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Dynamic Mechanical Properties of ABS Material Processed by Fused Deposition Modelling

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Abstract

This paper presents a study of dynamic mechanical properties of Fused Deposition Modelling (FDM) rapid prototyping processed material Acrylonitrile butadiene styrene (ABS). It involves the measurement of modulus and damping properties of the material as it is deformed under periodic stress. In this study, frequency sweep is performed in DMA 2980 equipment to determine modulus, damping and viscosity values. The effect of FDM process parameters of built style, raster width, and raster angle over these properties is investigated. Frequency sweep experiment is done with the range of 10 Hz to 100 Hz in three different isothermal temperatures. The effect of temperature over these properties is also determined. Results show that solid normal built style gives more strength when compared to double dense and sparse built styles. It is also found that the loss modulus increases with increase in temperature, but viscosity values decrease with the increase in the temperature.

Keywords- **Acrylonitrile Butadiene Styrene (ABS), Dynamic Mechanical Analysis, Fused Deposition Modelling, Rapid Prototyping.**

1. Introduction

Rapid prototyping is a new and developing manufacturing technology used to create parts by layer by layer addition of material [1]. Among the Rapid Prototyping technologies, FDM is one of the leading processes used in manufacturing industries. It is an extrusion type, solid-based process. In this process the build material is melted in an extrusion head where the temperature is controlled. The semi-liquid material in a filament form is extruded from the extrusion head and it is deposited in layer by layer fashion. Then the final product is removed and cleaned. Current FDM systems can produce parts with the materials like polycarbonate (PC), Polyphenyl-sulfone and Acrylonitrile butadiene styrene (ABS).

During the layer by layer fabrication process, the FDM material undergoes physical and thermal changes affecting their mechanical properties. Using the Dynamic Mechanical Analysis (DMA) technique, one can determine how the dynamic properties for the material changes through the FDM liquefier head and how the FDM process parameters affect such properties.

Not much work seems to have been done on dynamic mechanical behaviour of polymers after they have gone through the rapid prototyping processes such as the FDM. Moroni et al. [2] have carried out DMA on 3D fibre-deposited scaffolds and investigated the influence of pore geometry and architecture on dynamic mechanical properties. Mas et al. [3] investigated dynamic mechanical properties of polycarbonate (PC) and ABS blends and compared the results with other techniques like dielectric and calorimetric analysis. Chaudhury and Masood [4] have investigated the tensile properties of FDM processed ABS material. Masood and Umapathy [5] have investigated the effect of FDM parameters on the impact properties of FDM made ABS parts.

This paper presents the results of Dynamic Mechanical Analysis (DMA) of FDM fabricated ABS material under frequency scan and determines the properties like storage modulus, loss modulus, complex viscosity, and tan delta. DMA involves applying an oscillating force to a sample and analysing the material's response to that force. From this analysis, one can calculate properties like the tendency to flow, which is called viscosity and stiffness or modulus of the material under dynamic conditions [3]. Fabrication of test samples in ABS material is carried out with FDM Vantage machine, taking into account the variation of main FDM process parameters such as built style, raster angle and raster width. Results are discussed on the effects of these FDM parameters over these properties to determine the optimum parameters for parts used under dynamic conditions.

2. Fused Deposition Modelling

Fused deposition modelling (FDM) is a rapid prototyping process in which a 3D part is fabricated directly from CAD model by integrating the technologies like computer aided design (CAD), computer numerical control (CNC), polymer science, extrusion technology, etc [6]. The first step in this process is to generate a 3D model using CAD software. Then the part file is converted into Stereolithography (STL) file. The STL file is then converted into SLC file by slicing them into thin cross sections at a desired resolution. The sliced model is then changed into Stratasys modelling language (SML) file, which contains actual instructions code for the FDM machine tip to follow the specified tool path. Then the various parameters like raster width, built style and raster pattern are set and then the SML file is sent to the FDM machine.

