SABIC'S ULTEM™ AM9085F FILAMENT PERFORMANCE ASSESSMENT

Version 2

September 2017

OBJECTIVE:

This document describes the methodologies employed and the results of a study conducted to confirm the performance parity of filaments and printed specimens made using SABIC's ULTEM™ AM9085F filament with the Stratasys® filament made from ULTEM™ 9085 resin commercially sold for use in Fortus® machines.

INTRODUCTION:

SABIC has introduced filaments, manufactured from commercial resin grades, for FDM® (Fused Deposition Modeling) applications on the Stratasys Fortus 400mc and Fortus 900mc machines. The initial offering is expected to match the polyetherimide, polycarbonate and acrylonitrile-butadiene-styrene (ABS) filaments currently sold by Stratasys for use in Fortus machines. This paper discusses the results of a comparative study of ULTEM 9085 filaments, assessing SABIC's ULTEM AM9085F (9085 resin grade) and Stratasys filaments made with ULTEM 9085 resins. The key focus areas in this study include a comparison of the physical properties of the filaments, extrusion performance of SABIC's filaments and a comparison of printing and mechanical performance of the filaments.

PHYSICAL PROPERTY COMPARISON

Melt flow characteristics, glass transition temperatures, capillary rheology and densities for the Stratasys filaments were compared to the results for SABIC's filaments. The data was found to be comparable to the Stratasys filaments and within expected tolerances. These results indicate that extrusion behavior, filament deposition, interlayer adhesion and printing performance influenced mainly by material characteristics should be similar.

PHYSICAL QUALITY COMPARISON

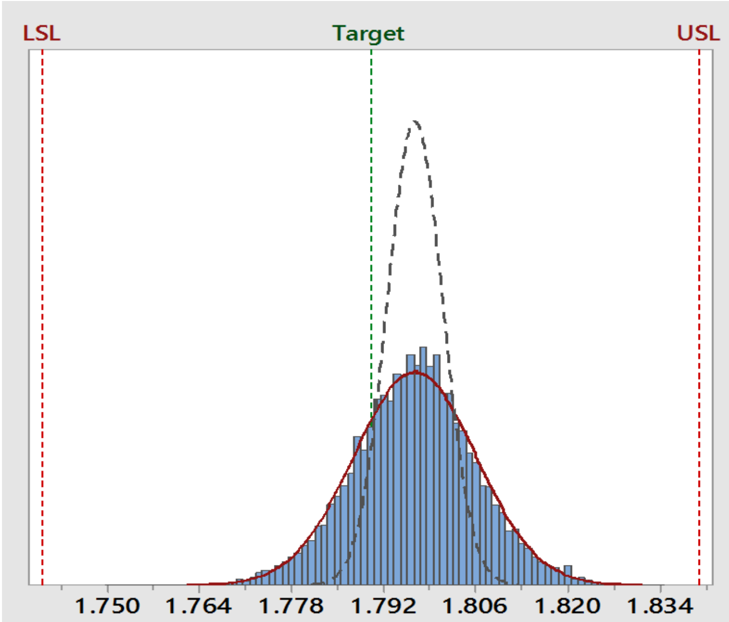
Physical characteristics of the filaments like diameter, roundness and consistency of these parameters across spools were evaluated in this study. The moisture content of each sample was measured to ensure that it was near the recommended 0.02% content and within 10% of each other. These parameters need to be controlled well to ensure consistent feeding of the filament into the print head and to avoid material jams that interrupt printing builds. Fill densities of printed specimens are also dependent on consistency of these parameters. Table 1 shows the tests and methods used to evaluate filament characteristics.

Tensile, flexure and elongation measurements on filaments can be used to evaluate mechanical strength and physical robustness. This data can also be an indicator of contamination, air or moisture voids and resin degradation.

