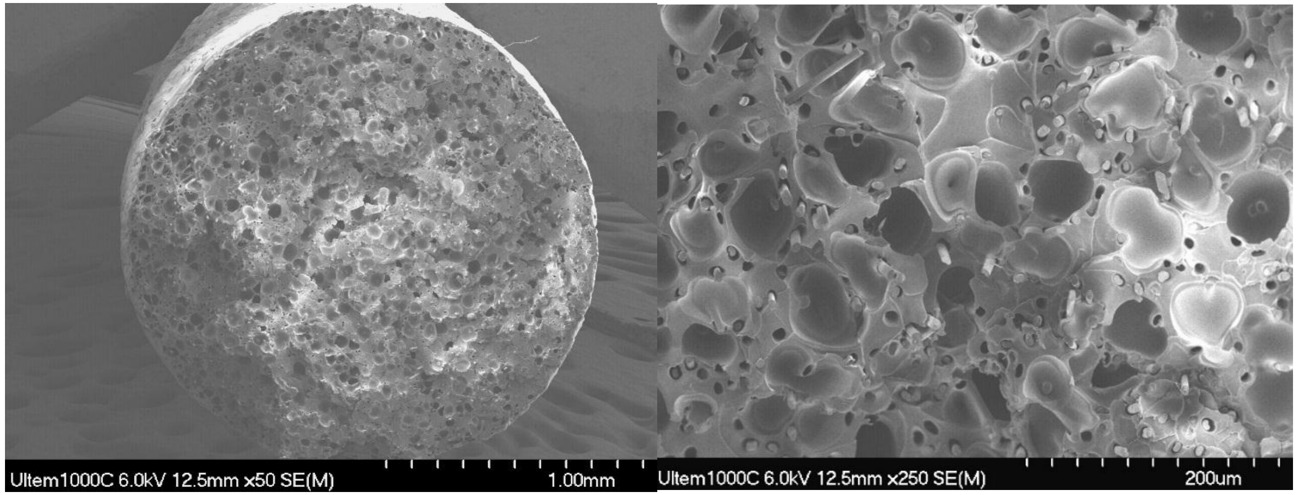


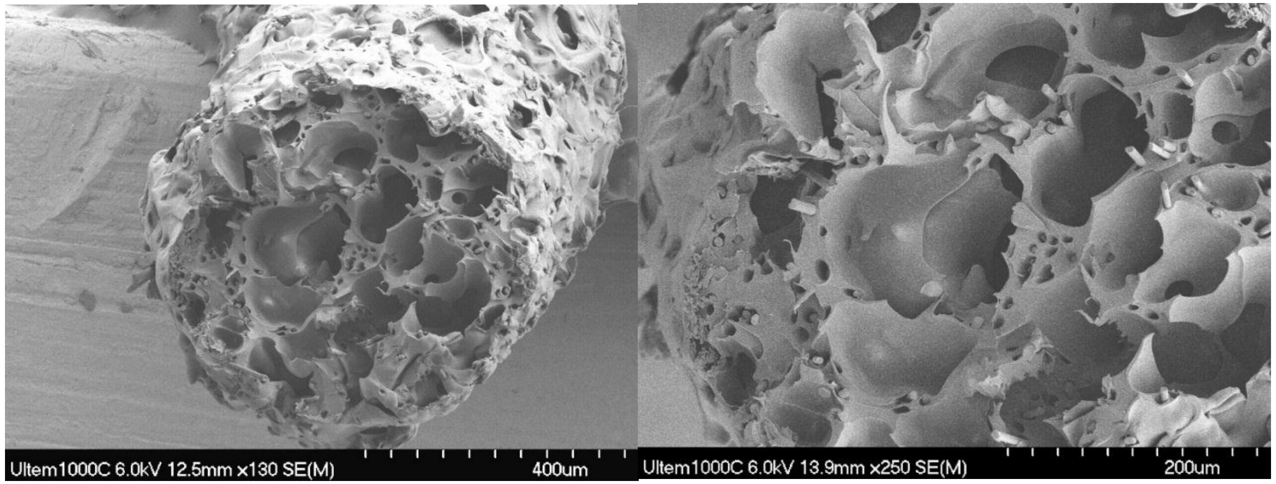


- ♦ **TGA-FTIR confirmed that the initial weight loss up to 300 °C was due to vaporization of the trapped water or other volatiles generated at 420 °C inside the extruded filaments**
- ♦ **Drying of the filament prior to printing recommended: 100 °C for a couple of hours → 200 °C for 6-14 hrs to prevent any potential softening blistering of filaments**
- ♦ **Ultimate remedy ⇒ dry filaments after compounding and keep them dry during filament extrusion process**

