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Research Article

Systematic Approach to Optimize Injection Molding and Microstructural Analysis of Fiber Reinforced Resins for Anisotropic Mechanical Characterization

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Abstract

Fiber reinforced resin materials are increasingly being used in aviation, automotive, mass transportation and healthcare industries. Engineers are keen to explore new design concepts with such materials, since these materials promises to offer high strength to weight ratio, elimination of secondary operations and ease in process ability to form complex shaped parts through injection molding. The mechanical properties of molded parts made from such materials depends on the orientation of the reinforcing fibers. Such orientation occurs in fiber-reinforced plastics, since the fibers in the plastic melt during processing, will orient in different directions under the influence of shear forces that are driven by flow pattern. This paper provides details on systematic and abusive injection molding of test specimens and characterizing anisotropic mechanical data that can be used for fiber orientation predictions in computer aided engineering programs. Systematic molding as compared to abusive molding, identifies optimum molding parameters that reduces part–to-part variation during injection molding, thereby reduces part rejections. It provides optimum part performance during application and the process settings are repeatable and reproducible. The intention of this paper is to share widely such a method to make this process less of a skill or art. The mechanical properties covered here are elastic, shear modulus and poisson ratio. Scanning electron microscopy (SEM) analysis revealed that most of the fibers are aligned in melt flow direction for systematic molded plaques, leading to higher stiffness and strength characteristics as compared to transverse to melt flow.

Keywords: Injection Molding; Microscope; Tensile; Modulus; Poisson Ratio; Molding Optimization

Introduction

Injection molded plastics are being evaluated for a wide variety of applications. The primary benefits are reduction in weight with adequate strength, elimination of secondary operations and ease in process ability to form complex shaped parts through injection molding. This value proposition of high strength to weight ratio, is of interest for design engineers to explore new design concepts. The addition of reinforcing fibers, such as glass fibers, increases the elastic modulus and strength of the resultant composite with a negligible effect on part weight.

The combination of high strength and low weight makes fiber reinforced plastics a material of interest for design engineers. The mechanical properties of such reinforced plastics are dependent on the orientation of reinforced filler [1,2]. Studied tensile properties of short glass fiber reinforced polyamide 6 with specimens machined in melt flow direction (i.e. parallel or 0^0) and transverse to the melt flow direction (i.e. perpendicular or 90^0) and tested at different strain rates and temperatures. Tensile strength and elastic modulus in the melt flow direction were a factor of two higher than transverse direction (i.e. perpendicular to the melt flow) due to anisotropic behavior of fiber orientation in the molded specimen [3]. Studied the effect of tensile behavior of short glass fiber polyamide-66 using different thickness specimens at various orientations (i.e. 0°, 10°, 30°, 45°, 60° and 90°). Tensile strength and elastic modulus decreased as the orientations increased. Such properties were measured using test specimens cut from large injection molded plaque at different orientations [4,5]. Indicated that the full potential of such materials are realized based on the orientation of the reinforcing fibers. The orientation direction and the degree of orientation of the fibers determine the mechanical properties of the molded part. In areas where fibers are aligned in the direction of the flow of the plastic melt, the material will have higher strength characteristics in that direction, but will be relatively weak in the perpendicular direction. In areas where the fibers are more randomly oriented, the material will not achieve maximum strength, creating a more isotropic like material. Such phenomenon occurs in fiber-reinforced plastics, since the fibers in the plastic melt during processing orient in different directions under the influence of shear forces that are driven by the flow pattern. Therefore, there are two points of interest to design engineers for them to predict anisotropic properties of final parts. First, the parts are injection molded in a manner that the fibers are oriented in the plastic melt flow direction [6]. Secondly, the mechanical properties for different directions (e.g. melt flow direction, transverse to the melt flow direction, etc.) are available.

