# SABIC’S CYCOLAC™ AMMG94F 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 CYCOLAC™ AMMG94F filament with Stratasys® ABS-M30 filament 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 Fortus 400mc and 900mc machines. This paper discusses the results of a comparative study of ABS filaments, assessing AMMG94F filament with the ABS-M30 filament. 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 ABS-M30 filament were compared to the results for the AMMG94F filament. The data was found to be comparable to the Stratasys ABS-M30 filament 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

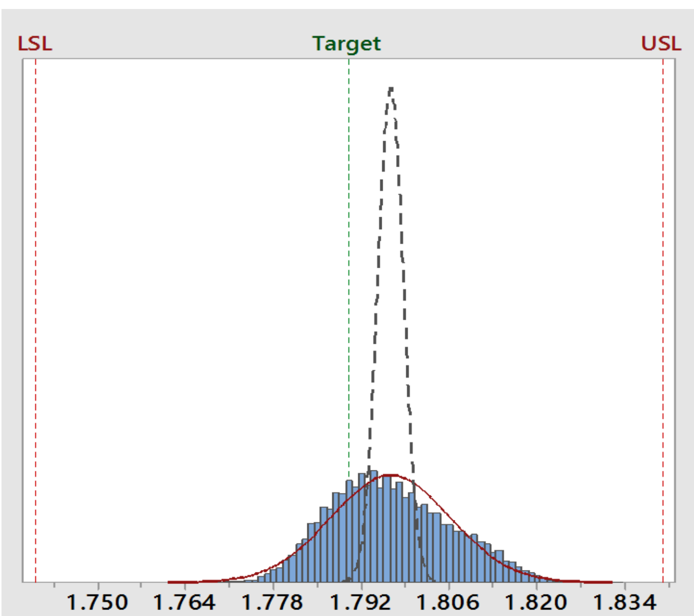
Physical characteristics of the filaments such as diameter, roundness and consistency of these parameters across spools were evaluated in this study. The moisture content of each sample was measured to ensure that it was near the recommended 0.1% content and within 10% of each other. These parameters 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 |

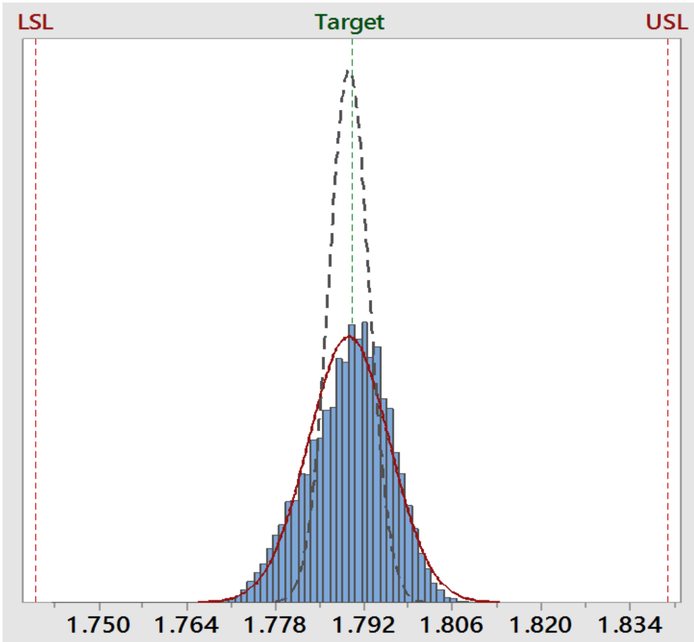
**Table 1.** Evaluation criteria for physical characteristics of filaments

Figures 1 and 2 show a statistical representation of diameter data for Stratasys and SABIC's filaments which is representative of multiple samples. 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. ABS-M30 and SABIC filaments had diameter ranges of 0.065mm and 0.070mm and long-term capability (Ppk) of 1.52 and 2.58 respectively. The diameter physical analysis results were comparable, but because the SABIC diameters had a tighter normal distribution, the capability appears greater for these filament lots. This trend will continue to be verified with additional filament samples.