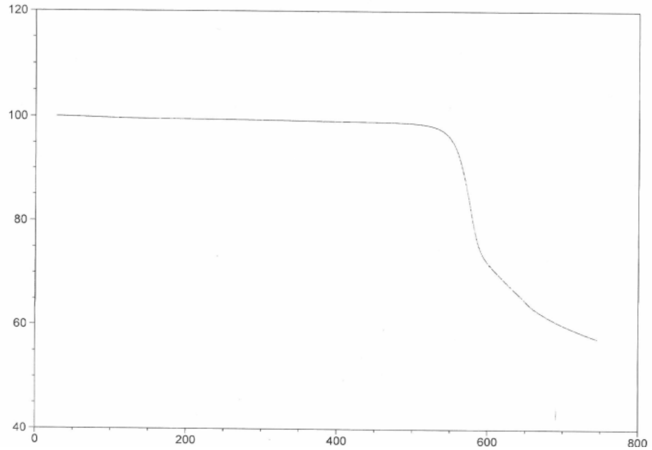
Ultem 1000 C-Filaments after Drying at 400°F/22 h

Dried Thick Filament





Dried Thin Filament

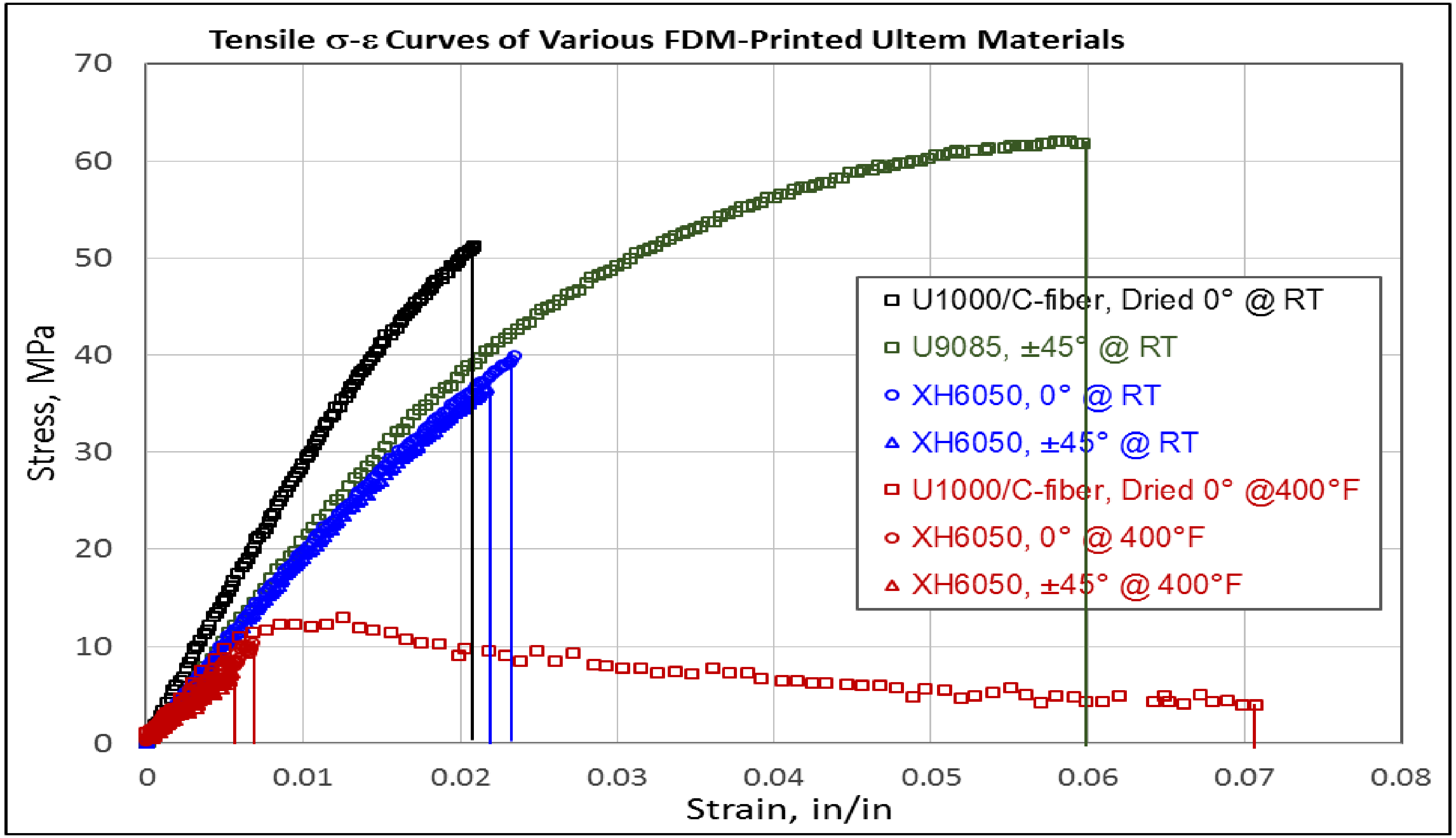


- ♦ After removing water, Ultem 1000 filaments still exhibits porosity at high liquefying temperature ≥ 420 °C
- ♦ Degradation gases from Ultem or air expand at ≥ 420 °C

Sample ID	FWF, wt%	FVF, v%	porosity, v%
As-rec Filament, thick	9.2%	6.8%	-1.2%
FDM-spun Filament, thin	9.3%	4.7%	30.9%
	9.3%	4.6%	31.6%
185 °C dried filament & cubes (samples received @ 8/25/14)			
As-dried Filament, thick	10.1%	6.7%	8.5%
FDM-spun Filament, thin	10.0%	5.3%	28.3%
204.4 °C dried filament (received @ 10/17/14)			
As-dried Filament, thick	8.5%	5.2%	16.5%
FDM-spun Filament, thin	5.2%	2.8%	24.5%

