

Process-induced Properties of FDM Products

A. Sherif El-Gizawy, Shan Corl, and Brian Graybill

Abstract—Direct digital manufacturing using fused deposition modeling (FDM) is a layered manufacturing technique that can be used to build functional products out of thermoplastic materials. The use of Polyetherimide (ULTEM 9085) material with this technology is growing very rapidly. This is because of the superior mechanical and physical properties of ULTEM 9085 compared with the commonly used thermoplastics with FDM technology. ULTEM 9085 is particularly ideal for the transportation industry due to its high strength-to-weight ratio and its FST (flame, smoke, and toxicity) rating. The present paper presents an effective approach for characterization of the evolved mechanical properties and internal structure of FDM processed ULTEM 9085. The developed approach uses the classical lamination theory for composite materials together with unique testing techniques for generation of properties needed for design and optimization of FDM ULTEM 9085 structures. A case study is presented in order to verify the developed approach.

Keywords—Direct Digital Manufacturing, Evolved Properties, FDM, Functional Products, Thermoplastics, ULTEM 9085.

I. INTRODUCTION

Direct Digital Manufacturing (DDM) is a term used to describe a relatively new class of manufacturing processes. These processes fabricate a part by adding material in thin cross-sections until the part is built (which is why these processes are also referred to as layered manufacturing (LM)). DDM is advantageous in many ways. One of the benefits most often cited is the ability to create part geometries that are impossible with conventional methods (e.g. ducting with internal features). These parts can also be built almost directly from a computer-aided design (CAD) and completed within hours. This, in combination with the fact that no expensive tools are required to produce a part dramatically reduces lead times that would otherwise be required to produce functional products. Additionally, DDM processes use much less material than conventional methods because fabrication is a result of adding material instead of removing it, thus reducing waste.

There are several industries with a very high interest in developing DDM technology for building functional products. Examples of these industries are the biomedical field, which could employ DDM to create bone splints specific to an individual in a matter of hours, and the aerospace industry, which typically manufactures in low volumes and would have use for parts with complex geometries. However, while there is a significant desire to use DDM for production, the technologies currently being used must be further developed and understood in order to design safe, robust parts that are fabricated with this technology.

One DDM process with considerable potential is Fused Deposition Modeling (FDM). A schematic of FDM process system is displayed in Fig. 1 [1]. This process creates parts by extruding an amorphic polymeric filament through a heated nozzle and depositing semi-molten filament on a work table. Several filaments are deposited in succession to create a single layer; then, the work table moves in the negative z direction to allow for deposition of the next layer. The simplicity of this fabrication process, along with the wide variety of materials available to DDM users are few of the reasons for FDM’s popularity.

Fig. 1 Fused Deposition Modelling (FDM) System [1]

Fusion deposition of functional products necessitates that the selected process delivers parts with the needed geometrical and physical specifications in order to satisfy service requirements. Accurate prediction and close control of physical and geometrical properties of FDM processed products is the key for the transition from Rapid Prototyping (RP) of parts for just visual appearance to layered Manufacturing (LM) of functional products. Reliable product design models are needed in order to evaluate the functionality of rapid manufactured products for strength and stiffness. As the tolerances on the variation of part size, shape, and integrity become tighter for these products, the need for prior determination of process-induced properties and internal structure is felt even more in the industry. Much work has already been done in the area of characterizing and optimizing the FDM process. Kulkarni and Dutta investigated the effect of extrusion pattern on part stiffness [2]. Pennington, Hoekstra,
and Newcomer found that part size, location in the work envelope, and oven temperature during the build all had significant effects on dimensional accuracy [3]. Reddy, Reddy, and Ghosh determined that road gap, extrusion temperature, and oven temperature all had a significant impact on part strength for parts fabricated from acrylo-nitrile butadiene styrene (ABS), a finding that holds for most materials [4]. Sun et al. researched the effect of processing conditions on bonding quality (which is critical to part strength) [5]. Warp deformation in FDM parts was characterized by Wang, Xi, and Jin and attributed to thermal stresses caused during deposition [6]. However, while this body of work is useful in determining how to create stronger parts, a model capable of predicting FDM part behavior is still lacking. The internal structure of FDM parts is analogous to the fiber layout in composite materials. As such, various researchers have attempted to apply classical lamination theory (CLT) to predict the failure criteria of FDM parts [7], [8]. Moderate accuracy was achieved with these equations. Three-dimensional finite element analysis (FEA) is another method being explored in the prediction of the mechanical behavior of FDM parts. A study to investigate the relationship between mechanical properties and porosity in FDM fabricated porous structures was performed by Ang, Leong and Chua [9]. Statistical analysis of the data was performed and a logarithmic relationship between the structure’s mechanical properties and porosity was formulated.