Characteristic	Purpose	Method
Diameter	Comparison of target capability and spread of data	Real-time optical multi-axial measurements
Roundness	Control of mass of material per unit length deposited during printing	Real-time optical multi-axial measurements
Tensile – strength and elongation	Evaluation of filament strength and the potential presence of voids and contaminates	ASTM D638 Uniaxial
Denier	Linear mass density	Weight of 1 spool of filament

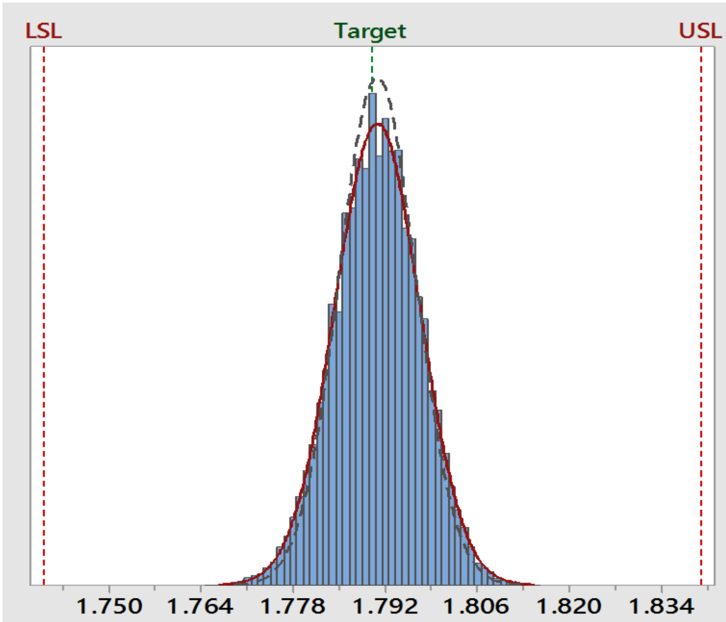
Table 1. Evaluation criteria for physical characteristics of filaments

Figures 1 and 2 show a statistical representation of diameter data for multiple lots of Stratasys and SABIC's filaments. The specification limits used for these analyses represent a centered range of the Fortus machine operating window that allows a safety margin at both upper and lower limits. Stratasys and SABIC's filaments had diameter ranges of 0.084mm and 0.050mm and long-term capability (Ppk) of 1.55 and 2.54 respectively. The diameter physical analysis results were comparable, but because the SABIC diameters had a tighter distribution, the capability appears greater for these filament lots. This trend will continue to be verified as additional filament samples become available.



Mean	1.7967 mm
StDev	0.0093
N	56442
Minimum	1.7500 mm
Median	1.7970 mm
Maximum	1.8340 mm
LSL	1.74 mm
Target	1.79 mm
USL	1.84 mm
Ppk	1.55

Figure 1 – Diameter analysis for Stratasys filament made with ULTEM™ 9085 resin



Mean	1.7907 mm
StDev	0.0065
N	42470
Minimum	1.7650 mm
Median	1.7910 mm
Maximum	1.8150 mm
LSL	1.74 mm
Target	1.79 mm
USL	1.84 mm
Ppk	2.54

Figure 2 – SABIC's ULTEM™ AM9085F Filament Diameter Analysis

FILAMENT EXTRUSION PERFORMANCE COMPARISON

Table 2 illustrates a list of tests that were used to characterize the way the filament flows from the print nozzle and fills predetermined contours.

Characteristic	Purpose
Fill Density Study	Compare the density of solid filled volumes at various print parameters for maximizing layer density
Contour Fill Study	Compare filament print fill resolution of several fill contour configurations for fill accuracy

Table 2. Evaluation criteria for extrusion performance of filaments

Table 3 shows the air gap parameters used to optimize percentage fill and the corresponding dimensions and weight of the solid filled partial cube printed at that setting. Extrusion behavior of both filaments was similar resulting in articles with similar densities of 1.2 g/cm^3. Figure 3 illustrates the results from a contour fill study comparing the raster diameter fills for various width contours using a T16 tip on Fortus 400mc and 900mc machines. The capability of both filaments to match the raster set-points is similar and statistically comparable.

Filament	Air gap	Weight (g)	X (in)	Y (in)	Z (in)	Density (g/cm^3)
SABIC's AM9085F	-0.0020	4.97	1.002	1.002	0.250	1.208
Stratasys 9085	-0.0020	4.96	1.002	0.999	0.251	1.205