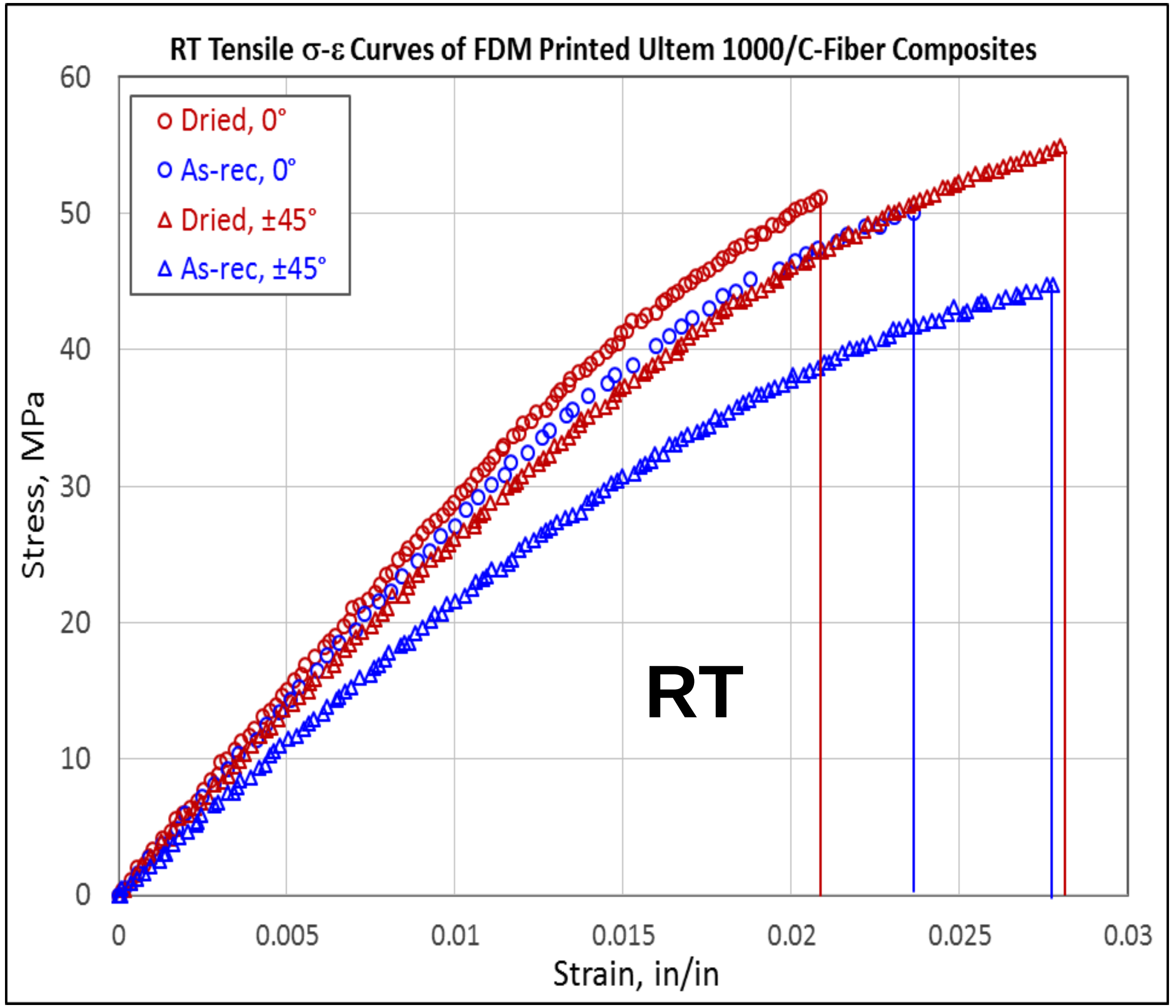
Tensile Strength of Ultem 9085, XH6050 and AS4-filled Ultem 1000