The application of FDM for building functional products is limited by the advances in materials used by this technology. The recent developments in this respect include high-performance production plastics that offer high strength at high temperatures. Polyetherimide (ULTEM 9085) is one of these materials that can be used in building functional products. ULTEM 9085 is a flame retardant high performance thermoplastic. It is ideal for the transportation industry due to its high strength-to-weight ratio and its FST (flame, smoke, and toxicity) rating. The present work introduces an effective approach for characterization of the evolved mechanical properties and internal structure of FDM processed thermoplastics. The developed approach uses analytical methods together with unique testing techniques for generation of properties needed for design and optimization of FDM ULTEM 9085 structures.

II. INVESTIGATIVE METHODS

A. Integrated Approach for Properties Characterization

The approach used in characterization of process-induced properties and structure, is displayed in Fig. 2. First, data on stiffness properties and images of internal structure of FDM processed samples with different raster angles and build orientation are collected. These data consists of mechanical properties along three principle axes, and scanning electron micrographs of internal structure of FDM processed materials. An analysis using CLT, and based on the work reported by the author and his coauthors [10] are used in the present work for determination of the anisotropic stiffness matrix for parts built by FDM. These tasks result in establishing constitutive relationships and models that predict the internal structure (mesostructure) of the FDM processed materials. These relationships are then used with finite elements analysis in order to check the FDM build structures for strength and stiffness. Case studies are presented in order to verify the effectiveness of the present approach.

![Fig. 2 Investigative Approach](image)

B. Experimental Procedures

All testing panels were constructed in a STRATASYS FDM FORTUS 400mc System. Two build directions were used in order to determine all needed anisotropic properties. One group of panels was build flat and the second was build vertically (upright). All machine settings were at default for ULTEM 9085. The extruder liquefier process temperature was at the default 375 °C set-point for ULTEM 9085. The followings were special adjustments in process parameters in order to maintain integrity of the FDM build structures in the present investigation: 1. custom groups were created in the operating system to force the internal fill raster to maintain the same angle at every layer; 2. the system mode “Thin-wall” was selected for the upright thin Z-panels. This reduces the set oven temperature to 185 °C to reduce warping of tall thin structures. (Note actual air temperatures at the build plane are about 10-15°C cooler than set-point on the FORTUS 400mc).

Room temperature mechanical properties of panels produced by FDM were determined using an MTS System equipped with 5.0 kN load cell and a data acquisition system for collecting the results. Tension test was performed using ASTM D 638-03 standard test method for tensile properties of polymer matrix composite materials. Testing speed was kept constant at 5mm/min. The strain data were recorded using tri-axis strain gages of the type WA-XX-060WR-120 series strain gages from Vishay Intertechnology, Inc. for measuring strains along the 0°, 45° and 90° directions. Weight, length, width and thickness measurements were recorded for each sample. Width measurements were taken at five different locations along the longitudinal axis of the samples.
C. Image-based Mesostructure

The cross-sectional surfaces of specimens of various raster orientations are prepared for Scanning Electron Microscopy. This is achieved by first making a lead cut of very small depth on each specimen where we expected to study the cross-section, with a blade on all 4 sides. Then the specimens are frozen by holding them for about 2-3 minutes in liquid Nitrogen. This makes the samples temporarily brittle and they are broken at the marked section by applying an impact force with a hammer. The cross-sections are then cleaned with a compressed gas duster and examined under SEM. Images are taken for all specimens and digitized for determination of the mesostructure features. They include average major and minor axes lengths of the fibers cross section (elliptic shape), the maximum gap and maximum overlap between adjacent fibers.