| | |
|---|---|
| Mean | 1.7966 mm |
| StDev | 0.0095 |
| N | 49964 |
| Minimum | 1.7680 mm |
| Median | 1.7960 mm |
| Maximum | 1.8330 mm |
| LSL | 1.74 mm |
| Target | 1.79 mm |
| USL | 1.84 mm |
| Ppk | 1.52 |

**Figure 1 –** Stratasys ABS-M30 Filament Diameter Analysis




| | |
|---|---|
| Mean | 1.7895 mm |
| StDev | 0.0064 |
| N | 48784 |
| Minimum | 1.7430 mm |
| Median | 1.7900 mm |
| Maximum | 1.8130 mm |
| LSL | 1.74 mm |
| Target | 1.790 mm |
| USL | 1.84 mm |
| Ppk | 2.58 |

**Figure 2 –** SABIC's CYCOLAC AMMG94F 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 1.000 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. There is no statistical difference between capabilities of both filaments for the raster set-points.

| Filament | Air gap | Weight (g) | X (in) | Y (in) | Z (in) | Density (g/cm$^3$) |
|---|---|---|---|---|---|---|
| SABIC's AMMG94F | -0.0015 | 4.11 | 1.003 | 1.003 | 0.252 | 0.992 |
| Stratasys ABS M30 | -0.0015 | 4.16 | 1.004 | 1.000 | 0.253 | 1.001 |

**Table 3.** Fill Density Study

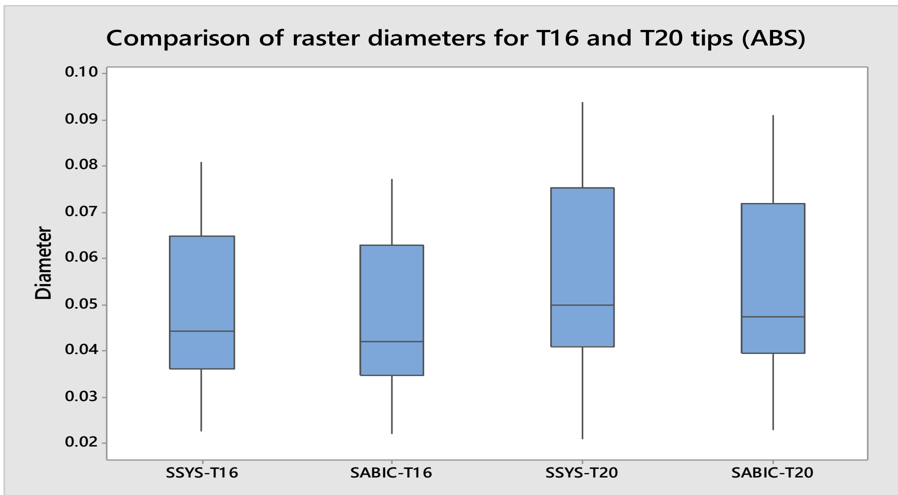



**Figure 3.** Stratasys (SSYS) ABS M30 and SABIC's AMMG94F Filament Extrusion Contour Fill Study

## 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 these 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 for the two materials. Figure 5 illustrates results from a contour study that compares the dimensions of various features such as single and double walled contours, pillars and holes created using the two filaments. The results are very 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 |