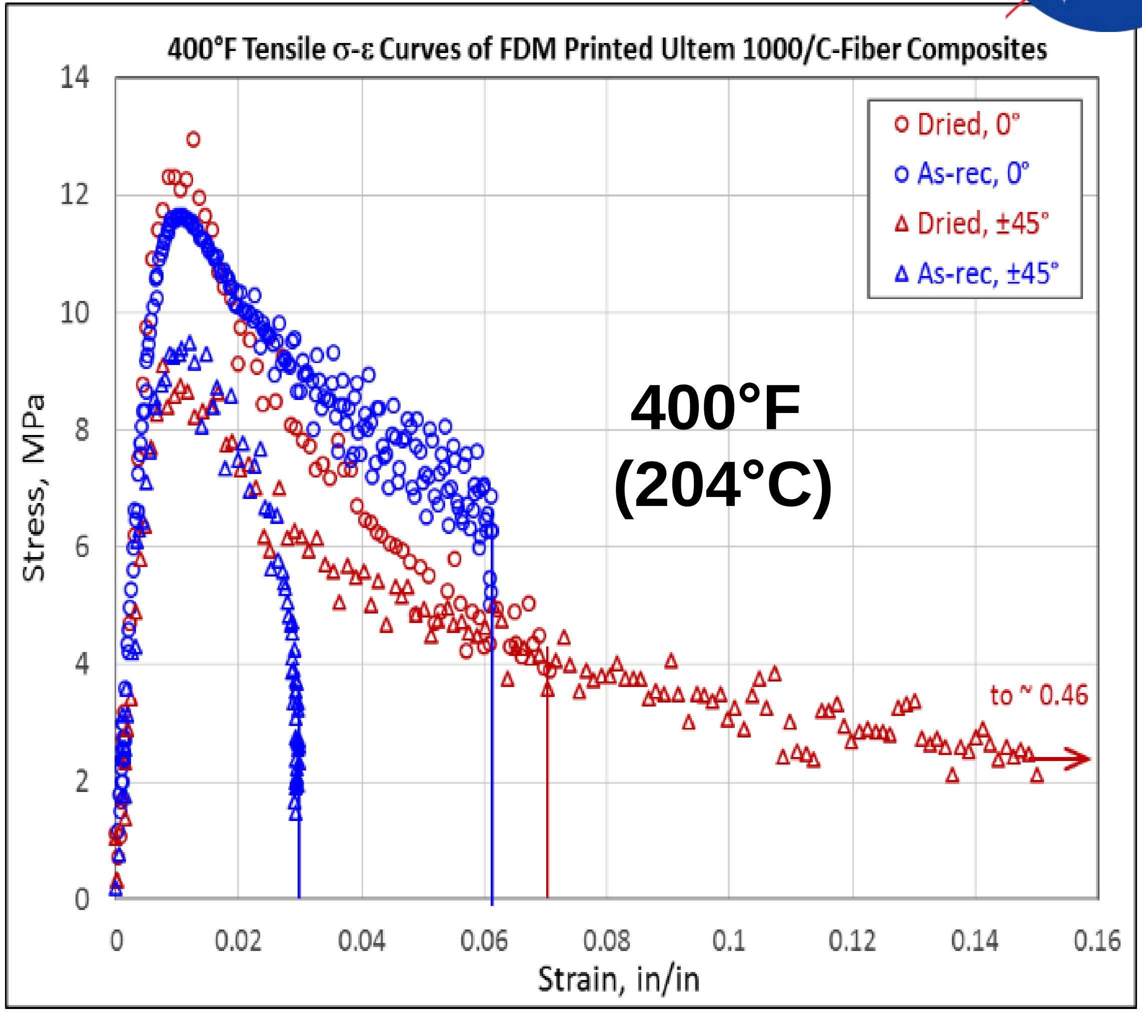
Printed by FDM



- ♦ Dried Ultem 1000 filled with 10% chopped AS4 showed 40% higher modulus than Ultem 9085.
- ♦ Ultem 9085 exhibited highest elongation.
- ♦ XH6050 (T_g= 245°C) displayed inferior strength than