**American Journal of Engineering and Applied Sciences 7 (3): 307-315, 2014**
ISSN: 1941-7020

doi:10.3844/ajeassp.2014.307.315 Published Online 7 (3) 2014 (http://www.thescipub.com/ajeas.toc)

# STUDY OF DYNAMIC MECHANICAL PROPERTIES OF FUSED DEPOSITION MODELLING PROCESSED ULTEM MATERIAL

**[1]Adhiyamaan Arivazhagan, [2]Ammar Saleem, [2]S.H. Masood, [2]Mostafa Nikzad and [1]K.A. Jagadeesh**

[1]Department of Mechanical Engineering, PSG College of Technology, Coimbatore, India
[2]Faculty of Science, Engineering and Technology, Swinburne University of Technology, Melbourne, Australia

Received 2014-07-23; Revised 2014-08-13; Accepted 2014-08-15

## ABSTRACT

Fused Deposition Modelling (FDM), a renowned Rapid Prototyping (RP) process, has been successfully implemented in several industries to fabricate concept models and prototypes for rapid manufacturing. This study furnishes terse notes about the material damping properties of FDM made ULTEM samples considering the effect of FDM process parameters. Dynamic Mechanical Analysis (DMA) is carried out using DMA 2980 equipment to study the dynamic response of the FDM material subjected to single cantilever loading under periodic stress. Three FDM process parameters namely Build Style, Raster Width and Raster Angle were contemplated. ULTEM parts are fabricated using solid normal build style and three values each of raster width and raster angle. DMA is performed with temperature sweep at three different fixed frequencies of 1, 50 and 100 Hz. Results were obtained for dynamic properties such as Maximum Storage Modulus, Maximum Loss Modulus, Maximum Tan Delta and Maximum Complex Viscosity. The present work discusses the effect of increasing the frequencies and temperature on FDM made ULTEM samples using different FDM process parameters.

**Keywords:** Fused Deposition Modelling, Dynamic Mechanical Analysis, ULTEM, Damping Properties

## 1. INTRODUCTION

Rapid Prototyping (RP) technologies widely used by many manufacturing industries have allowed greater levels of product validation in a short span of time and meeting customers' stringent requirements for new product developments. Fused Deposition Modelling (FDM), a prominent RP technology developed by Stratasys Inc, produces prototypes which can be used for early design verification and testing. In bio-medical engineering, it is finding applications for mass customization. In FDM process, parts are made through layer-by-layer deposition of extruded material from a nozzle using feedstock thermoplastic filament wound on a spool (Masood, 2014). Stratasys Inc limits the scope of material that can be used in FDM mainly to Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS), Polyphenyl-Sulfone (PPSF) and ULTEM.

Material properties of FDM prototype plays a major role during design verification and testing of the prototype. Research works are going on in analyzing the material properties of FDM made materials like PC and ABS. Anitha *et al.* (2001) analyzed the effect of process parameters on the surface roughness of the components produced in FDM. They used Taguchi method to optimize the parameters. Novakova-Marcincinova and Novak-Marcincin (2012) investigated the anisotropic material properties of FDM made ABS material considering the variables like raster orientation and air gap. They also compared the material properties with other RP technologies such as Stereolithography (SLA) and Laminated Object Manufacturing (LOM).

**Corresponding Author:** Masood, S.H., Swinburne University of Technology, Melbourne, Australia

FDM material undergoes physical and thermal changes affecting their mechanical and damping properties, during layer by layer deposition process. Using the Dynamic Mechanical Analysis (DMA) technique, we can determine how the dynamic properties for the material changes through the FDM extruder head and how the properties are affected by various FDM parameters. Works have also been done on DMA of polymers. Moroni *et al.* (2006) have carried out DMA on 3D fibre-deposited scaffolds and investigated the influence of pore geometry and architecture on dynamic mechanical properties. Más *et al*. (2002) investigated dynamic mechanical properties of Polycarbonate (PC) and ABS blends and compared the results with other techniques like dielectric and calorimetric analysis.

Very limited work has been carried out on FDM made ULTEM material properties. ULTEM 9085 is a flame resistant high performance thermoplastic, which is used for rapid prototyping as well as for the digital manufacturing. This study presents dynamic mechanical properties of FDM made ULTEM material considering the effect of FDM parameters namely raster pattern, raster width and raster angle.