Table 3. Fill Density Study

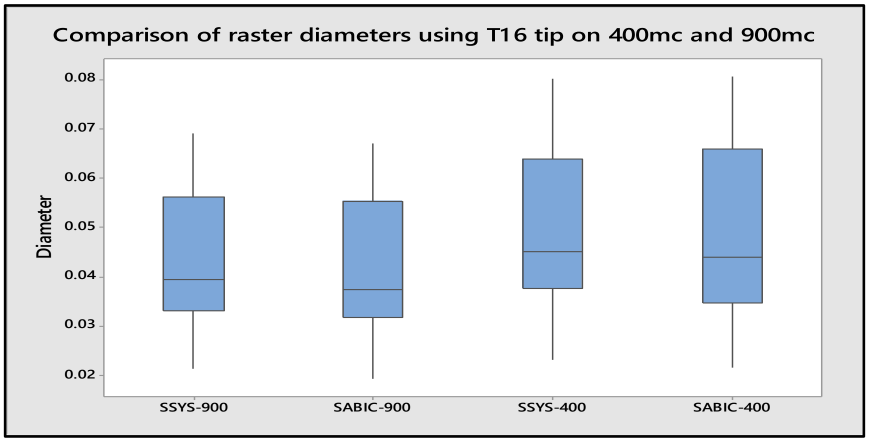


Figure 3. Stratasys (SSYS) 9085 and SABIC's AM9085F Filament Contour Fill Study

FILAMENT PRINT ARTICLE PERFORMANCE COMPARISON

This comparison of FDM filament printing characteristics and capability included evaluations of the build quality and repeatability of geometric accuracy, warpage, surface roughness, horizontal and vertical dimensions, roundness, sphericalness, angularity and flatness. This was achieved by using a test part which included features for creating drooping and bridging voids, diamond shaped lateral features and sections combining the severity of the stair-stepping and ramp features. The article also contained a range of progressive geometries varying in size and geometric shape for both extrusions and protrusions designed to create potential print failures. Because the actual test article used is proprietary, a representative article designed by the team at the W. M. Keck Center for 3D Innovations at the University of Texas at El Paso [1] is shown to illustrate the concept (Figure 4).

The articles were printed in two orientations, YXZ and YXZ +45, and included structures that were visually inspected for feature integrity and other structures that were inspected for dimensional accuracy. Results of the visual inspection for the T16 tip on the Fortus 400mc are shown in Table 4. Both materials showed good performance with respect to printing of overhangs, pillars, stepped angles and double contours. Adhesion to the support was also found to be similar. Figure 5 illustrates results from a contour study that compares the dimensions of various features like single and double walled contours, pillars and holes created using the two filaments. The results are comparable for both filaments. In conclusion, both filaments created comparable articles that were indistinguishable visually and dimensionally.

Table 1. Design Features of Test Part

Letter	Feature	Factor Tested
A	Square base	Dimensional accuracy
B	(+) Lateral ridges	
C	(–) Lateral ridges	
D	(+) Descending cylinders	
E	(–) Descending cylinders	
F	(+) Staircase	
G	(–) Staircase	
H	(+) Cylinders	
I	(–) Cylinders	
J	Ramps	Surface roughness
K	Rectangular prisms	Linear displacement error
L	Tensile Bar	Ultimate tensile strength

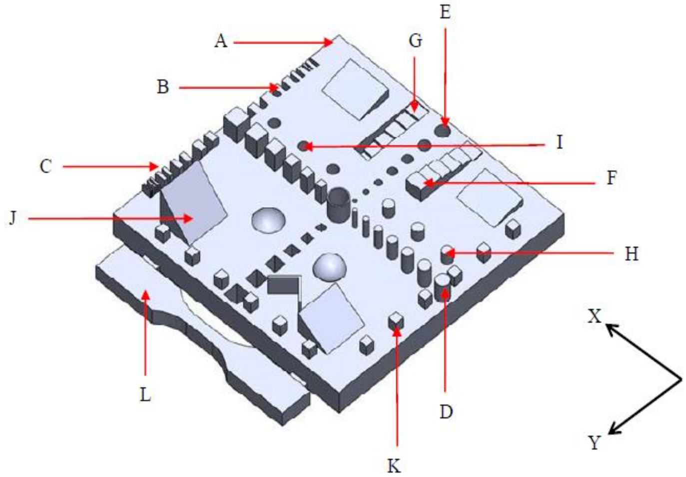


Figure 4. Test Part used to evaluate capabilities of various desktop printers [1]

Calibration Analysis		**Stratasys 400mc - T16 tip**	**SABIC 400mc - T16 tip**
Visual Inspection			
1	Did the parts print successfully?	Yes	Yes
2	Are there any physical deformities / defects to the parts?	No	No
3	Did the empty flat portion lift from the plate?	No	No
4	Did the part separate from the build sheet & support successfully?	Yes	Yes
5	Did the overhang print successfully?	Yes	Yes
6	Is there a significant visual difference between the solid and sparse pillars?	No	No
7	Did the stepped angle walls print successfully?	Yes	Yes
8	Did the double contour geometry shapes build successfully?	Yes	Yes
9	Is there significant feathering between specified pillar features?	No	No
10	Are there areas of overfill in the center portion of the inspected part?	No	No
11	Any other differences from the inspected part with the compared part?	No	No
		Pass	*Pass*