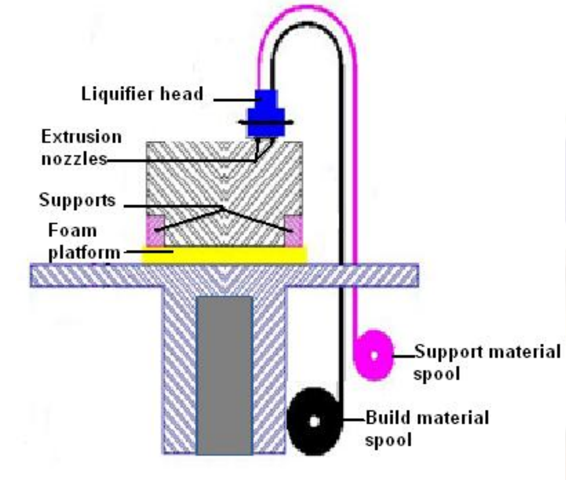

Figure 1 Schematic representation of FDM Process

Fig. 1 shows the schematic diagram of the FDM process. In the FDM machine, the liquefier head plays a major role, which is the key to the success of fused deposition modelling technology. The material in the filament form is pulled or pushed with the help of drive wheels which is attached to the electric motors and then enters into the heating chamber. The material flows through the liquefier tube and is deposited through an extrusion tip. The tip is extremely threaded and screwed up into the heating chamber exit. They reduce the diameter of the extruded filament to allow for better detailed modelling [7]. The extruded plastic bonds with the previously deposited layer and hardens immediately. The chamber, in which the entire system is held, is kept at a temperature just below the melting point of the plastic used, which aids the bonding process. Finally the part is removed from the chamber and no post processing is required in FDM.

The FDM vantage machine has number of parameters, which affect the part strength and mechanical properties. The key parameters considered in this study are built style, raster width, and raster angle [8].

2.1 Built style

It is the manner in which the beads are deposited by the FDM tip in each layer during the part building process. The three types of built style are used: solid normal, sparse-double dense and sparse. In solid normal, there is no air gap between the beads. The layer is filled completely and the part is solid with no void. It has single wall periphery. As shown in Fig. 2, each and every layer in solid normal type will be the same but with alternating raster pattern. In sparse double dense, there is certain air gap between the beads. In this case all layers are not same. As shown in Fig. 3, the first few bottom layer and the top few layers have no gap, but the tool path in middle layers is a crosshatch raster pattern rather than uni-directional in order to have additional strength than sparse. It has double wall periphery. As shown in Fig. 4, the sparse is very similar to double dense. The only difference is in the middle layers. In the middle layers, there is some air gap and the tool path is uni-directional and has less strength than double dense.

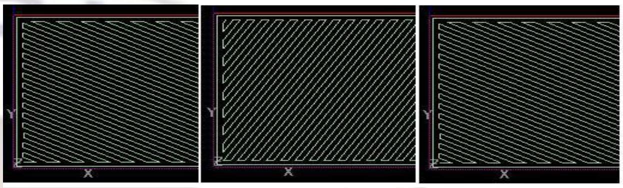

Figure 2 Solid normal built style with raster angle 30/60

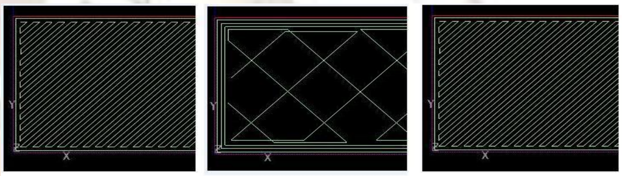

Figure 3 Sparse double dense built style with raster angle 45/45

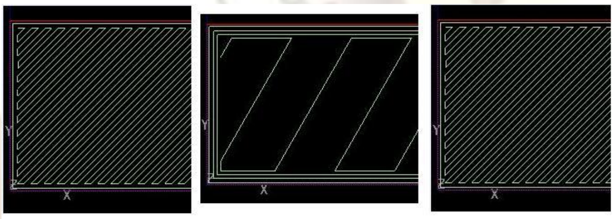

Figure 4 Sparse built style with raster angle 45/45

2.2 Raster width

Raster width is the width of the bead deposited on a layer [9]. The raster width varies according to the tip size chosen in FDM Vantage machine. It varies from 0.254 mm- 0.679 mm.