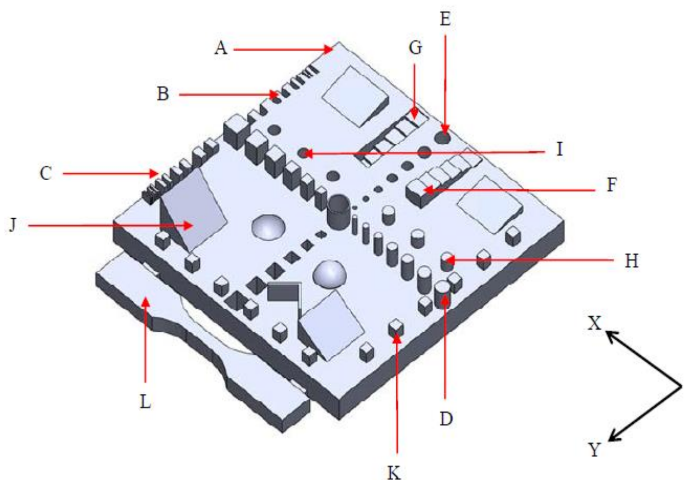



**Figure 4.** Test Part used to evaluate capabilities of various desktop printers [1]

| **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

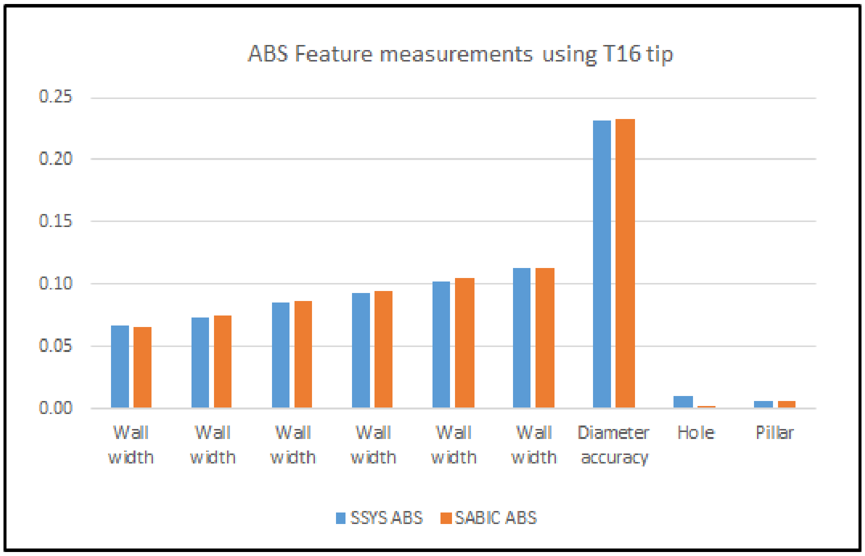



**Figure 5.** Measurements of features printed with T16 tip on Fortus 900mc

## 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 95% 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 factors 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.

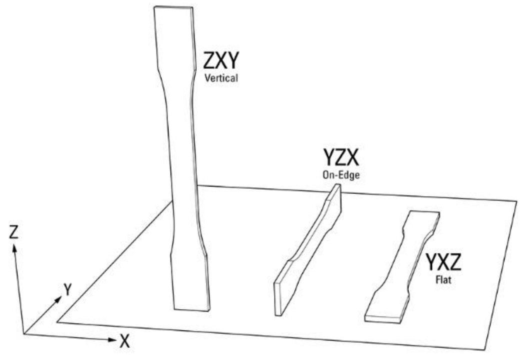



**Figure 6.** Test coupon orientation

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
Dielectric Strength: Method: ASTM D149

Five lots of SABIC's AMMG94F filaments and three lots of Stratasys ABS-M30 filaments were used to generate the data shown in the following sections of the report. Data for the on-edge and upright orientations is presented to compare with Stratasys published datasheet values (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. The results are consistent with the data published in the ABS-M30 datasheet. Statistical analysis of the data indicates the two populations were statistically indistinguishable from each other for tensile modulus and flexural modulus in both orientations, confirming parity of the two filaments.