Figure 3 illustrates different mesostructure features and the use of binary image for measurements. A hypothetical laminar cross-section is shown in Fig. 4, and at high magnification in Fig. 5, for illustration of different measurements of mesostructure features of FDM-processed materials. Ellipses are fitted to fibers and colored black. Each section is saved as an image to be used for image analysis. Un-shaded pixels are counted which lead to estimation of volume fraction of porosity within the structure. An algorithm is established to generate a random matrix of \((m \times n)\) centers of ellipses by considering the centers as functions of inter-thread spacing and the major & minor axis of the cross sections. The exact geometry of the ellipses, governed by the length of the major (a) and minor axis (b) is randomized by generating random values of ‘a’ and ‘b’ within the tolerances defined by the measurements obtained from mesostructure analysis explained in above. The MATLAB function ‘rand’ which generates pseudo-random numbers with a uniform distribution over the specified range, is used for this purpose. The horizontal and vertical separation between centers is given by ‘r’ and ‘q’ respectively. An \(m \times n\) matrix of ‘r’ and ‘q’ has to be generated the initiation of the algorithm to generate the centers \((h, k)\) of the ellipses. The relation between ‘h’, ‘a’ and ‘r’ and ‘k’, ‘b’ and ‘q’ is as follows,

\[
H_i = r_i + a_i
\]

(1a)

If \(i = 1\), \(h_i = H_i\) \hspace{1cm} (1b)

Otherwise if \(i > 1\), \(h_i = h_{i-1} + a_{i-1} + H_i\) \hspace{1cm} (1c)

\[
K_i = q_i + b_i
\]

(1d)

If \(i = 1\), \(k_i = K_i\) \hspace{1cm} (1e)

Otherwise if \(i > 1\), \(k_i = k_{i-1} + b_{i-1} + K_i\) \hspace{1cm} (1f)

Once we have the value of \((h, k)\) we can describe the ellipse using the parametric equation of an ellipse given by;

\[
x_i = h_i + a_i \cos(t)
\]

(2a)

\[
y_i = k_i + b_i \sin(t)
\]

(2b)
More details of the Mesostructure generating model could be found in [11].

**D. Analytical Methods**

Fiber orientation (raster angle) in each layer and stacking sequence of various layers affect mechanical properties of fusion deposition build structures. Figures 6-8 demonstrate how tensile properties of flat panels build with fibers oriented along, perpendicular, and at 45 degrees to the loading direction are used to determine modulus of elasticity along principle axes 1, and 2. Major and minor Poisson's ratios, and shear modulus are also obtainable from the above mentioned tests [2]. Because the inaccuracy of the assumption of transversely isotropic properties of layers deposited by FDM methods, the properties along the principle axis 3 were determined in the present work from testing upright panels build in the Z-direction with different raster orientations. Figure 9 displays methods of estimating the values $E_3$, $\nu_{31}$, and $\nu_{32}$. $E_3$ was obtained from the stress-strain curves. Poisson's ratios $\nu_{31}$ and $\nu_{32}$ were found using two direction (strain gages) rosettes. The ratio $\nu_{32}$ came from the 0° samples and $\nu_{31}$ came from the 90° samples (vertically build samples).

**III. RESULTS AND DISCUSSIONS**

**A. Mechanical Properties**

Table 1 summarizes major mechanical properties obtained from testing FDM build flat tensile panels with 0°, 45°, and 90° raster angles. These results are an average of testing 5 panels for each design. The standard deviations representing measurements variation from the average values are given with each property. Figure 7 displays the stress-strain curves of all FDM-processed samples in addition to a curve representing the injection molded case for comparison. Strength, ductility, and toughness of the injection molded samples have higher properties than the FDM-processed ones. The reported decrease in strength and ductility can be attributed to thermal degradation of FDM-processed material’s mechanical properties. This is caused by the polymer molecular deterioration as a result of heating. At high temperatures, components of the long chain backbone of ULTEM 9085...
begin to separate (molecular scission) and react with one another resulting in reduction of strength and ductility of FDM processed ULTEM 9085.