Ultem 9085 (T_g= 186°C), despite higher T_g.

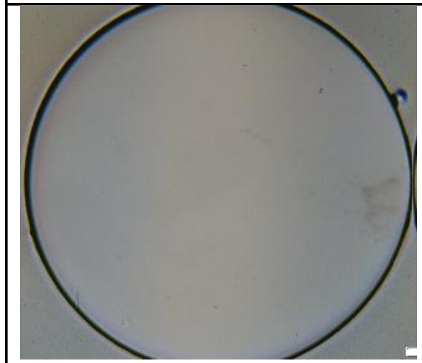
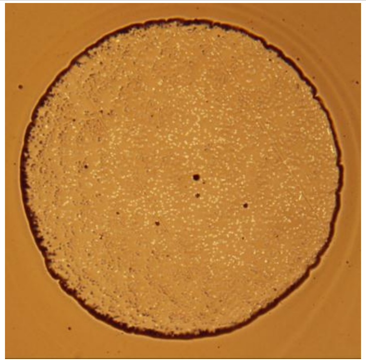
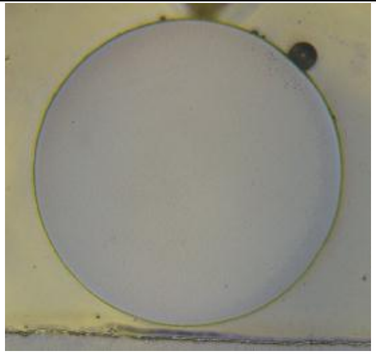
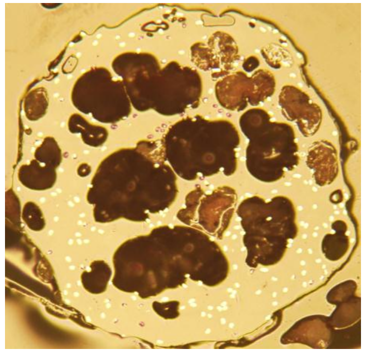
Tensile Strength of C fiber-Filled Ultem 1000