Table 4. Results of visual inspection of calibration articles

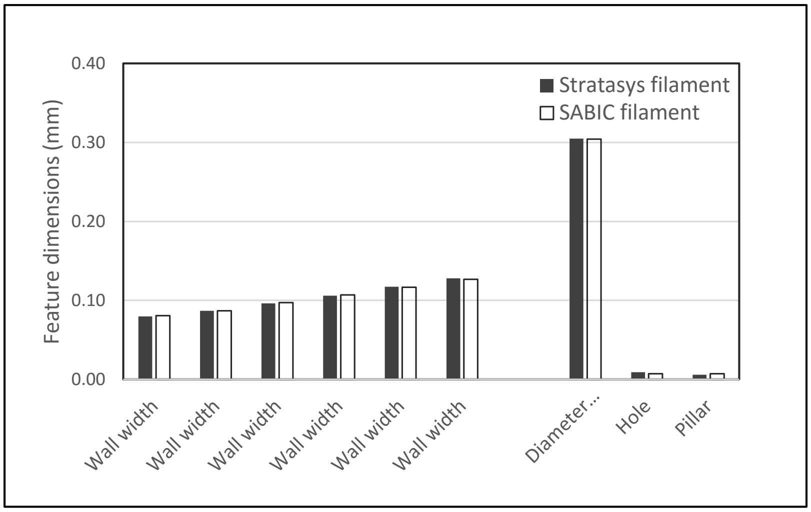


Figure 5. Measurements of features printed with T20 tip on Fortus 900mc

MECHANICAL PROPERTY PERFOMANCE COMPARISON

Three build orientations, shown in Figure 6 below, were evaluated for this study. The parts were printed under standard parameters and default fill densities, except for Izod impact bars, which were printed at a higher fill percentage of about 89-93% to maximize part density. This comparison included evaluation of many common mechanical properties specified on datasheets that are important for material selection. Tensile, flexure and Izod impact properties used as performance indicators when comparing the behavior of filaments are presented in this report. Thermal and electrical properties including coefficient of thermal expansion (CTE), heat deflection temperature (HDT), volume resistivity, dielectric constant, and dissipation factor have been evaluated and compared to datasheet values. Other properties shown below are also of interest and will be evaluated in the future to add to the datasheets.

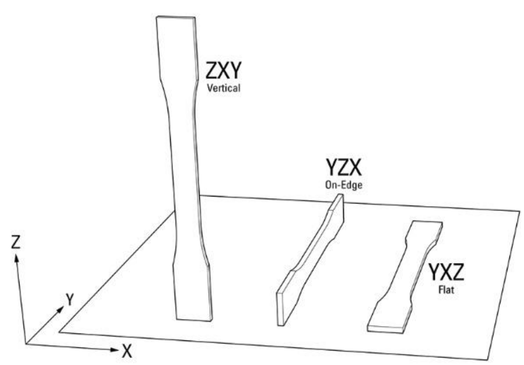


Figure 6. Test coupon orientation

ASTM Mechanical Properties –

Tensile Properties: Method: ASTM D638
Flexure Properties: Method: ASTM D790
Compression Strength: Method: ASTM D695
Shear Strength: Method: ASTM D732
Izod Impact – including notched: Method: ASTM D256
Short Beam Shear Strength (z-strength): Method: ASTM D2344

ASTM Thermal Properties –

Coefficient of Thermal Expansion: Method: ASTM E831
Heat Deflection: Method: ASTM D648

ASTM Electrical Properties –

Volume Resistivity: Method: ASTM D257
Dielectric Constant, Dissipation Factor: Method: ASTM D150-98
Dielectric Strength: Method: ASTM D149-09 Method A

Two lots of filament from SABIC and four lots of filament from Stratasys (SSYS) were used to generate the data shown in the following sections of the report. Data for the on-edge (Y) and upright (Z) orientations is presented in order to be able to compare with published datasheet values from Stratasys (shown by solid lines in the graphs). Figure 7 compares the tensile modulus and flexural modulus data for specimens printed using the two filaments. As expected, modulus values for bars printed in the upright direction are lower than the values for bars printed in the on-edge direction due to lower interlayer strength in this orientation. This is consistent with the data published in the datasheet for Stratasys filament made with ULTEM 9085 resin. It is interesting to note that most of the values for both the upright and on-edge orientations are equal to or exceed datasheet values. Statistical analysis of the data indicates that the two populations are indistinguishable from each other in the on-edge orientation. In the upright orientation, average values for SABIC's filament are slightly higher than Stratasys. However, the practical differences between the upright values are small, and therefore the two filaments would be considered to be at parity with each other.