Mechanical properties of such fiber-reinforced materials depend on parameters of injection molding conditions. If the processing parameters are not optimized, it will lead to a part where the maximum strength is not realized. The purpose of this paper is therefore to provide guidelines for optimizing the injection molding parameters (i.e. systematic molding), to avoid trial and error approach (i.e. abusive molding) in optimizing material utilization and time, yielding good part quality. Systematic molding as compared to abusive molding, identifies optimum molding parameters that reduces part–to-part variation during injection molding, thereby reduces part rejections. It provides optimum part performance during application and the process settings are repeatable and reproducible. The intention of this paper to share widely such a method to make such a process less of a skill or art. The molding parameters considered here are fill time, peak injection pressure, holding pressure and time, melt temperature and mold temperature. The orientations of reinforcing fiber were confirmed with SEM. The images were taken at 1.75mm from the surface to ensure these are taken at the bulk of the specimen and the surface artifacts (i.e. skin layer) were avoided. The mechanical properties of such materials were characterized and compared to the properties arrived at from abusive molding conditions. Such mechanical data can be used for fiber orientation predictions in computer aided engineering (CAE) programs.

Experimental

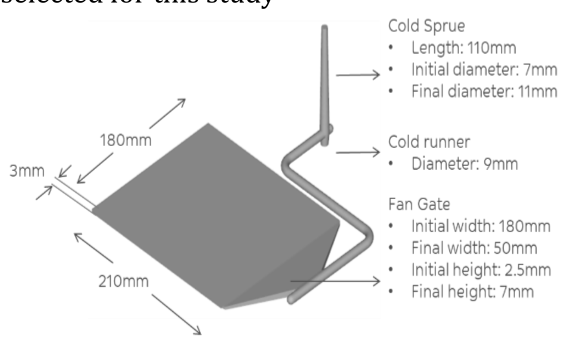
Material

A glass fiber filled engineering thermoplastic (blend of polyphenylene oxide) was selected for this study. It is an engineering thermoplastic, which is processed in injection molding.

Mold geometry

Computer aided engineering (CAE) study of injection molding flow analysis was run to determine the plaque dimensions. A 2D model was initially created and this was imported for injection molding analysis [7]. Subsequently a 3D model was created. The optimum feed system such as sprue, runner, gate, were designed, considering uniform melt filling through plaque, with no flow restriction, weld line or air entrapment, as shown in the (Figure 1).

Figure (1): Model of plaque and feed system selected for this study



Injection molding machine

Selection of appropriate injection molding machine is a critical aspect of injection molding process, since it affects the material residence time inside the barrel, leading to poor mechanicals [8]. Based on the mold dimensions indicated earlier, a 200T injection molding machine manufactured by L&T was selected for this study, details provided in (Table 1).

Table (1): Injection molding machine details

Parameters	Value	Unit
Screw diameter	45	mm
Maximum Injection pressure	250	MPa
L/D ratio	25	
Compression ratio	2.4	
Nozzle diameter	5.5	mm

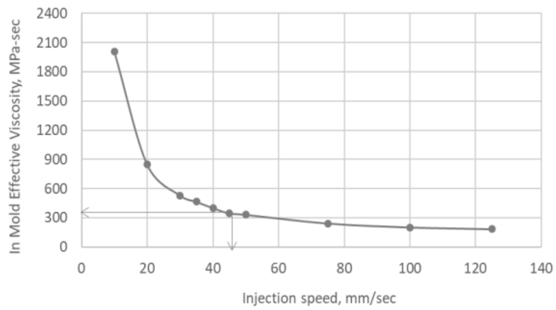
Systematic approach to optimize molding process parameters

In this section, we describe a systematic methodology to optimize the molding parameters, to avoid trial and error approach in optimizing material utilization and time, yielding good part quality. The molding parameters considered here are fill time, peak injection pressure, holding pressure and time, melt temperature and mold temperature [7].

Fill time and peak injection pressure optimization

During mold cavity filling in Injection Molding process, materials are subjected to large amount of shear rates. Such shear rates are inversely proportional to the fill time used in the process. If the shear rates are in the non-Newtonian region of the curve [5], then small variations in the shear rate will cause a large change in viscosity. This will lead to shot-to-shot variation and affect the mechanical properties. A melt viscosity curve was generated during melt processing [9]. Initially, melt and mold temperature were set, as per material datasheet recommendation, with zero holding phase. Hereafter, switch over point was selected wherein, 95-98% of the cavity was filled in the filling phase and the remaining 5-2% of the cavity was compensated during holding phase. In-mold effective viscosity (i.e. product of fill time and peak injection pressure) was plotted against injection speed, as shown in (Figure 2).