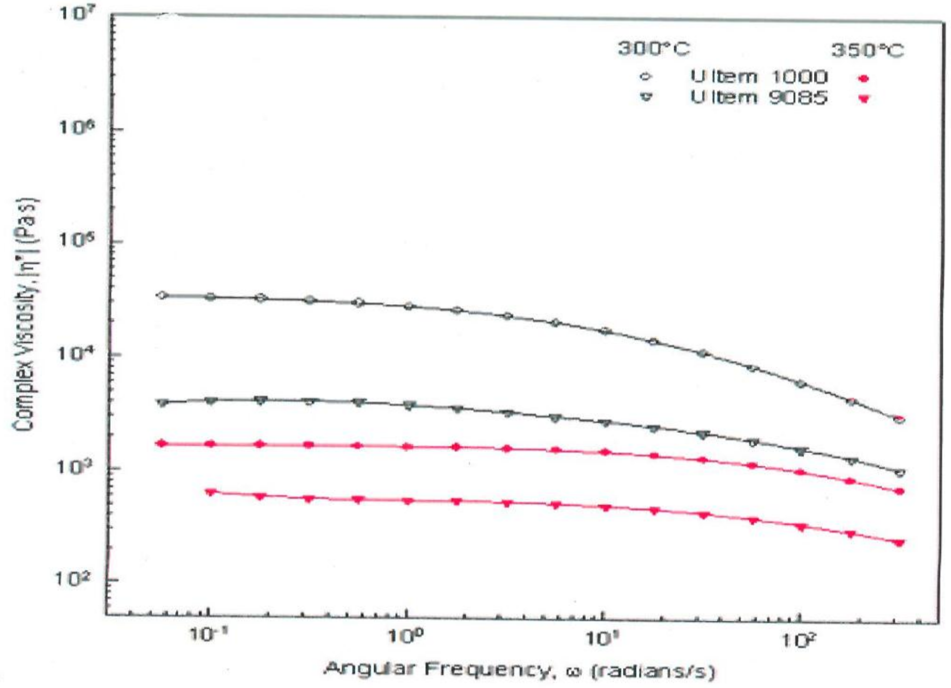


- ♦ Drying improve the strength of carbon fiber-filled Ultem 1000 composites.
- ♦ At 204 °C, Ultem 1000 lost its strength due to degradation, use temp = 175 ºC (350°F).

Approaches to Reduce Porosity in Fiber-Filled Ultem 1000 for FDM

Ultem 9085 As-Received 0.3-0.4% moisture	Fiber-filled Ultem 1000 As-received 0.6% water moisture
	
Ultem9085 FDM-extruded@375°C	Fiber-filled Ultem 1000 FDM-extruded@420°C
	

- ♦ **Ultem 1000 viscosity is 3-fold higher than that of Ultem 9085**
- ♦ **Porosity in FDM printing of Ultem 1000 at 420°C caused by volume expansion of moisture, trapped air & degradation gases**
- ♦ **<u>Solution</u>: Produce Ultem 1000 with controlled molecular weight with similar viscosity as Ultem 9085 to enable printing Ultem 1000 at 380°C**



Complex Viscosity of Ultem 9085 and Ultem 1000

Summary and Conclusion

- FDM-printed Ultem 9085 acoustic liner components exhibited similar performance in a wind tunnel as the conventional liners made of honeycombs and facesheets.
- Unconventional liners printed by FDM potentially could modulate multiple frequencies instead of just a single frequency in conventional liners.
- Composite vanes were printed by FDM at 420°C with 25% porosity and tested in a cascade rig, using Ultem 1000 filled with 10% carbon fiber.
- The porosity of FDM printed ultem 1000 with fibers were caused by volume expansion of absorbed moisture (0.6%), trapped air during extrusion and degradation gases generated at high liquefying temperature at 420°C.
- Fiber-filled Ultem 1000 filaments become more brittle, but drying improved the tensile strength.
- Need to produce Ultem 1000 with controlled molecular weight to lower its viscosity comparable to Ultem 9085 in order to allow printing at 380°C to reduce the porosity of Ultem 1000 by FDM.
- FDM properties depends on built direction, raster angle, filament thickness, tool path generation and air gap between rasters
- FDM printed specimens exhibited lower mechanical properties than injection molded parts due to inherent porosity associated with FDM

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