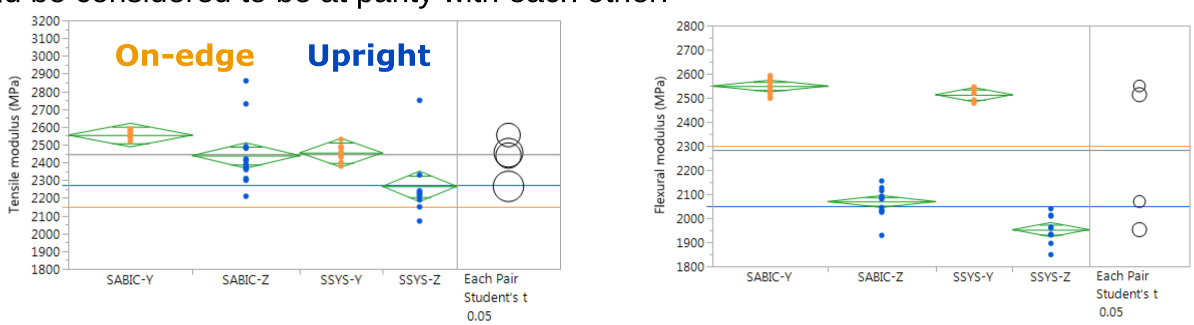


Figure 7. Tensile modulus and flexural modulus analysis for printed specimens

A comparison of the tensile strength at break for the two sets of specimens (Figure 8) shows that the on-edge specimens show values that are higher than the published datasheet values. The average value of tensile strength for the SABIC samples is slightly higher than Stratasys in both orientations. The on-edge build orientation allows for evaluation of the true material strength of the specimen with minimal interference from the individual layers. Conversely, for specimens built in the upright orientation, since the force is applied in a direction perpendicular to the build axis, results would be influenced greatly by interlayer adhesion characteristics and the sample would fail at the weakest print layer. Tensile elongation values are low for this brittle material and all samples show numbers equal to datasheet values. A comparison of the two datasets indicates that the samples are statistically indistinguishable from each other.

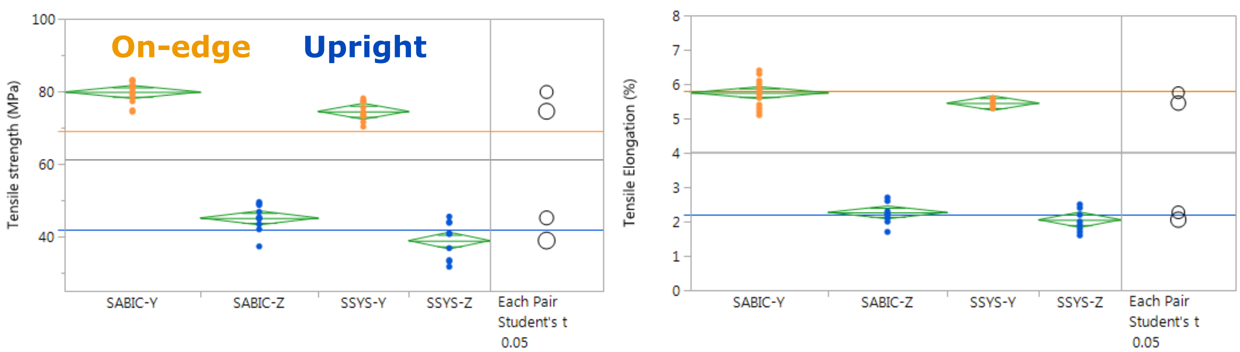


Figure 8. Tensile strength and percent elongation for printed specimens

Figure 9 compares the toughness of the specimens (notched and un-notched) printed with the two filaments. The results for bars built in the on-edge orientation are statistically indistinguishable, despite a complex fracture phenomenon involving both weld lines and deposition layers. The results for bars built in the upright direction where the force of impact is parallel to the weld lines differ slightly in notched Izod impact according to statistical analysis, but the values are similar. This is reasonable because the strength of the weld lines would strongly influence results and may cause greater variability. The upright un-notched Izod results are statistically indistinguishable.