## 2. FUSED DEPOSITION MODELLING

Fused Deposition Modelling (FDM) is a RP process to convert 3D CAD model into a physical prototype. The CAD model is first converted into Stereolithography (STL) file. The STL file is then exported to FDM slicing and pre-processing software package called Insight. After preprocessing and slicing into thin layers in the Insight software, the STL file is then transformed into Stratasys Modelling Language (SML) file which has the instructions codes for the FDM extrusion head to follow the specific path according to the original 3D model. Various process parameters available on the particular FDM machine are selected during the preprocessing stage.

As shown in the **Fig. 1** the material is extruded from FDM head through a nozzle in a semi-molten state and it is deposited according to the specified tool path. The semi-molten state is achieved with the presence of heat element in the FDM head. The newly deposited material bonds with the adjacent material, which has been already deposited. The FDM head can be moved in X-Y direction in accordance with the part geometry. The table which holds the part can be moved vertically in Z direction.

The support material is also deposited in a similar way to support the prototypes, which has cavities or overhangs. Support material can be removed after the fabrication is completed (Novakova-Marcincinova and Novak-Marcincin, 2012).

Stratasys FORTUS 900 mc FDM machine is used for making test samples, which has parameters like raster pattern, raster angle, raster width, envelope temperature, layer thickness, deposition speed. This study focuses on the effect of only key process parameters of Raster pattern, Raster angle and Raster width.

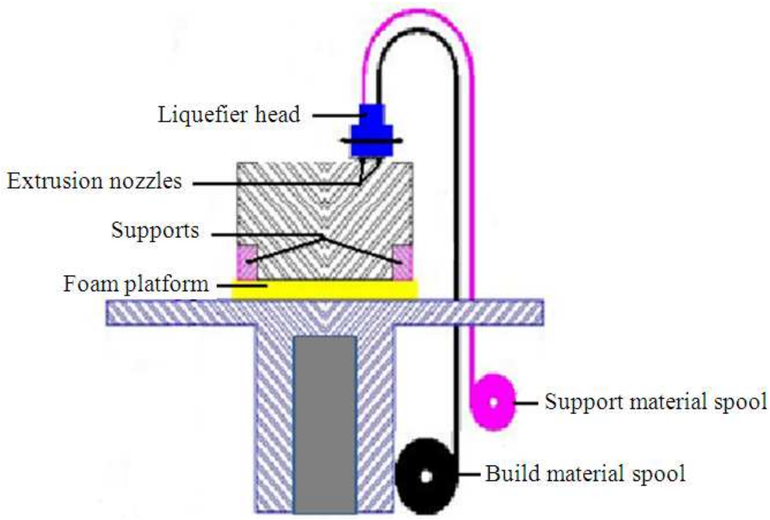


**Fig. 1.** FDM working principle

Raster pattern is the build style pattern in which the beads are deposited from the FDM nozzle in layer by layer fabrication. It is determined by the air gap between the beads. If the there is no air gap between the beads, then it is termed as solid normal. The pattern with small air gap is termed as sparse-double dense. If there is more air gap between the beads, then it is called as sparse. This study considers only on solid normal build style because of its characteristics of having no voids which can strengthen the material property.

Raster width is the width of the bead deposited in a layer. It is determined by the tip size used by the FDM head. In this study, we carried out the experiment with T16 tip size. For this tip size, the raster width varies from 0.406 to 0.781 mm.

Raster angle is the angle which the beads make with the X-axis of the horizontal table. The selected raster angles in FORTUS 900 mc are 0°/90°, 45°/45° and 30°/60° as shown in **Fig. 2-4**.