**TABLE I**
Mechanical Properties of ULTEM 9085 Flat Panels

<table>
<thead>
<tr>
<th>Raster Angle</th>
<th>Modulus of Elasticity (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Ductility Elong. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>2539.40 ± 104</td>
<td>78.60 ± 3.44</td>
<td>57.5 ± 4.60</td>
<td>43.8 ± 0.15</td>
</tr>
<tr>
<td>45°</td>
<td>2424.6 ± 166</td>
<td>56.76 ± 4.64</td>
<td>44.89 ± 4.14</td>
<td>3.31 ± 0.38</td>
</tr>
<tr>
<td>90°</td>
<td>2327.8 ± 178</td>
<td>45.70 ± 8.71</td>
<td>42.85 ± 6.19</td>
<td>2.37 ± 0.81</td>
</tr>
</tbody>
</table>

Table II summarizes major mechanical properties obtained from testing FDM build upright (z) tensile panels with raster angles range 0° - 90° in increments of 15°. Reported results are average of testing 5 panels for each design. The standard deviations representing the measurements variation from the average values are given with each property. Comparing the results in Table I and II reveals that strength and modulus of FDM materials along the build (Z) direction are lower by about 20% in average than those of the other directions.

**FIGURE 10**
Stress-strain curves for FDM ULTEM 9085 flat panels with different raster angles, compared with properties of injection molded ones.

**TABLE II**
Mechanical Properties of ULTEM 9085 Upright Panels

<table>
<thead>
<tr>
<th>Raster Angle</th>
<th>Modulus of Elasticity (MPa)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Yield Strength (MPa)</th>
<th>Ductility Elong. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>2163.5 ± 26.6</td>
<td>52.0 ± 2.4</td>
<td>43.8 ± 2.3</td>
<td>2.79 ± 0.2</td>
</tr>
<tr>
<td>15°</td>
<td>2180.8 ± 98.2</td>
<td>42.5 ± 5.9</td>
<td>46.5 ± 2.2</td>
<td>2.1 ± 0.4</td>
</tr>
<tr>
<td>30°</td>
<td>2154.2 ± 44.8</td>
<td>50.4 ± 6.8</td>
<td>47.1 ± 1.5</td>
<td>2.6 ± 0.4</td>
</tr>
<tr>
<td>+45°</td>
<td>2170.7 ± 120.6</td>
<td>51.9 ± 5.8</td>
<td>45.5 ± 1.7</td>
<td>2.7 ± 0.4</td>
</tr>
<tr>
<td>60°</td>
<td>2211.4 ± 53.6</td>
<td>48.9 ± 5.8</td>
<td>46.4 ± 1.4</td>
<td>2.4 ± 0.4</td>
</tr>
<tr>
<td>75°</td>
<td>2169.6 ± 35.9</td>
<td>50.9 ± 5.7</td>
<td>45.1 ± 0.7</td>
<td>2.7 ± 0.4</td>
</tr>
<tr>
<td>90°</td>
<td>1991.7 ± 92.0</td>
<td>54.3 ± 1.4</td>
<td>43.7 ± 0.8</td>
<td>3.4 ± 0.1</td>
</tr>
</tbody>
</table>

**B. Structural Mechanics of FDM Build Products**
An analysis using classical lamina theory (CLT) and based on the work reported by the author and his coauthors [10, 11] was used in the present work for determination of the anisotropic stiffness matrix for parts built by FDM. Each lamina is subjected to normal stresses $\sigma_1, \sigma_2$ and $\sigma_3$ and shear stresses $\tau_{23}, \tau_{13}$ and $\tau_{12}$. These stresses are related to strains as shown in Eq. (3).

$$ \mathbf{e} = \begin{bmatrix} E_{11} & -v_{12}E_{12} & -v_{13}E_{13} \\ -v_{12}E_{11} & E_{22} & -v_{23}E_{23} \\ -v_{13}E_{11} & -v_{23}E_{22} & E_{33} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{bmatrix} $$

(3)

Where $E_1$, $E_2$, and $E_3$ are the Young’s moduli and the Poisson’s ratios are $v_{12}, v_{21}, v_{13}, v_{23}, v_{31}$, and $v_{32}$ and the Shear moduli are $G_{12}$, $G_{23}$, and $G_{32}$. Eq. 3 can take the following form (Eq. 4).

$$ \mathbf{e} = [\mathbf{S}] \mathbf{\sigma} $$

(4)

Where $[\mathbf{S}]$ is the compliance matrix, $\mathbf{e}$ is the strain column vector and $\mathbf{\sigma}$ is the stress column vector.

