Study on Effects of Process Parameters on Mechanical Behaviors of Injection Molded Glass Fiber Reinforced Polypropylene Matrix Composite

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Abstract. Currently, there is an expanding demand of composite materials for various engineering applications. Glass fiber reinforced polymer composites, prepared by injection molding, is among these composites. Injection molding method has basic process parameters which determine the mechanical behaviors of polymer matrix composites (PMCs). However, only few studies have been reported on the effects of injection molding process parameters for a typical short glass fiber reinforced polypropylene composites. In this study, process parameters such as melting temperature, mold temperature, packing pressure and flow rate were used for fabrication of the specimens. The modeled specimens, loaded by a compression force, were simulated and analyzed using moldflow (R2018) and ansys (R19.2) software. The specimens were also subjected to experimental studies of compression testing to study the effects of process parameters on mechanical properties of the composites. As a result, it is found that fiber orientation, deflection and mechanical properties of the composites are significantly affected by the injection molding process parameters. So, in pursuit of increasing the mechanical properties of the composite, set of injection molding process parameters of 80°C mold temperature, 240 °C melt temperature, 60 cm^3/s flow rate and 40 MPa packing pressure are required. From the numerical and experimental studies, variations of melt temperatures significantly influence the mechanical properties of the short glass fiber reinforced polypropylene composite parts molded by injection molding.

Keywords: Polypropylene · Glass fibers · Mechanical properties · Process parameters · Injection molding

1 Introduction

Polymeric composite materials have extensive applications in many engineering areas due to their advantages of light weight, high specific strength and stiffness, good heat and

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sound insulation, excellent energy absorption, and good damping capacity [1]. Some of the application areas of polymer composites are aeronautic, automotive, naval, construction, sporting goods, home appliances, furniture, packaging and electronic devices [2]. Polymer composite processing methods are injection molding, hot press compression molding, vacuum assisted resin infusion, resin transfer molding, and so on. Among these methods, injection molding is widely used for the development of thermoplastic-based composite products [3, 4]. A composite of polypropylene with short glass fiber is one of the feedstock into injection molding process [5, 6]. Injection molding has fundamental process parameters that influence the mechanical properties of polymeric composite products. Injection molding process parameters also determine warpage of the polymeric composite parts in which warpage is an effect occurred during cooling. Process parameters also affect the level of residual stresses which also causes part warpage [5, 7]. Selection of gate location is also an important factor in ensuring uniform and complete mold filling with appropriate flow paths rapid as possible [6]. Uncontrolled deviations from the proper process parameters could significantly affect both morphology distributions and final material properties which in turn lead to the premature failure of a product/part [8]. The fiber orientation and fiber length, affected by process parameters, importantly determines the mechanical properties of composites [9–12]. Melting temperature, mold temperature, flow rate and packing pressure are process parameters for this study due to their high impact on part properties.

There is a kinetics creation and destruction of entanglements of the polymer molecules during the injection molding process which leads to a very complex shear thinning (non-Newtonian) fluid flow behavior a composite. This complex fluid flow behavior will influence the fiber orientation in the composite. Hence, the shear flow of the melt affects fiber orientation through aligning some of the fibers with the flow direction, and some other fibers with a typical skin-shell-core orientation distribution. Melt temperature changes viscosity of the matrix in the composite. At higher melt temperature, viscosity of the melt reduces and increases its flow velocity into the mold. This results the melt to enter to the mold and settle in an ordered manner of molecular orientations which provides reduced residual stresses but increased the yielding stresses. Consequently, the failure strain decreases. The residual stresses increase the failure strain of the composite part [8, 13, 14]. However, higher melt temperature results high molecular weight of melt in the molded part which maximizes energy consumption in molding and longer cycle time [15]. When a melt of the composite at high melt temperature enters to the mold at lower mold temperature, a frozen layer is formed between the surface of the mold and inner melt. The fibers in this frozen layer can’t be oriented and are spread most randomly. The inner melt which is close to this frozen layer also experiences a large shear stress. This effect diminishes for the flow further away of this frozen layer and consequently the alignment is diminished. With increasing mold temperature, orientation of fibers can be higher but it shouldn’t be too high for good quality of parts. If it is too high, weld-lines will occur and parts will stick to the mold and difficult to remove it [16]. Mold temperature has also an influence on the viscosity when in packing stage. In this case when the mold temperature is reasonably high, the flow of heat from the melt to the mold decreases and this leads to maintain viscosity of the melt to some extent [17]. Basically mold temperature is ranging from 10 °C to 95 °C as a standard