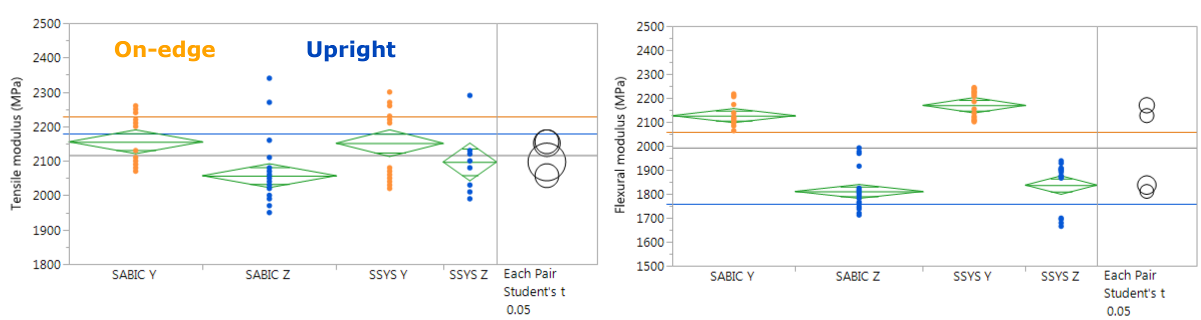



**Figure 7.** Tensile modulus and flexural modulus for printed specimens

A comparison of the tensile strength at break for the two sets of specimens (Figure 8) shows that the on-edge specimens are nearly statistically indistinguishable from each other with no practical difference in the values. 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. The values of tensile strength are similar in this orientation and the samples are again statistically indistinguishable, indicating similar interlayer adhesion as well as material strength. Tensile elongation values are low for this material and all samples show numbers near the datasheet values. A comparison of the two datasets indicates that the upright samples are statistically indistinguishable from each other, and on-edge samples are similar.

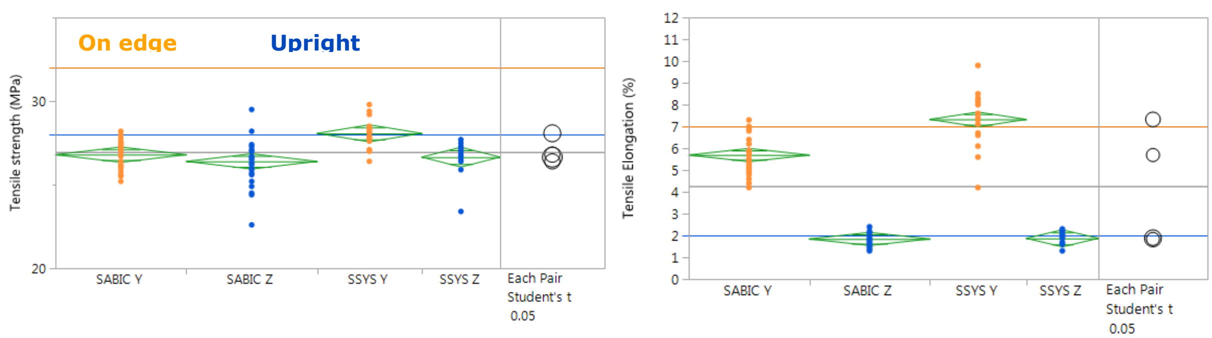



**Figure 8.** Tensile strength and percent elongation for printed specimens

Figure 9 compares the toughness of the specimens (notched and un-notched) printed with the two filaments. The on-edge results are near or above the published datasheet values, and the notched results are statistically indistinguishable. The un-notched results are statistically different, likely as a result of variability due to 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 are statistically indistinguishable for the un-notched samples. The values for the notched upright samples are also at or above the datasheet values, and while they are statistically different, the difference in actual values is not significant for this test. There is no published datasheet reference for the upright samples.

