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CHARACTERIZATION OF MECHANICAL PROPERTIES OF ULTEM® 9085 USING FDM

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ABSTRACT: It is well known that for additive manufactured parts, mechanical properties are strongly influenced by the printing process parameters. This paper investigates the effect of the coupon shape and geometry on the mechanical properties, in particular, tensile strength of parts manufactured using Ultem® 9085, printed using Stratasys Fortus 900MC. Three different types of coupon geometry, namely ASTM D638 Type I, Type II and ASTM D3039 are tested according to the respective standard requirements, and it was found that there is significant variation in the tensile strength between the specimens. Subsequently, fracture surface of the 3 different specimens are then examined under the Scanning Electron Microscope (SEM) to provide potential explanations for the difference in mechanical strength.

KEYWORDS: Fused Deposition Modelling, ULTEM® 9085, Tensile testing, Additive Manufacturing

Introduction
Additive manufacturing (AM) is a layered manufacturing technique, which is able to turn digital data into physical parts. Fused Deposition Modelling (FDM), one of the most used additive manufacturing methods, was developed by Stratasys Ltd. (Casavola et al., 2016). FDM process consists of extruding semi molten thermoplastic filament from the nozzle and depositing them layer by layer (Upadhyay et al., 2017). One of the most popular FDM materials for aviation industry, Ultem® 9085, due to its ability to fulfil the flammability, smoke and toxicity, and heat release stipulated by the aviation authorities. Due to the high material costs and the requirement of an industrial grade printer, Ultem® 9085 parts have yet to be studied in as much detail as compared to other FDM materials printable on cheaper desktop printer, such as Acrylonitrile-Butadiene-Styrene (ABS).

FDM is one of the widely researched polymer AM techniques, and many researchers have attempted to characterize the process, and investigate the influence of parameters on the mechanical properties.
Garg and Bhattacharya (2017) carried out finite element (FE) modelling and simulation, taking into consideration the necking formation and air voids between the filaments by examining the microstructure of the printed coupon. They subsequently printed the coupons to validate the observations made from the simulation. ASTM D638 Type IV specimens were utilized but no explanation for the reason for the particular choice of specimen was offered. Ahn et al. (2002) reported an issue with using ASTM D638 Type I specimen. They switched from ASTM D638 Type I coupons to ASTM D3039 for the tensile test coupons after experiencing premature failure especially for the specimens with raster angled at 0°. However, provision of the tensile test coupon breakage location was not common. Casavola et al. (2016) attempted to use classical laminate theory (CLT) to describe the mechanical behavior of FDM parts. They utilized ASTM D638-10 Type I specimens for determination of tensile properties such as Young’s Modulus and Ultimate Tensile Strength, and ASTM D3518-94 for determination of shear modulus for comparison with the prediction made from the CLT. Riddick et al. (2016) investigated the effect of the different raster angle and build orientation on the mechanical strength using ABS coupons printed according to ASTM D638 and employed scanning electron microscope (SEM) images to investigate the failure mechanism for ABS specimens. However, the type of coupon used not specified and the failure location not specified. Koch et al. (2017) investigated the effect of the raster and bead orientation, layer height and solidity ratio on the effect of the ultimate tensile strength of the coupon. ASTM D638 Type I coupon was utilized and similarly, failure location not specified. Li et al. (2017) examined the effects of melt viscosity, and indirectly, the extrusion temperature of the PA12 and ABS filament have on the tensile strength and sintering of the filaments. They have used ASTM D638 Type I but again, failure location was not specified.

Due to the lack of standards specifically catered to AM, characterization of AM parts is often evaluated using conventional standards. Moreover, the printing process introduces material anisotropy during the manufacturing process. Hence, conventional standards assuming homogenous and isotropic material properties may not be suitable for the characterization of AM parts. As evident, most literature utilizes ASTM D638 to determine the tensile strength of the specimens but did not explore the effect of different types of specimens on the tensile properties. Moreover, most literature did not take into consideration breakage location of the specimens, which can influence the mechanical properties derived.

This paper aims to investigate the effect of the specimen geometry on the mechanical properties with different tensile test coupons namely ASTM D638 Type I, ASTM D638 Type II, and ASTM D3039. ASTM D638 Type I specimen are selected as it is frequently used in literature. Ahn et al. (2017) found that the specimen broke outside of the narrow section. Hence, according to the D638, Type II with a narrower gage width is then recommended (ASTM, 2015). Hence D638 Type I and Type II is investigated in this paper. In addition, coupons from D3039 is also investigated, due to the similar anisotropic nature of the FDM specimens and the composite specimens.