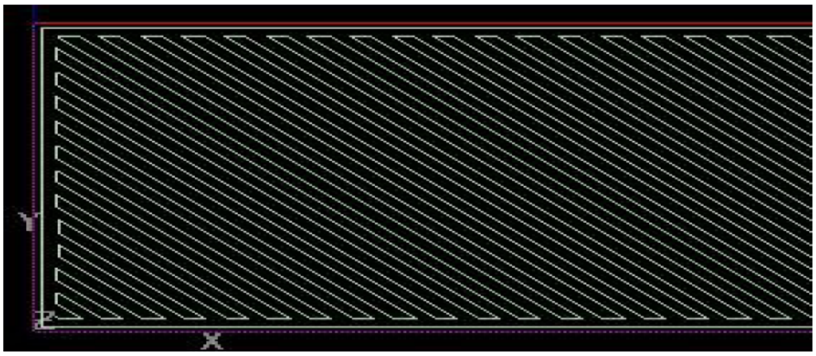


**Fig. 2.** Solid normal build style with 45°/45° raster angle

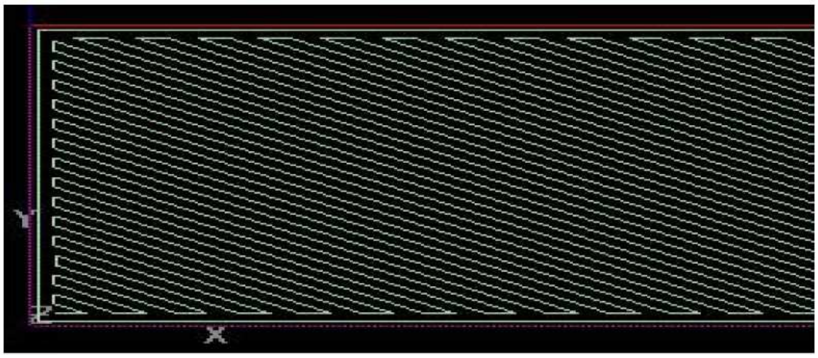


**Fig. 3.** Solid normal build style with 30°/60° raster angle

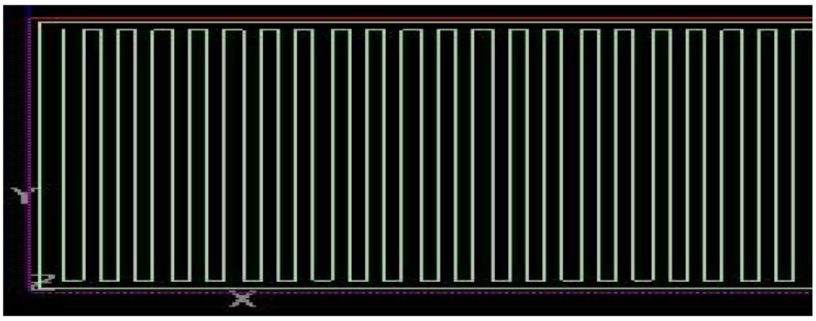


**Fig. 4.** Solid normal build style with 0°/90° raster angle

## 3. DYNAMIC MECHANICAL ANALYSIS

Dynamic Mechanical Analysis (DMA) involves imposing a small cyclic stress or stain on a sample and measuring the resulting responses. DMA is used to study both molecular relaxation process i.e., modulus, as well as inherent mechanical or flow properties i.e., viscosity, as a function of time and frequency. From the responses of sample obtained, one can determine the properties like storage modulus, loss modulus, complex viscosity and glass transition temperatures. The modulus value gives us the stiffness of the samples i.e., the material's resistance to deformation. Glass transition temperature, Tg corresponds to the expansion of free volume, allowing the greater mobility of polymer chain beyond this transition. The ability of the material to store energy is called storage modulus and the ability to lose energy is called loss modulus. Tan δ is the ratio of loss modulus to the storage modulus. This is also called as loss tangent or damping factor (Menard, 2008).

In DMA experiment, we can sweep across temperature or frequency range. In temperature sweep, we can vary temperature in the range of 20°C to more than 200°C keeping the frequency at constant. In frequency sweep, frequency can be varied from 0.01 to 100 Hz at a constant temperature (Menard, 2008). This study focuses on temperature sweep, where the temperature is varied from 20 to 250°C at three different fixed frequencies such as 1, 50 and 100 Hz.

## 4. EXPERIMENTAL SETUP

The ULTEM samples are fabricated using FORTUS 900mc by varying FDM process parameters. In this study, the solid normal build style is selected and three values for raster width for tip size T16 (0.406, 0.606 and 0.781 mm) are considered and three values of raster angles like (0°/90°, 45°/45°, 30°/60°) are used. Thus a total of 9 test samples (3 identical samples for each set of three parameters) are fabricated as shown in **Table 1.**

Dynamic Mechanical Analysis is done on these 9 samples. In this study, DMA2980 manufactured by TA instruments is used to carry out DMA. There is a clamping system which is provided to hold the sample. The DMA 2980% a vast range of sample geometries. Usually the choice of the sample geometry is governed by the investigations that are held on the sample and the clamp that we chose.