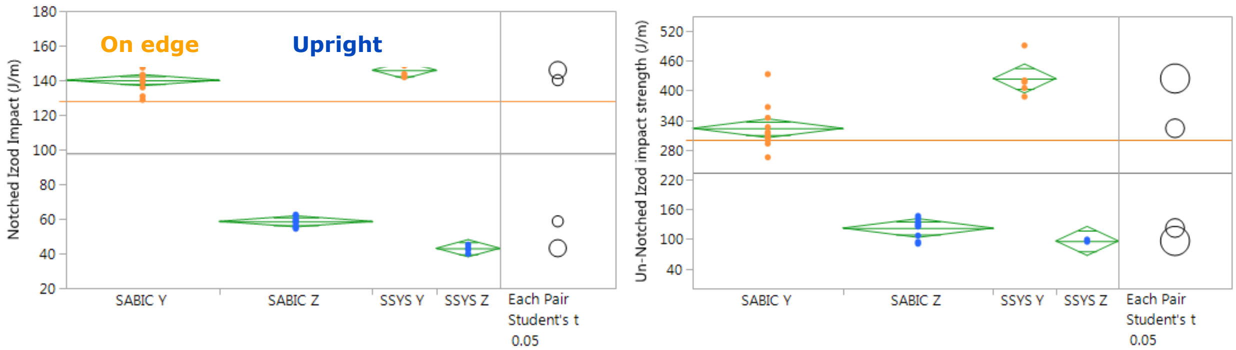



**Figure 9.** Izod (notched and un-notched) impact data for printed specimens

Figure 10 shows the thermal and electrical properties of SABIC's AMMG94F filament parts 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 SABIC samples 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 15-20 °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 under investigation, 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 ABS M30 Datasheet | SABIC AMMG94F Filament – Printed Part Experimental Data | | |
|---|---|---|---|---|---|
| | | | **Flat** | **On-edge** | **Upright** |
| **Thermal Properties** | | | | | |
| HDT – 3.2 mm, 1.82 Mpa | °C | 82 (literature value) | 100 | 100 | 98 |
| CTE – flow (print direction) | µm/(m* °C) | 88.2 (literature value) | 76.3 | 76.7 | 82.4 |
| CTE – cross-flow | µm/(m* °C) | 84.6 (literature value) | 75.4 | 76.8 | 79.2 |
| **Electrical Properties** | | | | | |
| Volume resistivity | Ohm-cm | 4.0E+15 – 3.3E+16 (average of flat and on-edge/upright) | 4.13E+14 | 1.31E+15 | |
| Dielectric constant – 100 MHz | | 2.6 – 2.86 (no frequency specified, average of flat and on-edge/upright) | 2.44 | 2.46 | |
| Dissipation factor – 100 MHz | | 0.0048-0.0054 (no frequency specified, average of flat and on-edge/upright) | 0.003 | 0.003 | |
| Dielectric constant – 500 MHz | | | 2.43 | 2.45 | |
| Dissipation factor – 500 MHz | | | 0.006 | 0.006 | |
| Dielectric constant – 1000 MHz | | | 2.41 | 2.43 | |
| Dissipation factor – 1000 MHz | | | 0.005 | 0.00467 | |

**Figure 10.** Thermal and electrical properties for CYCOLAC ™ AMMG94F 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"). CYCOLAC MG94 resin meets UL94 HB. Since additive manufacturing is being increasingly adopted as a new manufacturing process, UL now requires new Blue Card submissions and qualifications for filaments and other materials used in additive manufacturing processes. Flame bars printed using SABIC's CYCOLAC MG94 filaments were tested for UL-94 HB compliance at 3.0mm. The bars were printed in the flat, on-edge, and upright orientations using green flag (default) conditions at the desired thicknesses. Three specimens were evaluated per the UL-94 protocol. The specimens were conditioned for 48h at 23 °C and 50% RH. The results are shown below:

- 3.0mm thick specimens **PASSED** HB requirements for the three build orientations at standard print density

Other properties that are typically found on the CYCOLAC MG94 resin yellow card or datasheet are in the process of being measured.

## SUMMARY

This study indicates rheological parity between ABS 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 demonstrated 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. In most cases where statistical differences in populations were observed, the values would not be considered different for practical applications, and the slight differences could be attributed to the influence of build orientations. The printed SABIC specimens also met UL94 HB ratings. 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.