**Experiment**

For this experiment, experiment coupons from ASTM standards D638 – 14 (Standard Test Method for Tensile Properties of Plastics) and D3039/D3039M -14 (Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials) were used. From the D638 – 14, specimen dimensions for the Type I and Type II coupons were referenced, and as for D3039, dimensions for fiber orientation for balanced and symmetric were used. Figures 1, 2, and 3 show the respective dimensions of the coupon.
The models of the coupons were drawn in Creo 3.0, and subsequently converted to Stereolithography (STL) file, and sending the STL file to Stratasys proprietary software, Insight 11, for slicing, generation of support and material extrusion paths. Table 1 shows key parameters that are used in the Insight software setting. All coupons were printed using Stratasys Fortus 900mc, using ULTEM® 9085. The tip used was T16, which gave a corresponding constant layer thickness of 0.254mm for all printed coupons. The printed orientation of the coupons was flat with respect to the build sheet.

Table 1 Critical parameters used for printing specimens

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<th>Parameters</th>
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<td>Raster and contour Width</td>
<td>0.508 mm</td>
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<tr>
<td>Air Gap</td>
<td>0 mm</td>
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<tr>
<td>Layer Thickness</td>
<td>0.254 mm</td>
</tr>
<tr>
<td>Raster angles</td>
<td>+45° / -45°</td>
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<tr>
<td>Layers between alternating of raster angles</td>
<td>1</td>
</tr>
<tr>
<td>Coupon orientation</td>
<td>XYZ</td>
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Subsequently, the tensile tests were performed in Nanyang Technological University, on a 10kN Shimadzu Tensile Testing machine fitted with a non-contact digital video extensometer TRViewX. All strain measurements were made by the digital video extensometer.

The SEM analysis was then performed for the samples in Nanyang Technological University, on a JEOL made Field Emission Scanning Electron Microscope 7600 series. The analysis was then carried out on images taken with 5kV and 40x magnification.

Results and Discussion

![Graph showing ultimate tensile stress for D638 Type I, D638 Type II, and D3039](image)

Each of the tensile tests coupon was printed and tested 3 times. However, due to an experimental error, one of the results from the D638 Type II could not be used and thus not included in the results. For the same specimen, the degree of variation, measured by coefficient of variation, is relatively small. The coefficient of variation for the strength at break for each of the specimen is less than 5%, as for the strain at break, the variability is larger, but is still within 10%. However, the variations are extremely large, if compared between the different specimen types.

R.J. Zaldivar et al. (year) postulated that coupons from D3039 were expected to give a high ultimate strength, as more continuous fibers were spanning the gage length. However, such prediction was not observed here. In fact, D3039 coupons provide the lowest strength among the 3 different types of specimen. D638 Type II on the other hand, has the highest strength at break, followed by D638 Type I. The same trend is observed with the strain at break.

In addition, the failure locations of each specimen are shown in Figures 5, 6, and 7. For D638 Type I, the failure location is consistently outside the gage length and the narrow section. According to ASTM D638-14, Section 7.3, such breakage location is not acceptable, and retests should be made.
unless such flaws constitutes a variable to be studied. For such failure location, the standard recommends using Type II instead. For the D638 Type II specimen tests in this experiment, failure locations are consistently at or around the gage length but are within the narrow section of the specimens. As for the D3039 specimens, the failure locations deviate from specimen to specimen, but are within the grips of the tensile test machine. The following figures show the breakage location. The gage length is annotated by the red markings.

One of the possible explanations for the difference in the failure location for D638 Type I and Type II is due to the difference in stress concentration around the curved region of the specimen. It was found through Finite Element Analysis that D638 Type I had a higher stress concentration factor at the arc area (Garrell et al., 2003). In addition, the location of the maximum von Mises stress is also closer to the gage length in the Type II specimens as compared to the Type I specimens.
As shown in Figure 8, brittle failure is observed at the contours, which are aligned along the loading direction. A more ductile failure is observed for raster aligned at those directions not parallel to the loading direction. Such observation is interesting, as plastics tend to undergo ductile failure. Yet in this sample, both failure types can be distinctly observed.

In Figure 9, it is observed around the area connecting contour and raster of the coupon, the air gap between each filament is widen. This observation suggests that inter filament bonding fails before the failure of filament itself. Possible explanations for this are that the ULTEM® 9085 filament strength is much higher than the filament bonding strength, and also the raster experiences out of plane loading. A different failure mechanism which filament and filament bonding failure can occur at the same time (Ahn et al., 2002). Hence, the higher strength of Type II tensile specimen as compared to the other two specimens can be possibly explained by the contour to overall raster ratio. The higher the contour to overall raster ratio, the higher the strength as filament exhibit highest strength along the loading direction.

**Conclusion**

In this paper, 3 different types of tensile specimens were tested and the tensile strength from the D638 Type I, D638 Type II and D3039 was found to vary significantly. Scanning Electron Microscopy was used to examine the fracture surface to provide possible explanation. It has been found that different in contour to overall raster ratio across specimen can contribute to the difference in mechanical strength. This research can further expand to investigate the other types of specimens available in the ASTM D638 standard. Possible future work can involve exploration on the relationship between the contour to raster ratio on the mechanical strength.
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REFERENCES