**Table 1.** List of FDM parameters used for various sets of ULTEM samples

| Sample number | Build style | Raster width | Raster angle |
|---|---|---|---|
| 1,2,3 | Solid normal | 0.406 mm | 30°/60° |
| 4,5,6 | Solid normal | 0.606 mm | 45°/45° |
| 7,8,9 | Solid normal | 0.781mm | 0 |

The most commonly used geometry is the bending mode geometry and this utilizes the common sized bars of the sample that has to be tested. The most accurate and exact modulus are produced using the simply supported modes such as the 3 point bending and the cantilever bending. The geometry for the single cantilever bending clamp is in accordance with the sample geometry. The dimensions of the rectangular test samples fabricated on FDM are 35 mm in length, 12.7 mm in width and the thickness is 3.20 mm.

Dynamic Mechanical Analysis is done on these 9 samples. In this study, DMA2980 manufactured by TA instruments is used to carry out DMA. There is a clamping system which is provided to hold the sample. The DMA 2980% a vast range of sample geometries. Usually the choice of the sample geometry is governed by the investigations that are held on the sample and the clamp that we chose. The most commonly used geometry is the bending mode geometry and this utilizes the common sized bars of the sample that has to be tested. The most accurate and exact modulus are produced using the simply supported modes such as the 3 point bending and the cantilever bending. The geometry for the single cantilever bending clamp is in accordance with the sample geometry. The dimensions of the rectangular test samples fabricated on FDM are 35 mm in length, 12.7 mm in width and the thickness is 3.20 mm.

## 5. RESULTS

Once the experiments are finished, each test will have a temperature scan graph generated with storage Modulus (MPa) on left Y axis and Loss Modulus (MPa) on right Y axis against the temperature (°C) on X axis by the Thermal Advantage Universal Analysis software. The left and right Y axis can be changed to get other property values like flexural Modulus (MPa), Tan δ and complex viscosity (MPa*sec). All the graphs of the samples with solid normal build style and at particular frequencies are overlaid. **Figure 5** shows such an overlaid graph of samples of solid normal build style with Storage modulus, Loss modulus and Tan $\delta$ on left and right Y axes. Similarly **Fig. 6** show overlaid graph with flexural modulus and complex viscosities on Y axes.

From the **Fig. 5** it is clear that, as the temperature increases at a constant frequency, the storage modulus decreases and loss modulus increases. This is due to the relaxation in the polymer chain with the tendency to store energy decreases with the increase in temperature and tendency to lose energy increases with increase in temperature. Glass transition temperature value is given by the temperature corresponding to the peak of the Tan Delta curve.

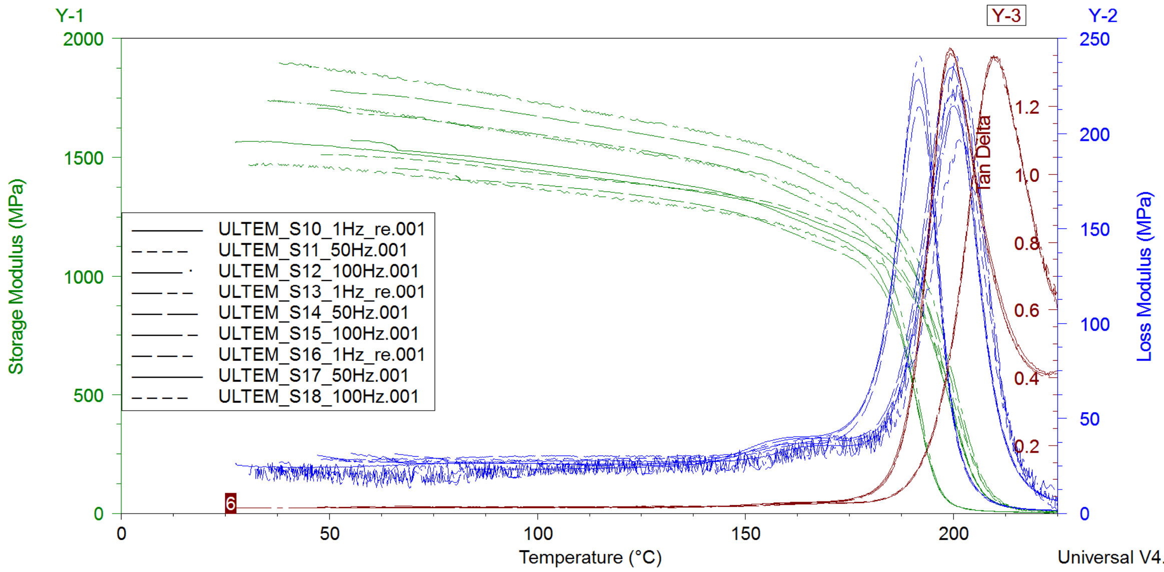


**Fig. 5.** Temperature scan graph of storage modulus, loss modulus and tan delta of ULTEM samples at three different frequencies