Figure (2): In-mold effective viscosity curve for the material under consideration



The inflection point where viscosity of the material stabilizes, the corresponding injection speed and pressure, were considered as optimized conditions for the process, as indicated in (Table 2).

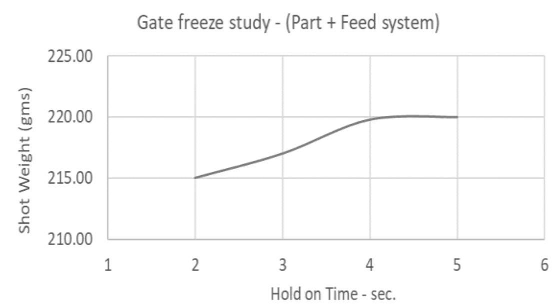
Table (2): In mold effective rheology evaluated for the material under consideration

Screw speed mm/sec (A)	Fill time sec (B)	Shear Rate 1/sec (1/B)	Peak Pressure MPa (C)	In-mold effective viscosity MPa-sec (B*C)
10	11.08	0.09	181.19	2007.61
20	5.65	0.18	149.95	847.23
30	3.69	0.27	143.70	530.27
35	3.27	0.31	142.14	464.80
40	2.85	0.35	140.58	400.65
45	2.46	0.41	140.58	345.83
50	2.31	0.43	143.70	331.96
75	1.54	0.65	157.76	242.95
100	1.20	0.83	168.70	202.44
125	1.02	0.98	181.19	184.82

Holding time and Holding pressure optimization

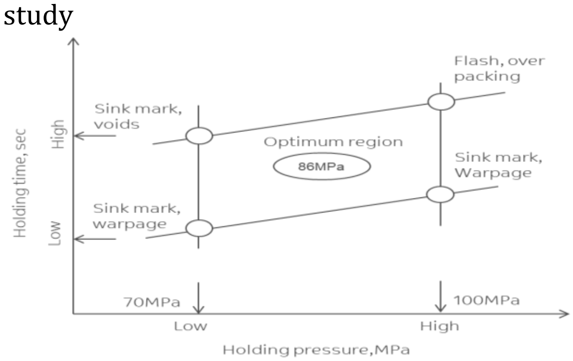
Once the required amount of plastic was injected into the cavity, it must be contained in the mold until the gate freezes off. Holding time was optimized through gate-seal study, where the part weight was plotted against time. Once the gate freeze off occurred, part weight was monitored until, it stabilized. The time required until the part weight stabilized is referred to as gate-seal time [9]. Gate seal study was conducted by setting holding pressure to 70% of optimized peak injection pressure. Molding was continued thereafter by increasing the holding time starting from 1 second. Samples were collected for each holding time and shot weight was recorded. (Figure 3), indicates that at 4 sec holding time, part weight stabilized for this material.

Figure (3): Holding time optimization for the material under consideration



In order to ensure optimum holding pressure, molding was carried out with three different holding pressure and time, as shown in (Figure 4).

Figure (4): Holding pressure vs. holding time study



The region of the graph where no sink mark, warpage, flash, over packing or voids were observed, was considered as optimum holding pressure for the material under consideration. The holding pressure recorded was 86MPa for the material under consideration.

Melt temperature measurement

Melt temperature is often used to indicate temperature of molten resin in an injection molding process. Usually the injection barrel temperature profile is set in such a manner that the resin in the last zone of the barrel is maintained at required melt temperature. In practical cases, it is however observed that the temperature of the melt is higher than what is kept in the last zone of the barrel, due to shear forces, the melt experiences while it flows out of nozzle tip. Difference in set barrel temperature and measured melt temperature is an indication of robustness and preciseness of process settings used in plasticizing phase, which will in turn have an effect on the molded part performance [10]. 30/30 method [11] was used to measure melt temperature. The temperature of probe was raised to approximately 300^{0}C above the anticipated melt temperature and was kept in contact with the hot melt puddle for 30 seconds. The temperature probe was continuously moved inside the melt puddle, for it to quickly reach a state of equilibrium. The lowest temperature recorded in this time was the temperature of the melt.