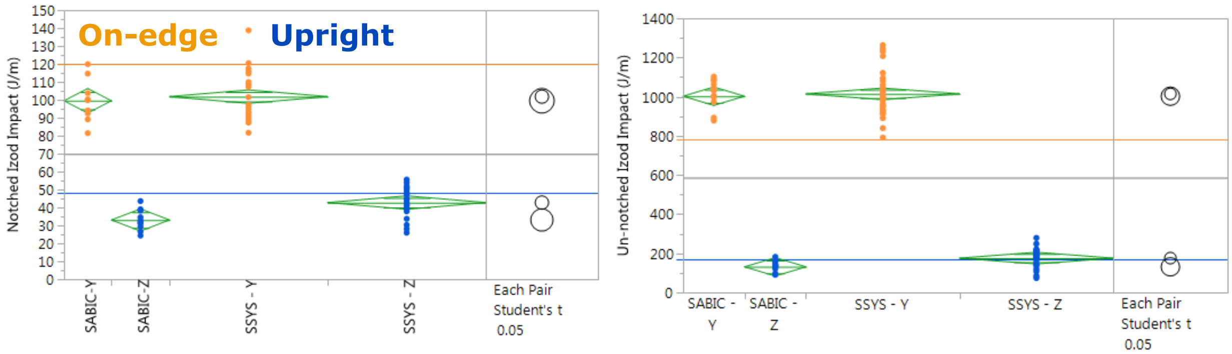


Figure 9. Izod (notched and un-notched) impact strength for printed specimens

Figure 10 shows the thermal and electrical properties of parts made with SABIC's AM9085F filament printed in three orientations (or two orientations for square plaques with sides of equal diameter) with default fill densities. The values are compared to Stratasys datasheet values. It should be noted that the Stratasys datasheet thermal properties are specified as literature values (taken from injection molding datasheets), and electrical property datasheet values are reported as an average of flat and upright/on-edge square plaques printed under default fill densities. The frequencies for dielectric constant and dissipation factor are not specified on the Stratasys datasheet. Therefore, the samples made with SABIC's filament were measured at 100, 500, and 1000 MHz to cover a range of commonly used frequencies.

The CTE, volume resistivity, dielectric constants and dissipation factors for the SABIC samples in each orientation are similar to the Stratasys datasheet values considering variation due to possible differences in test methods, test equipment, printing parameters, and sample preparation. Interestingly, the HDT values for the printed parts average about 10-20 °C higher than the literature value taken from injection molding datasheets. This has been observed for several different material types (ULTEM™ filament, LEXAN™ filament, and CYCOLAC™ filament). The reason for this HDT difference between printed and injection molded parts is being researched, but it could be due to the anisotropy of the printed parts, sensitivity to stresses experienced by the part, and/or the differences in residual stresses in the injection molded and printed parts.

	Units	SSYS 9085 Datasheet	SABIC AM9085F Filament – Printed Part Experimental Data		
			Flat	On-edge	Upright
Thermal Properties					
HDT – 3.2 mm, 1.82 Mpa	°C	153 (literature value)	175	175	165
CTE – flow (print direction)	µm/(m* °C)	65.27 (literature value)	57.1	60.6	62.1
CTE – xflow	µm/(m* °C)		58.3	61.1	62.9
Electrical Properties					
Volume resistivity	Ohm-cm	4.9×10^{15} - 8.2×10^{15} (average of flat and on-edge/upright)	1.07E+15	1.1E+15	
Dielectric constant – 100 MHz		3 – 3.2 (no frequency specified, average of flat and on-edge/upright)	2.54	2.73	
Dissipation factor – 100 MHz		0.0026 – 0.0027 (no frequency specified, average of flat and on-edge/upright)	0.00233	0.003	
Dielectric constant – 500 MHz			2.53	2.72	
Dissipation factor – 500 MHz			0.005	0.00567	
Dielectric constant – 1000 MHz			2.52	2.71	
Dissipation factor – 1000 MHz			0.004	0.004	

Figure 10. Thermal and electrical properties for ULTEM AM9085F filament printed specimens compared to Stratasys (SSYS) datasheet values

REGULATORY COMPLIANCE

Many industries require that additively manufactured parts meet criteria set by regulatory bodies like Underwriters Laboratory ("UL") and Federal Aviation Administration ("FAA"). ULTEM 9085 resin meets UL94 V0 and FAA requirements and is a common grade used for aerospace applications. Since additive manufacturing is being increasingly adopted as a new manufacturing process, UL now requires new Blue Card submissions and qualifications for filament and other materials used in additive manufacturing processes.