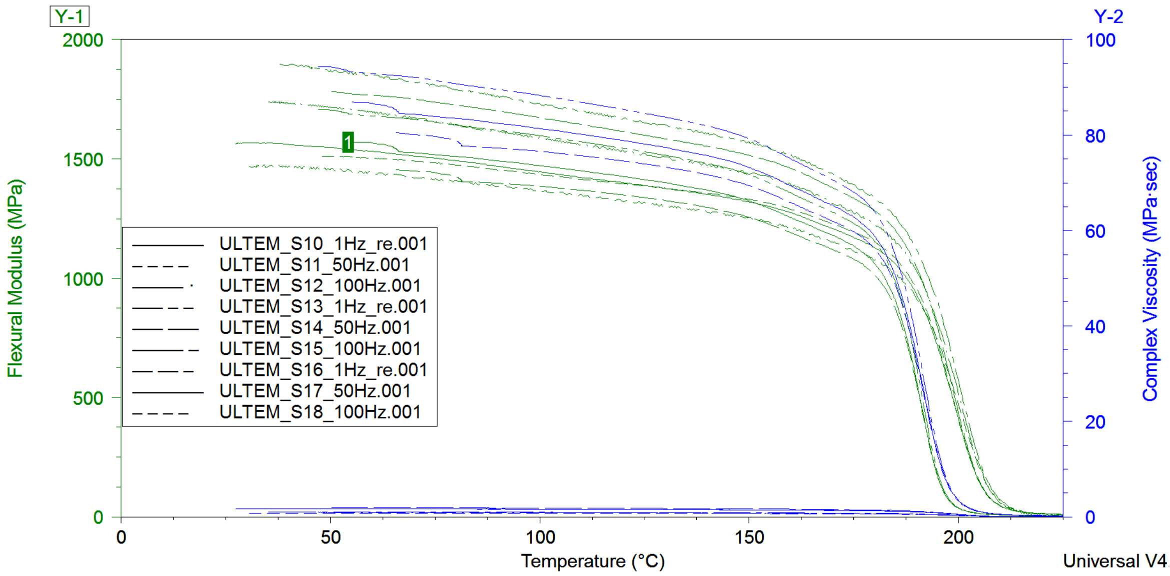


**Fig. 6.** Temperature scan graph of complex viscosity and flexural modulus of ULTEM samples at three different frequencies

**Table 2.** Maximum value of the properties of the ultem samples

| Sample number | Frequency (Hz) | Build style | Raster width (T16) | Raster angle | Max storage modulus (MPa) | Max loss modulus (MPa) | Peak of tan delta | Max flexural modulus (MPa) | Max complex viscosity (MPa*sec) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Solid Normal | 0.406 | 30°/60° | 1554.7 | 222.4 | 1.340 | 1554.7 | 85.9350 |
| 2 | 50 | Solid Normal | 0.406 | 30°/60° | 1488.8 | 220.1 | 1.351 | 1488.8 | 1.6450 |
| 3 | 100 | Solid Normal | 0.406 | 30°/60° | 1596.8 | 224.6 | 145.860 | 1596.8 | 0.8825 |
| 4 | 1 | Solid Normal | 0.606 | 45°/45° | 1533.7 | 214.9 | 1.351 | 1533.7 | 84.7710 |
| 5 | 50 | Solid Normal | 0.606 | 45°/45° | 1522.3 | 204.5 | 1.357 | 1522.3 | 1.6820 |
| 6 | 100 | Solid Normal | 0.606 | 45°/45° | 1654.2 | 216.6 | 78.816 | 1654.2 | 0.9140 |
| 7 | 1 | Solid Normal | 0.781 | 0°/90° | 1741.8 | 245.7 | 1.380 | 1741.8 | 96.2740 |
| 8 | 50 | Solid Normal | 0.781 | 0°/90° | 1664.1 | 224.3 | 1.366 | 1664.1 | 1.8390 |
| 9 | 100 | Solid Normal | 0.781 | 0°/90° | 1832.0 | 232.3 | 24.380 | 1832.0 | 1.0120 |

Similarly from the **Fig. 6**, the complex viscosity and flexural modulus decreases with the increase in temperature. From these graphs the maximum property values are taken and consolidated and are shown in **Table 2**. Graphs are plotted from the data taken from **Table 2** and the maximum property values are analyzed according to the variations in FDM parameters like raster width and raster angle.