Mold surface temperature measurement

Mold temperature can have an influence on appearance, strength and dimensional accuracy of molded part and therefore it needs to be measured during injection molding process. It is of interest to measure the actual surface temperature as against the mold temperature set through the control unit. A pyrometer with probe was used to measure the mold surface temperature while 10-15 molding shots were taken. Three successful measurements were taken across various section of the mold cavity. The mold surface temperature measured and recorded was 105°C for the material under consideration.

Molding conditions considered for the study

As elaborated earlier, systematic methodology was adopted to arrive at optimized molding parameters. Abusive molding, which indicates random selection of molding parameters was also adopted for such a study. The details of such molding conditions are summarized in (Table 3).

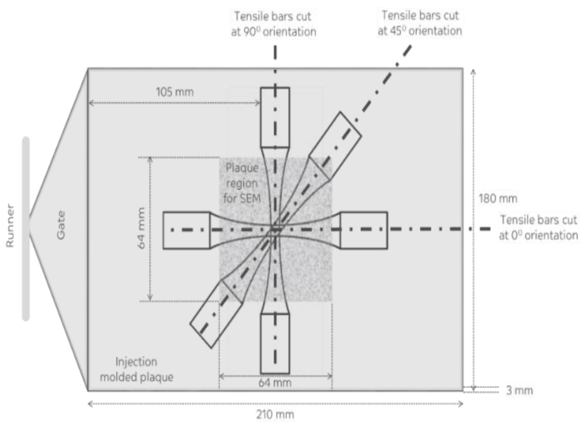
Table (3): Optimized-molding profile used for the study.

Molding parameters	Unit	Optimized molding conditions	Abusive molding conditions
Melt temperature	°C	295	290
Mold temperature	°C	105	90
Peak Injection pressure	MPa	141	149
Holding pressure	MPa	86	47
Switch over position	mm	20	20
Injection speed	mm/sec	40	70
Fill time	sec	2.88	1.88
Hold time	sec	4	3
Cooling time	sec	35	30
Screw speed	rpm	75	120
Back pressure	MPa	0.6	0.8

Scanning Electron Microscopy

From each plaque, glass fiber orientation was measured on tensile specimen prepared as shown in (Figure 5).

Figure (5): Schematic view of the plaque and region selected for SEM imaging



Each tensile bar has a gauge length of 64mm. Hence, for SEM imaging, specimens was prepared from a 64 x 64-mm^2 area at the center of the plaque. Samples for SEM were was first cut to size using a handsaw and then sectioned at the middle using a diamond wheel cutter and exposed surface was gold coated to a thickness of 3nm. During sample preparation, appropriate marking was done to identify the GATE location. SEM imaging was done in back scattered mode using a ZEISS make EVO-18 instrument. The images were taken at the center of the plaques, at 1.75mm from the surface to ensure these are taken at the bulk of the specimen and the surface artifacts (i.e. skin layer) were avoided [12]. Each acquired image had an area of 6 mm x 4.5 mm. Hence, from the entire 64 x 64-mm^2 area, images were collected in a matrix of 12 x 16 in separate four batches. Images were filtered using 'ImageJ' and collaged. Fiber length was measured using 'ImageJ' and histogram of the fiber length was plotted using 'Minitab'.

Tensile Testing

Uniaxial tensile tests were run on a universal testing machine manufactured by Zwick, having capability to measure both flow and cross flow strains, in accordance with ISO 527-1B standard. Dumb-bell shaped test specimens were machined from injection-molded plaques, with gauge length of 50 mm. A crosshead speed of 5 mm/min was used throughout the test. Average value of five specimens was reported for each orientation. Elastic modulus, Poisson ratio and shear modulus were computed as discussed below. Elastic Modulus is ratio of stress to strain applied on the test samples, as shown in (equation 1).

$$\text{Elastic Modulus} = \frac{\text{Stress}}{\text{Strain}} \qquad \text{Equation (1)}$$

Poisson ratio is the ratio of lateral strain to linear strain. This was determined using a video extensometer (non-contact type) for measuring change in width of the specimen and a clip on extensometer to measure to change in length of the specimen in the gauge length region, as shown in (equation 2).