Flame bars printed using SABIC's ULTEM AM9085F filaments were tested for UL-94 V0 compliance at 1.5mm and 3.0mm. The bars were printed in the upright, flat and on-edge orientations using green flag (default) conditions at the desired thicknesses. Five specimens were evaluated at each test condition (48 hours, 23 ^{o}C and 168 hours, 70 ^{o}C) per the UL-94 protocol. The results are shown below:

- 3.0mm thick specimens **PASSED** V-0 requirements for the three build orientations at standard print density with average flameout times of less than 2 seconds at each condition.
- 1.5mm thick specimens **PASSED** V-0 requirements for the three build orientations at standard print density with average flameout times of less than 4 seconds at each condition.

Other properties that are typically found on the ULTEM 9085 resin Yellow Card such as dielectric strength and glow wire ignition are in the process of being measured. A detailed analysis of the effects of printing variables and build orientations on flammability is also being considered.

Many sectors of the aerospace industry require materials to meet fire and flammability criteria set by the FAA. Burn, smoke and heat properties of printed specimens using SABIC's AM9085F filament were tested. Standard conditioning and testing protocols specified by the standards were employed and the results are outlined below.

Method: FAR 25.853. Sample form: printed specimens

- FAA Flammability: Vertical Burn – 60 seconds: PASSED at .060" thickness for single build orientation at standard print density
- FAA Flammability: Vertical Burn – 12 seconds: PASSED at .060" thickness for single build orientation at standard print density
- FAA Flammability: Horizontal Burn – 2.5" rate: PASSED at .060" thickness for single build orientation at standard print density
- FAA Flammability: 45-degree Burn – 30 seconds: PASSED at .060" thickness for single build orientation at standard print density
- FAA Flammability: Ohio State Heat Release: PASSED at .060" thickness for single build orientation at standard print density
- FAA Flammability: NBS Smoke Density - Flaming: PASSED at .060" thickness for single build orientation at standard print density
- FAA Flammability: Toxicity - Flaming: PASSED at .060" thickness for single build orientation at standard print density
- FAA Flammability: NBS Smoke Density – Non-flaming: PASSED at .060" thickness for single build orientation at standard print density
- FAA Flammability: Toxicity – Non-flaming: PASSED at .060" thickness for single build orientation at standard print density

SUMMARY

This study indicates rheological parity between ULTEM AM9085F filaments produced by SABIC and those commercially available from Stratasys. Filament extrusion conditions were also optimized to achieve diameter control and to minimize spool-to-spool variation for printing consistency. Evaluation of printing performance using torture geometries verified similarities in visual attributes and dimensional accuracy. These similarities included adhesion to and separation from build sheets and support materials. Testing of mechanical properties showed the specimens to be statistically indistinguishable in most cases. Cases where differences in populations were observed could be attributed to the influence of build orientations on test results as opposed to inherent material properties resulting in larger variability. The printed specimens using SABIC's ULTEM AM9085F filament also met UL-94 vertical burn ratings and flame, smoke and heat criteria specified by the FAR 25.583 standard. Ongoing work includes assessment of multiple lots of SABIC's filament as well as investigation of the influence of machine-to-machine variability, printing parameters and build orientations on mechanical, electrical and flame properties.

REFERENCES

[1] Perez, MA, Ramos, J, Espalin, D, Hossain, MS & Wicker, RB 2013, 'Ranking model for 3D printers' in 24th International SFF Symposium - An Additive Manufacturing Conference, SFF 2013. University of Texas at Austin (freeform), pp. 1048-1065, 24th International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2013, Austin, TX, 12-14 August. Reprinted with the permission of David Espalin, Associate Director, The W.M. Keck Center for 3D Innovation, The University of Texas at El Paso; and David Bourell, Professor of Mechanical Engineering and Materials Science and Engineering, The University of Texas at Austin.