## 6. DISCUSSION

As we can see from **Fig. 7**, that in all 9 samples, the raster width of 0.781 mm and raster angle 0°/90° gives the highest value of Storage Modulus of 1832.0 MPa. It is observed that, by increasing the raster width of the sample storage modulus increases. Also, storage modulus is higher in the frequency of 100 Hz. This is because; the material is solid normal and tightens itself when frequency increases. Also the main reason that the material becomes tougher with the increase in frequency is due to nil air gaps between the layers and the beads in the test sample. The Storage Modulus is lower in all of the cases with the frequency of 50Hz. So it is inferred that the ability to store energy increases with the increase in raster width and frequency.

**Figure 8** depicts the maximum loss modulus values with various raster widths and raster angles. We can see variations in loss modulus in all of the samples. Here again the highest value is in the raster width and raster angle of 0.781 mm and 0°/90° and at frequency of 100 Hz respectively. Raster width plays an important role because it is the width of the material bead that is deposited on the surface of the FDM sample. To some extent in some cases, the frequency increases the loss modulus and in some cases raster width increases the toughness of the material. In case of storage modulus, 100 Hz frequency exhibits the higher values but in Loss Modulus sample no 9 does not have the highest value that it should be, according to the trend.

Similarly **Fig. 9** suggests that, again in the frequency of 100 Hz Tan Delta is higher as compared to 1 and 50 Hz. So it is understood that, the property values increases by increase in the frequency. We can say that the ability to store and lose energy in material depends upon the frequency applied.

**Figure 10** illustrates the variation of flexural modulus with the FDM parameters. The flexural modulus increases with the increase in the frequency. As well as, the property value increases with the increase in raster width and raster angle.

**Figure 11** outlines the maximum values of complex viscosity. Liquids and oils are classified as Newtonian, whereas polymers, slurries are not. So we are dealing with the Non-Newtonian materials which can deviate from ideal behavior (Menard, 2008). As it is observed from the graph, viscosity depends upon the applied frequency. Higher the frequency, lower the value of the viscosity and it also depends upon the raster width and raster angle because for raster width 0.406 mm, the complex viscosity is 85.93 MPa*sec and for 0.781 mm, the complex viscosity is 96.27 MPa*sec.

**Figure 12** presents the Glass transition Temperature (Tg) values obtained from the peaks of tan delta curves. From the graph, Tg increases with the increase in the frequency. We can say that increasing the frequency, raster width and raster angle increases the Tg of the material. Sample no 3 has the highest value of Tg of 241.6°C and sample no 7 has the lowest value of Tg of 199.4°C.