2.3 Raster angle

Raster angle is the angle of the beads deposited with respect to the x axis of the build table [9]. The typical raster angles are 45°/45°, 0°/90°, and 30°/60°.

In this study, DMA test samples in ABS were fabricated on the FDM Vantage machine using several combinations of all three FDM parameters of built style, raster width, and raster angle. Table 1 shows the combination of the parameters. As shown in the table, each parameter has three values. Built style has solid normal, sparse-double dense and sparse. Raster width is chosen according to the tip size what we choose during the fabrication process. In this case tip size T12 is chosen and the raster widths are 0.305mm, 0.454mm, and 0.679mm. Raster angles are $0/90^0$, $45^0/45^0$, and $30^0/60^0$ are chosen.

Table 1 FDM Parameters and their types

S. No	FDM parameters	Units	Types or Values		
1	Built style	-	Solid normal	Sparse-double dense	Sparse
2	Raster width	mm	0.305	0.454	0.679
3	Raster angle	degrees	$0/90^0$	$45^0/45^0$	$30^0/60^0$

With these nine parameter values, twenty seven sets of ABS samples with all possible combinations of parameters were fabricated. Each set requires one sample. The ABS was the standard FDM material supplied by Stratasys Inc.

3.Dynamic Mechanical Analysis (DMA)

In dynamic mechanical analysis, periodically varying stress, usually sinusoidal of angular frequency is applied to the sample [9]. From the response of the sample to this treatment, information like stiffness of the material, which is quantified by elastic moduli and the ability of the sample to dissipate energy, which is given by damping, can be obtained. The strain obtained from the periodic stress will also be periodic, but it will be out of phase with the applied stress because of the dissipated energy in the form of heat or damping. In dynamic mechanical test, we measure the material stiffness. The sample stiffness depends on the modulus of the material. The modulus is defined as the stress per unit area divided by the strain resulting from the applied force. Young's modulus is the slope of the initial portion of the stress-strain curve. Therefore modulus is the measure of material's resistance to deformation. The higher the modulus, the more rigid the material is [10]. 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 called loss tangent or damping factor.

One of the main advantages of DMA is that, for every sine wave generated, we can get the modulus value, which allows us to sweep across temperature or frequency range. If an experiment is run at 1 Hz, one can get the modulus value for every second. It can be done by varying the temperature at the rate of 10^0C/min, so that the temperature change per cycle is not significant. The experiment can be run over 200^0 C temperature range in 20 minutes. This is called temperature sweep. Similarly, scanning over a wide range of frequency of 0.01 to 100 Hz at a constant temperature in less than 2 hours, will give a frequency sweep. In this paper we use doing frequency scan at isothermal temperature.

Viscoelastic materials exhibit some sort of flow behaviour or unrecoverable deformation [9]. With the help of frequency scan, one can collect the information of viscosity and flow behaviour of the sample at desired temperature.

In this study, the instrument used is DMA2980 manufactured by TA instruments, which is the standard equipment used for dynamic mechanical analysis. There is a clamping system which is provided to hold the sample. Dual cantilever clamp was used in this study.

The major components of a DMA include drive motor. The periodic stress to the sample is supplied by this motor through the drive shaft. The amplitude and frequency of the response of the sample is measured by the displacement sensor. Clamps used in DMA 2980 should have high stiffness, low mass and should be easy to load and adjust the samples.

The sample geometry is chosen according to the clamp chosen in the DMA equipment. Since dual cantilever clamp is used in this study, the dimension of the sample is similar to the dimensions chosen for flexural testing (61.44 mm long, 12.7 mm wide and 3.20 mm thick). This dimension is used for fabricating the ABS samples.