$$\text{Poisson ratio} = \frac{\text{Lateral strain}}{\text{Axial strain}} \qquad \text{Equation (2)}$$

Shear Modulus was calculated as shown in (equation 3).

$$G_{xy} = \frac{1}{\left(\frac{4}{E_{45}}\right) - \left(\frac{1-2n_{xy}}{E_0}\right) - \left(\frac{1}{E_{90}}\right)}. \qquad \text{Equation (3)}$$

Where,

G_{xy} is shear modulus in X-Y direction

n_{xy} is Poissions ratio in X-Y direction

E_0 is Elastic Modulus in 0^0 orientation (flow direction)

E_{45} is Elastic Modulus in 45^0 orientation

E_{90} is Elastic Modulus in 90^0 orientation (cross flow direction).

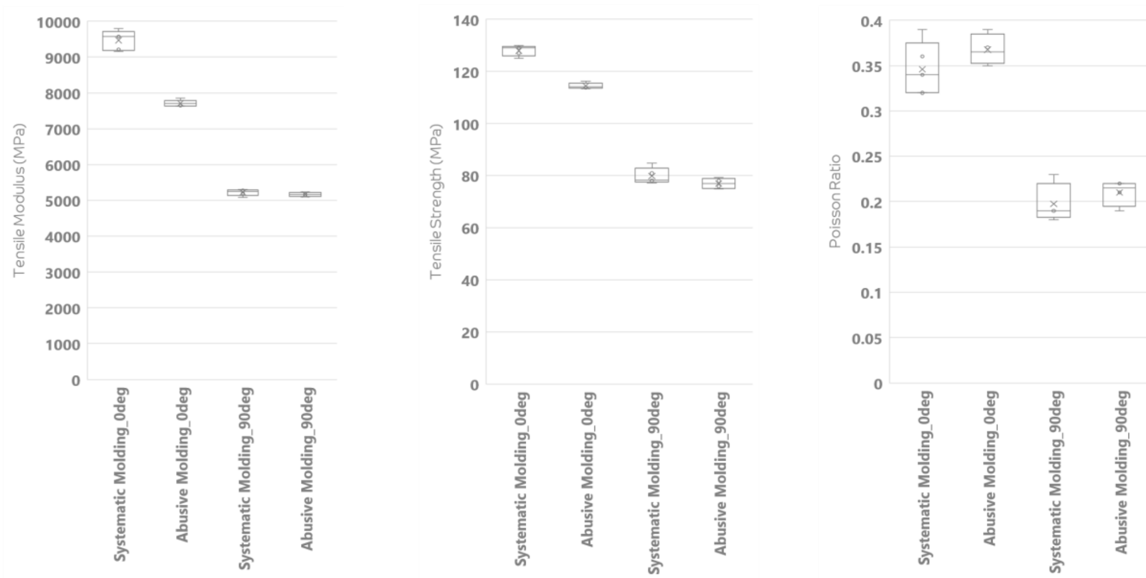
Result and Discussions

Mechanical Property evaluation

Tensile bars were cut from the center location of the plaques using milling machine. These tensile specimens were then tested for modulus, strength and poisson ratio, using universal testing machine. (Figure 6) indicates the tensile measurements of the materials cut out from molded plaques, both from systematic and abusive molding, across two orientations, namely melt flow direction (i.e. parallel or 0^0) and transverse direction to the melt flow (i.e. perpendicular or 90^0). Such a process can be used to cut test specimens for 45^0 orientation for estimation of shear modulus, as per equation 3. Based on the elastic modulus available across 0^0, 45^0 and 90^0 orientation, the shear modulus can be computed and it was estimated to be 2101 MPa, if the material was systematically molded.

The anisotropy in the mechanicals was evident as observed in the difference in mechanical properties in melt and transverse to melt direction. The mechanical properties were found to be higher in the melt direction. Additionally, systematic molding indicates higher anisotropy than abusive molding, which is explained, through glass fiber orientation study, using scanning electron microscope.