The assumption of plane stress allows for setting the stress components $\sigma_{13}$, $\tau_{23}$ and $\tau_{13}$ to zero and the 1-2 plane of the principal material co-ordinate system is in the plane of the layer (lamina). This gives the reduced stiffness matrix presented in Eq. 5.
Where \([Q]\) is the Compliance matrix and, \(\sigma_x, \sigma_y, \tau_{xy}\) are the in-plane stresses, and \(\varepsilon_x, \varepsilon_y, \gamma_{xy}\) the in-plane strains.

Stiffness properties of FDM-processed ULTEM 9085 were determined from the results of mechanical testing. The results are presented in Table III.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_1)</td>
<td>2539.4 MPa</td>
</tr>
<tr>
<td>(E_2)</td>
<td>2327.9 MPa</td>
</tr>
<tr>
<td>(E_3)</td>
<td>2159.6 MPa</td>
</tr>
<tr>
<td>(\nu_{12})</td>
<td>0.46</td>
</tr>
<tr>
<td>(\nu_{13})</td>
<td>0.39</td>
</tr>
<tr>
<td>(\nu_{23})</td>
<td>0.40</td>
</tr>
<tr>
<td>(G_{12})</td>
<td>635.5MPa</td>
</tr>
<tr>
<td>(G_{13})</td>
<td>635.5MPa</td>
</tr>
<tr>
<td>(G_{23})</td>
<td>582.82MPa</td>
</tr>
</tbody>
</table>

C. Evaluation of the Present Approach

In order to evaluate the effectiveness of the presented integrated approach for characterization of the evolved mechanical properties and mesostructure of FDM processed ULTEM 9085, a finite element method (FEM) for simulation of mechanical testing of FDM-processed materials were conducted using the experimentally determined stiffness properties of fibers modified by the predicted volume fraction of voids of the investigated materials. The ABAQUS/Standard platform utilizes Newton’s method to solve systems of nonlinear equilibrium equations and was used in the simulation. Because these cases involve history-dependent responses, the solution is obtained as a series of time increments. Within each increment, iterations are performed to insure solution convergence. Figure 11a shows the FEM model used for simulation. Hexagonal 3D quadratic stress elements were used for meshing the part. Boundary conditions are applied to the gripping areas. They do not allow for translation or rotation about any of the three axes. The external force is applied as a distributed load to one side of the gripping area over 109 nodes (see Fig. 11b). During simulation, the deformation loads are applied incrementally starting from zero loads until the total sum of the distributed forces reached the yielding force. The simulation results of the evolved stresses and deformation under the given loads of one of the tension tests are presented in Fig.11c. Figure 12 displays comparison between the experimentally determined stress-strain curve and the predicted one using the presented approach. The comparison reveals the close match between them. This is an indication of the accuracy of the proposed models for evaluating the integrity of the FDM-processed products under service loading conditions (product design for strength and stiffness).
The present paper presents an effective approach for characterization of properties of FDM processed materials. This approach uses analytical methods together with unique testing technique for predicting the stiffness properties and the evolved Mesostructure needed for design of FDM build structures. The focus of the present work was on the new aerospace material "ULTEM 9085" because of its high strength-to-weight ratio and its FST (flame, smoke, and toxicity) rating. The experimental observations indicate reduction of strength, ductility, and toughness of FDM-processed ULTEM 9085 compared with the injection molded ones. This fact might be due to the molecular deterioration of the polymer as result of heating during the deposition process. The present approach was verified using an experimental case study. Simulation results using the presented approach with FEM modeling technique agree well with the experimental observations. The developed approach helps in generation of properties needed for design and optimization of FDM functional products.

ACKNOWLEDGMENT

The authors wish to acknowledge the financial supports of The Boeing Company and STRATASYS, Inc., for the present research. Our appreciations are also extended to Mr. Gregg R. Bogucki and Mr. Michael Hayes of Boeing Research and Technology, and Mr. Jeffery DeGrange, of STRATASYS for their technical advice and encouragements during the course of the present work.

REFERENCES