[5]. The other important process parameter is injection speed (flow rate). The injection time of an injection molding process is very short it which mostly less than one second. A too low injection speed (flow rate) can result in flow marks; whereas, a too high flow rate results less fiber orientation and incomplete mold filling, and can cause air to be trapped in parts which can lead to burn marks [18]. On the other hand, packing pressure tends to rotate fibers and the level of alignment of fibers tends to decrease. The viscosity of the melt determines the rate of this effect [17].

The injection molding process consists of two stages. In the first stage, the velocity is controlled and most of the cavity is filled. The pressure during this stage is variable and depends on the viscosity of the material. In the second stage, the velocity control is switched to pressure control and the pressure is lower as in the first stage. It is important to set the switching point correctly which shouldn't be too early or too late. Too early switching can lead to incomplete filling while switching too late can cause the part to flash and damage of mold and tools. The switch over from velocity controlled to pressure controlled is usually when the mold is 95% filled [13, 19].

To the understanding of this author, there are few studies conducted on investigation of effects of process parameters on injection molded glass fiber reinforced polypropylene (PP) matrix composites. But, similar studies haven't been studied on profile parts of the short glass fiber reinforced polypropylene (Sabic PP Compound G3220) matrix composites. Since Sabic PP Compound G3220 is designed for under-the-hood and structural applications [20], the influence of processing parameters should be studied for better performance of parts. Therefore, this study was conducted to investigate the effects of process parameters on mechanical performances of injection molded profile parts of short glass fiber reinforced Sabic PP Compound G3220 matrix composite.

2 Materials and Methods

2.1 Materials

The polypropylene (Sabic PP Compound G3220A) matrix and short E-glass fiber (1 mm length) were used for fabrication of the specimens. The density of the PP is 1.04 g/cm^3 and 210–270 °C process melt temperature. The shrinkage value of the PP is around 1% but this can slightly be changed with different sets of injection molding process parameters. The young's modulus of the PP is also 4.9 GPa [21, 22]. The glass fibers (GFs) have high strength (1,500 MPa), high young's modulus (72 GPa) and have a good thermal stability. In this study, 20% short glass fibers (SGFs) were used for fabrication of the composite specimens. This amount was used for the case of fast processing and providing good performer profiles [20].

2.2 Method

Injection molding process was used for fabrication of the specimens. The 80% PP matrix material and 20% short glass fiber were used for the composites development. Various sets of injection molding process parameters were applied for preparation of the composite. Hence, variable melt temperature and mold temperature, and constant injection speed (flow rate) and packing pressure were used for fabrication of the specimens. The switch over point was set at 95% filling of the volume.

2.2.1 Fabrication of Specimens

The specimens were fabricated with three profiles having different corners at the mid-point. The volume fractions used were 20% SGFs and 80% PP matrix. Silicon-free mold release agent (C-150) was used for demolding the specimens from mold cavity. Injection molding with various sets of process parameters was used for fabrication of the specimens. Accordingly, nine specimens of three profiles each were fabricated with various sets of process parameters shown on Table 1.

Table 1. The sets of process parameters of injection molding.

Set of process parameters	Process parameters			
	Melting temp. (°C)	Mold temp. (°C)	Flow rate (cm^3/s)	Packing pressure (MPa)
Set 1	210	20	60	40
Set 2	210	50	60	40
Set 3	210	80	60	40
Set 4	240	20	60	40
Set 5	240	50	60	40
Set 6	240	80	60	40
Set 7	270	20	60	40
Set 8	270	50	60	40
Set 9	270	80	60	40

The profiles of the specimen have a rectangular geometry cornered at the mid-point. The dimensions of profiles of the specimen were 30 mm width, 3 mm thickness and 90 mm^2 contact area. The three profiles of the specimen, however, have different inner radii at the corner positions. The dimensions were selected according to the European Standards of profile specimens. The left profile of the specimen shown on Fig. 1 has inner radius equal to halve its thickness. The middle profile of the specimen is a zero the inner radius. The right profile of the specimen has the inner radius equal to the thickness. The thickness of the three profiles of the specimen is 3 mm. The inner radius of the profiles of the specimen is the radii of them at the cornered parts (mid-point). The three profiles of the specimen were fabricated connectively together but experimentally tested separately.