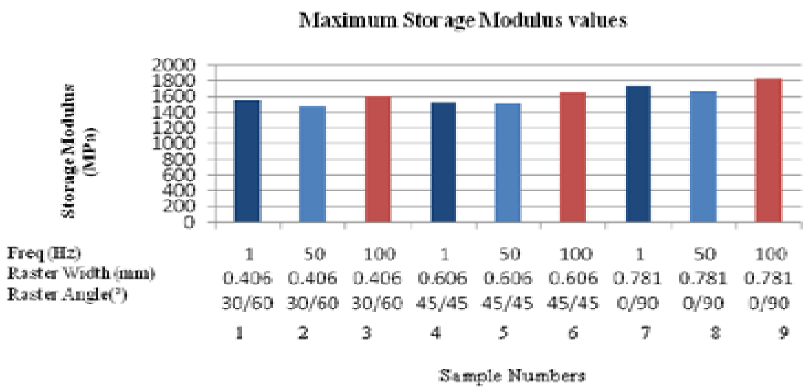


**Fig. 7.** Maximum storage modulus for solid normal build style

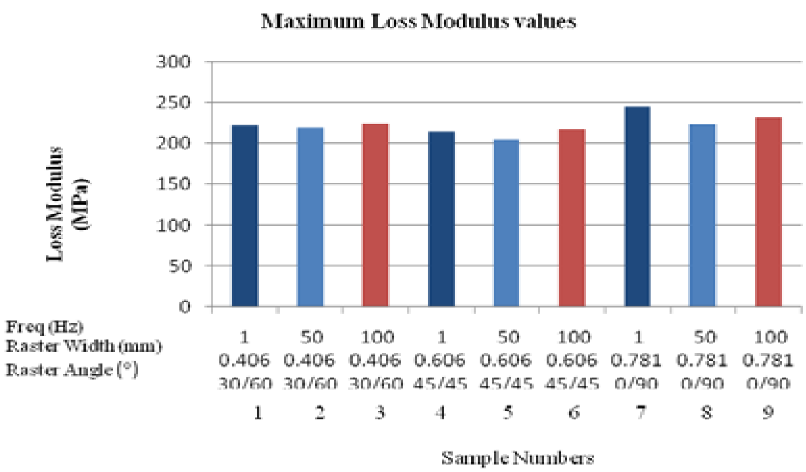


**Fig. 8.** Maximum loss modulus for solid normal build style

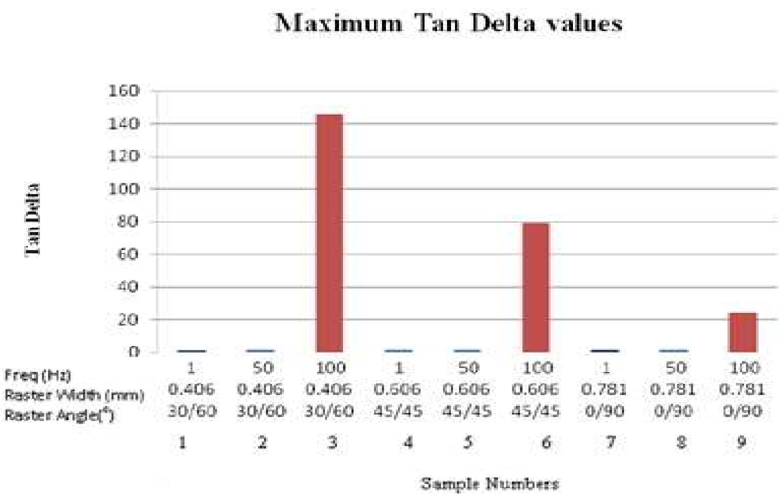


**Fig. 9.** Maximum tan delta for solid normal build style

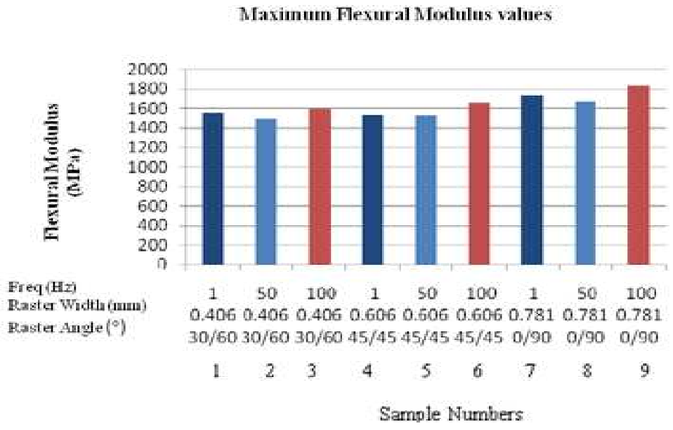


**Fig. 10.** Maximum flexural modulus for solid normal build style

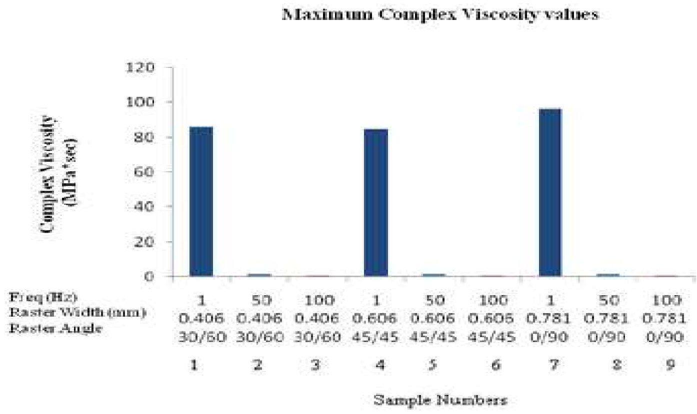


**Fig. 11.** Maximum complex viscosity for solid normal build style

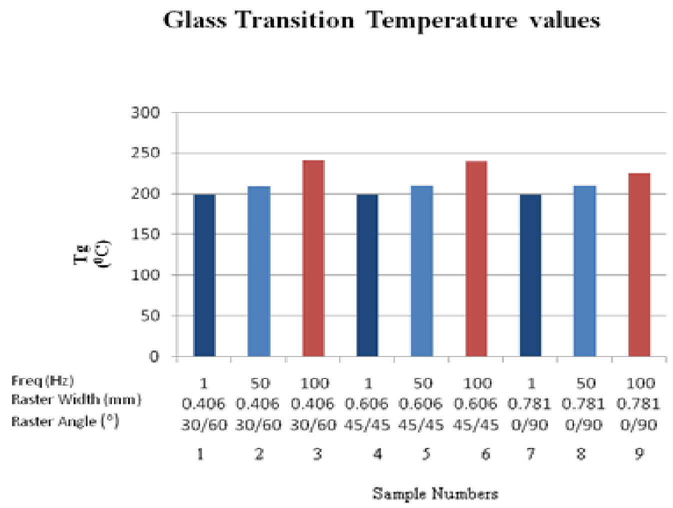


**Fig. 12.** Maximum glass transition temperature for solid normal build style

## 7. CONCLUSION

This study investigated the dynamic mechanical properties of FDM processed ULTEM material considering the effect of FDM parameters. In dynamic mechanical analysis, the work has been focused on temperature sweep and the results are obtained for various samples with different FDM parameters. For the solid normal build style, the storage modulus, flexural modulus, tan delta and glass transition temperature increase with the increase in the frequency, while other properties like loss modulus and complex viscosity decrease with the increase in frequency.

FDM parameter raster width and raster angle also affect the property values. As in case of storage modulus, loss modulus and flexural modulus, the property values has little variations when the raster width and raster angle increases. But in the case of tan delta and glass transition temperatures, the property values increases with the increase in raster width and raster angle. Similarly complex viscosity also increases with the increase in raster width and raster angle. All in all, it is concluded that FDM parameter raster width and raster angle has much influence on the dynamic properties of FDM made ULTEM parts.