For doing the frequency scan, the selected frequency range was 10 Hz to 100 Hz. Within this range, we obtained the response of the sample. The frequency scan experiment is done with three different isothermal temperatures. For each sample the frequency scan is done for three different temperatures. These temperatures are based on the melting point of the materials in order to avoid melting of the sample. For ABS samples we choose temperatures like 40, 60 and 90 degree Celsius. The equipment uses software called Thermal Advantage. This software is integrated with a computer, which is connected to the DMA2980. The software gives the values of the properties directly after completion of the test. The frequency scan graph is also generated automatically in the software.

4. Results and Discussion

After each experiment a frequency scan graph is generated with storage modulus (MPa) on left Y axis and complex viscosity (MPa.sec) on right Y axis against the frequency (Hz) on X axis. For each sample with different parameters (by keeping built style constant and varying raster width and raster angle) a frequency scan graph is obtained. All the graphs of the samples with particular built style and at particular temperature are overlaid. Fig. 5 shows such an overlaid graph of samples with solid normal built style and at temperature 90^0C.

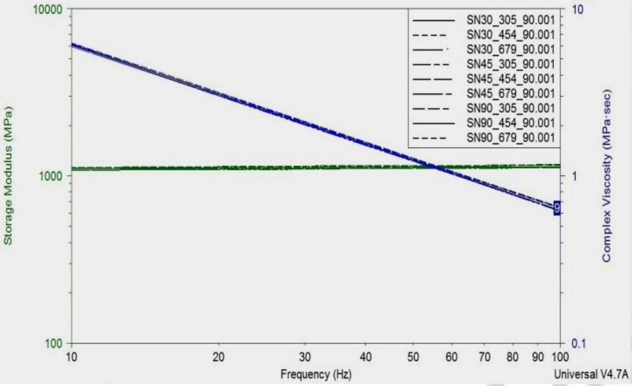

Figure 5 Frequency scan graph of Solid normal ABS samples at 40^0 C.

Similarly for each built style (solid normal, sparse-double dense, and sparse) and at three different temperatures (40^0C, 60^0C, 90^0C), the overlaid graphs are obtained. Apart from these results, the property values of tan δ and loss modulus can also be obtained with the help of the software.

Fig. 5 shows that for the graphs of solid normal samples at 40^0C, the FDM parameter with built style solid normal, raster angle 30^0 and raster width 0.305 mm gives the maximum values for both modulus and viscosity (1335 MPa and 7.208 MPa.sec). At the temperature 60^0 C, the graphs for solid normal samples show that the FDM parameter with built style solid normal, raster angle 90^0 and raster width 0.679 mm give the maximum values for both modulus and viscosity (1238 MPa and 6.691 MPa.sec). The graphs of solid normal samples at 90^0 C shows that the FDM parameter with built style solid normal, raster angle 90^0 and raster width 0.679 mm give the maximum values for both modulus and viscosity (1172 MPa and 6.237 MPa.sec).

In case of sparse double dense samples, at 40^0 C, the FDM parameter with raster angle 30^0 and raster width 0.454 mm gives the maximum values for both modulus and viscosity (948.2 MPa and 5.144 MPa.sec). At the temperature 60^0C, the FDM parameter with raster angle 45^0 and raster width 0.679 mm gives the maximum values for both modulus and viscosity (906.2 MPa and 4.847 MPa.sec). At 90^0 C the FDM parameter with raster angle 30^0 and raster width 0.305 mm gives the maximum values for both modulus and viscosity (857.4 MPa and 4.531 MPa.sec).

In case of sparse samples, it gives lower values when compared to other built style due to its porous nature. At a temperature 40^0C, the FDM parameters with raster angle 30^0 and raster width 0.454 mm give the maximum values for both the modulus and viscosity (754.2 MPa and 4.055 MPa.sec). At the temperature 60^0C the FDM parameters with raster angle 30^0 and raster width 0.454 mm give the maximum values for both modulus and viscosity (684.7 MPa and 3.674 MPa.sec). At a temperature 90^0C, the FDM parameters with raster angle 30^0 and raster width 0.679 mm give the maximum values for both the modulus and viscosity (627.9 MPa and 3.313 MPa.sec).