3 Numerical Simulation Analysis

The inputs parameters used for numerical simulations were geometry of profiles of the specimen with dimensions and meshes, compression load and the various sets of injection molding process parameters (melt temperature, mold temperature, injection speed and packing pressure, and others such as cooling time kept as standard values).

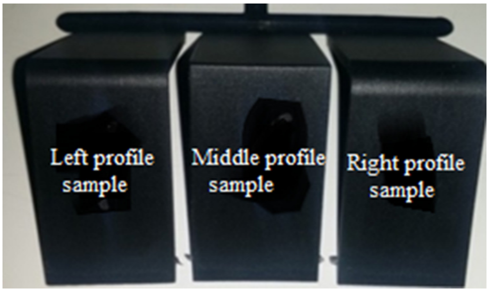


Fig. 1. The fabricated three profiles of the specimen.

3.1 Fiber Orientation

The properties of reinforced thermoplastic composites parts/products molded by injection molding depend on the state of fiber orientation and geometry of the part molded [23]. Fiber orientation is also affected by the injection molding process parameters and their sets. Increasing mold temperature delays heat transfer from the melt to mold walls (reduction of melt viscosity) which increases the degree of transverse alignment of fibers at the core layer during packing stage. This way, mold temperature affects fiber orientation of a composite. Packing pressure also increases the degree of transverse orientation of fibers at the core layer of the molded part [10]. This leads to rotation of fibers which increases transverse stress on fibers. The transverse stress also brings transverse orientation of fibers. Flow rate of the melt is also a factor influencing fiber orientations. At high flow rate (injection speed) of the melt, fiber loading content decreases and then fiber orientation gets decreased [24, 25]. Figure 2 illustrates effects of the melt temperature and mold temperature on orientation and alignment of fibers. The left-hand side figure indicates the specimen for the set of process parameters 1 (210 °C melt temperature and 20 °C mold temperature), and the right-hand side figure indicates the specimen for the set of process parameters 9 (270 °C melt temperature and 80 °C mold temperature). In this scenario, both melt temperature and mold temperature are increased for the set of process parameters 9 when compared with the set of process parameters 1, and the fiber orientations of the two specimens are different (as shown on Fig. 2 through color distributions indicating fiber orientations). The vertical bars representing ranges of fiber orientations on specimens are with merits of very high, high, medium, low and very low. As shown on Fig. 2 for example, the concentration and distribution of yellow color is higher for the right-hand side specimen (process parameters set 9) which means higher fiber orientation.

Another scenario was also examined to study the fiber orientation (as shown on Fig. 3). The left-hand side figure indicates the specimen for the set of process parameters 3 (210 °C melt temperature and 80 °C mold temperature), and right-hand side figure indicates the specimen for the set of process parameters 7 (270 °C melt temperature and 20 °C mold temperature). As shown on Fig. 3, the numerical simulation results indicate that fiber orientations of specimens are slightly different due to various sets of process parameters.

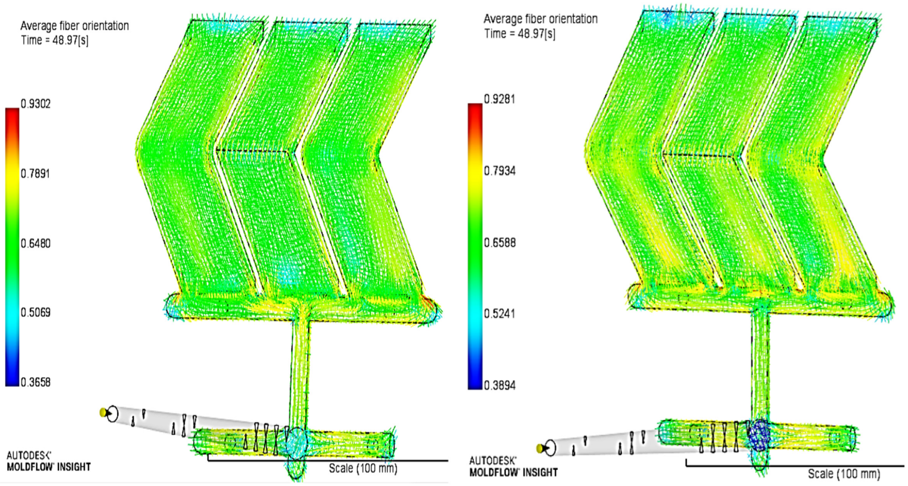


Fig. 2. Fiber orientation of specimens for sets 1 and 9 (Color figure online).