## 8. ACKNOWLEDGEMENT

This study is a joint research work of PSG College of Technology, Coimbatore, Tamil Nadu, India and Swinburne University of Technology, Melbourne, Australia. Fabrication of samples is done in Stratasys FORTUS 900mc in India at TIFAC CORE, PSG College of Technology. Tests are conducted in DMA 2980 equipment in Australia at School of Engineering, Swinburne University of Technology.


## 9. REFERENCES


Anitha, R., S. Arunachalam and P. Radhakrishnan, 2001. Critical parameters influencing the quality of prototypes in fused deposition modelling. J. Mater. Process. Technol.. 118: 385-388. DOI: 10.1016/S0924-0136(01)00980-3

Menard, K.P., 2008. Dynamic Mechanical Analysis: A Practical Introduction. 2nd Edn., CRC Press, ISBN-10: 1420053132, pp: 240.

Más, J., A. Vidaurre, J.M. Meseguer, F. Romero and M. Monleón Pradas *et al*., 2002. Dynamic mechanical properties of polycarbonate and acrylonitrile-butadiene-styrene copolymer blends. J. Applied Polymer Blends, 83: 1507-1516. DOI: 10.1002/app.10043.

Moroni, L., J.R De Wijn and C.A. Van Blitterswijk, 2006. 3D fiber-deposited scaffolds for tissue engineering: Influence of pores geometry and architecture on dynamic mechanical properties. Biomaterials, 27: 974-985. DOI: 10.1016/j.biomaterials.2005.07.023.

Novakova-Marcincinova, L. and J. Novak-Marcincin, 2012. Testing of materials for rapid prototyping fused deposition modelling technology. World Acad. Sci. Eng. Technol, 6: 396-399.

Masood, S.H., 2014. Advances in Fused Deposition Modeling. In: Advances in Additive Manufacturing and Tooling, Masood, S.H. (Ed.)., Comprehensive Materials Processing, Elsevier Science Direct, UK, pp: 69-91.