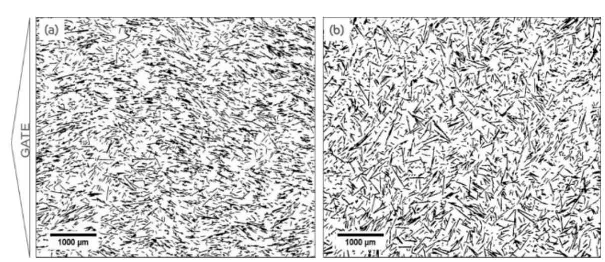
Figure (6): Tensile Modulus, Tensile strength and Poisson ratio measurements



Glass Fiber orientation evaluation

(Figure 7) shows filtered SEM images of systematic and abusive injection molded plaques. Gate of the injection mold is on the left hand side of the images. A representative cross-sectional filtered SEM image is included here for discussion.

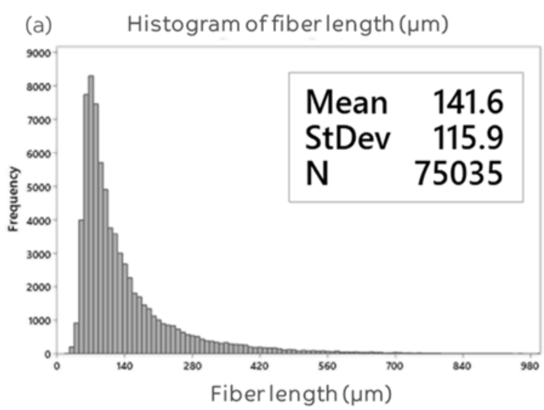
Figure (7): SEM image (Filtered) showing fiber orientation in (a) systematic molded and (b) abusive molded plaques.



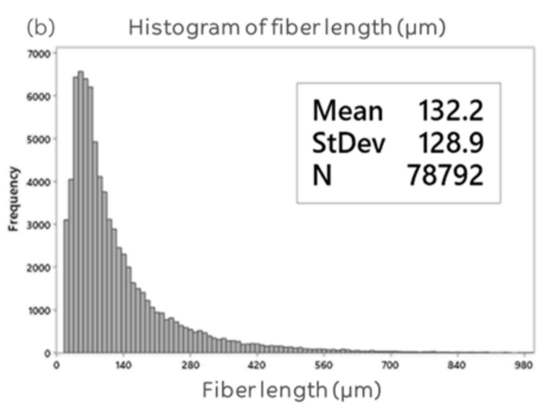
As seen from the images, plaques made using systematic molding technique show good amount of fiber orientation in melt flow direction, which is from left to right of the images. However, in plaque, which has been molded, using abusive conditions, we observe random fiber orientation. However, dispersion of fiber seems to be good in both the cases. Average fiber length as shown in (Figure 8), in systematic molded plaque is around 142 µm (standard deviation 116 µm), and that in abusive molded plaque is 132 µm (standard deviation 116 µm).

Figure (8): Histogram of fiber length measured from SEM images of

(a) systematic molded



(b) abusive molded plaques.



Conclusions

Measurement of anisotropic mechanical properties of fiber-reinforced materials is vital for prediction engineering. Mechanical properties of such materials depend on parameters of injection molding conditions. If the processing parameters are not optimized, it will lead to a part where the maximum strength is not realized. The present work provide guidelines for optimizing the injection molding parameters (i.e. systematic molding), to avoid trial and error approach (i.e. abusive molding) in optimizing material utilization and time, yielding good part quality. In-mold effective viscosity studies indicated that the inflection point where the viscosity of the material stabilizes, the corresponding injection speed and pressure should be considered as the optimized conditions for the process. Holding time was optimized through gate seal studies until the part weight stabilized over time. 30/30 method was used to measure melt temperature, while pyrometer with a probe was used to measure the mold temperature.

The present work was able to compute the elastic, shear modulus and Poisson ratio of the material. Samples made from systematic molded plaques, showed higher tensile strength in melt flow direction, as compared to the ones made using abusive molding conditions. SEM analysis of the molded plaques revealed, that most of the fibers were aligned in melt flow direction for systematic molded plaques, whereas for abusive molding the fibers were randomly oriented. Such mechanical data can be used for fiber orientation predictions in CAE programs.

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