All in all, for ABS material, from these above results, we conclude that built style solid normal is stronger than sparse double dense and sparse, and raster angle $30^0/60^0$ gives higher values in all three built styles, so its stronger than other angles, and raster width 0.454 mm gives maximum values in all the three built style, so it's better than other raster width.

As mentioned earlier, other than frequency scan, some property values like loss modulus, and tan delta have been obtained in the experimental run. These maximum values are taken from the graphs which are similar to Fig. 5. These maximum values of the properties are plotted against the built style parameter at different temperatures.

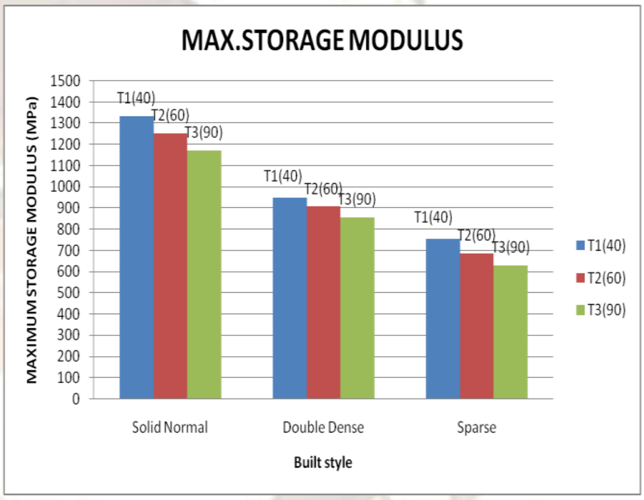

Figure 6 Maximum storage modulus vs built style

Fig. 6 represents the graph drawn with maximum storage modulus on X axis and built style on Y axis. From this figure, it is clearly seen that the storage modulus decreases with the increase in the temperature. The decrease in the storage modulus with the increase in the temperature is due to the relaxation in the polymer chains. Such relaxations along with the large Tan δ peaks (shown in subsequent paragraphs) mean that a molecular energy dispersion mechanism operates. Such mechanisms are responsible for toughness in the materials (ABS) [11]. So this result shows that FDM made ABS samples are tough materials. As already discussed, the solid normal built style has more strength when compared to others, which is evident in the Fig. 6.

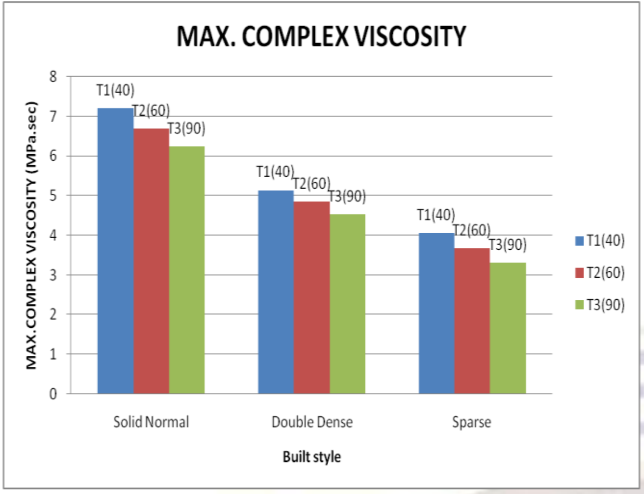

Figure 7 Maximum complex viscosity Vs Built style.

Fig. 7 represents the graphs with maximum complex viscosity values on X axis and FDM parameter built style on Y axis. Liquids and oils are classified as Newtonian, where as polymers, slurries are not. So we are dealing with the Non-Newtonian materials which can deviate from ideal behaviour [9]. In such a case, the complex viscosity decreases with the increase in the temperature due to relaxation in polymer chains, and also solid normal built style has more values when compared to other built styles.

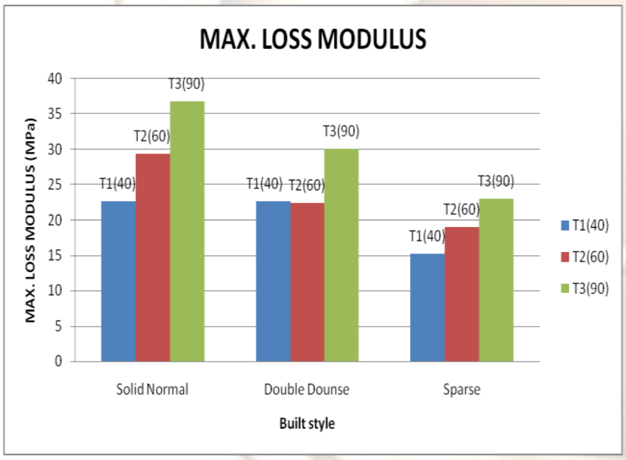

Figure 8 Maximum loss modulus Vs Built style

The graph between maximum loss modulus and built style is shown in the Fig. 8. Loss modulus is the ability to lose energy, which is reverse of storage modulus. So what we saw in storage modulus was decrease in modulus when temperature increases, but in loss modulus, the value increases with the increase in temperature. Loss modulus is inversely proportional to storage modulus, which is the ability to store energy. Again solid normal built style gives high value, which proves that, it is better than the other built style. Double dense style lies between solid normal and sparse, due to its average values. As already discussed, the middle layers of double dense style has cross hatch pattern and are stronger, when compared to sparse style, which has uni directional pattern in the middle layers.

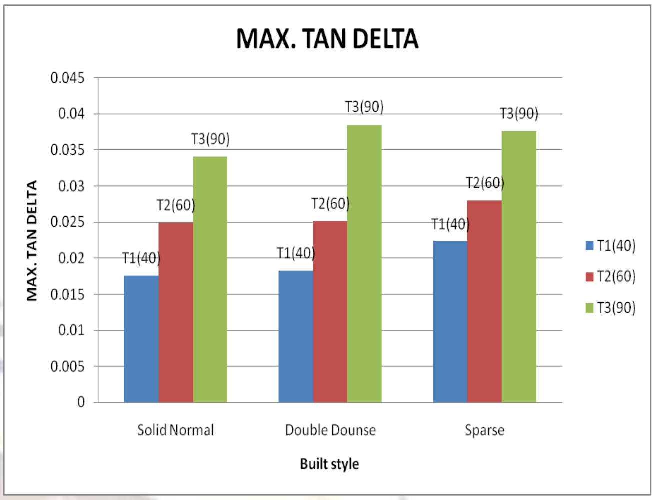

Figure 9 Maximum Tan δ Vs Built style

Fig. 9 shows the graph between maximum tan δ and built style. From this figure, it is noted that the peaks of tan δ go higher with increase in temperatures. As we already discussed in the previous section, tan δ peaks indicates that molecular energy dispersion mechanism operates, which means material is tougher. Tan δ is the ratio of loss modulus to the storage modulus. So the ratio is increasing with the increase in temperature as in loss modulus, because tan δ is directly proportional to loss modulus.

5. Conclusions

This research has focussed on the frequency scan of the FDM made ABS material in order to find out both modulus and viscosity values and the effect of FDM parameters over these properties. The results of the dynamic mechanical properties of FDM made ABS material, it is clear that solid normal built style has more strength than double dense and sparse built style, due to the fact that it is more solid with fewer pores when compared to other built styles. In ABS material, the best raster angle and raster width is the same for all the three built styles. These values, the raster angle $30^0/60^0$ and raster width 0.454 mm give the maximum values, so these parameters are considered good for ABS material. These experiments were done in the frequency range of 10 to 100 Hz, at constant isothermal temperature. Results have shown that, when we consider the temperatures, the loss modulus values increase with increase in temperature, but storage modulus is decreasing with the increase in the temperature and also the viscosity values decrease with the increase in the temperature.

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