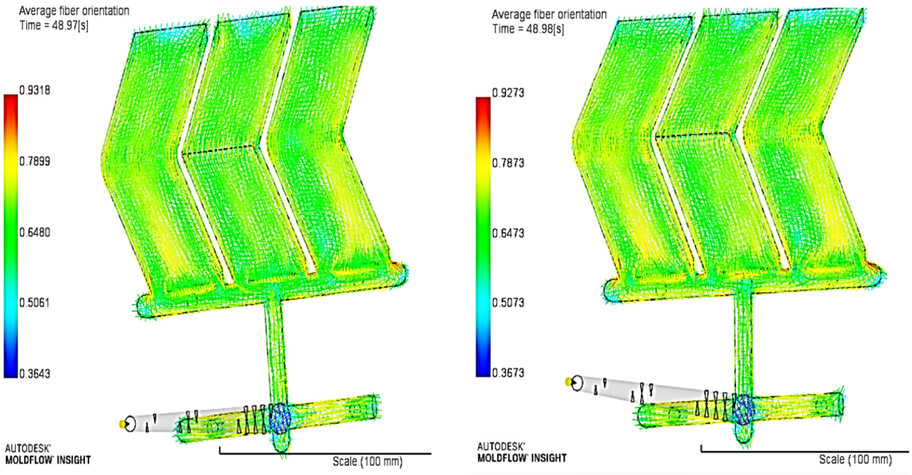


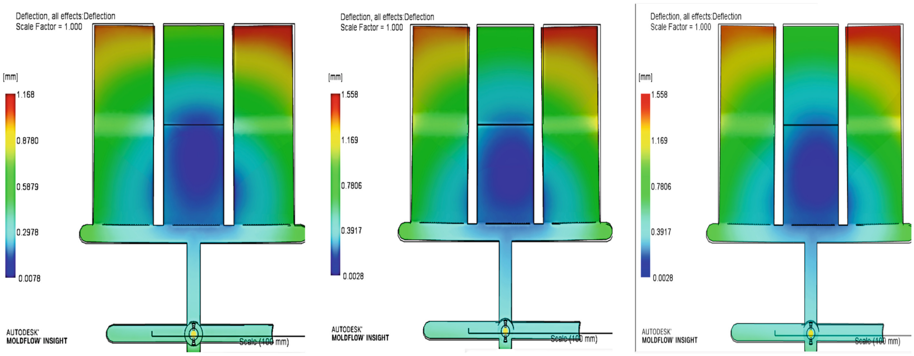
Fig. 3. Fiber orientation of specimens for sets 3 and 7 (Color figure online).

From Figs. 2 and 3, fiber orientations of the specimens for sets of process parameters 1 and 7 are different due to variation of the melt temperatures. Fiber orientation of the specimen for the set of process parameters 1 is lower than that of the specimen for the set of process parameters 7. At higher melt temperature of the part molded, there is high fiber orientation obtained. That means melt temperature has an effect on the fiber orientation of the part molded by injection. Again from Figs. 2 and 3, fiber orientations of the specimens for sets of process parameters 1 and 3 are different due to mold temperatures variation. This case, the two sets have the same melt temperatures but various mold temperatures. Fiber orientation of the process parameters set 3 is higher due to its higher mold temperature. Whereas when sets of process parameters 7 and 9 are compared, they have the same higher melt temperatures and variable mold temperatures. The numerical simulation results (Figs. 2 and 3) indicated that the two specimens seem has similar fiber orientations for sets of 9 and 7. From these analyses, it is possible to say that higher fiber orientation is achieved when either melt temperature or mold temperature is, or both are increased. But, melt temperature has slightly higher influence than mold temperature in fiber orientation (refer Fig. 3 of sets of process parameters 3 and 7).

Fiber orientations on faces of the specimens before and after the corner at the mid-point (gate location as a reference) are also different. It is higher result of fiber orientations on the faces of the specimens before the corner due to different reasons. This might be due to change of viscosity of the melt before and after the corner, incomplete mold filling and geometry of specimen molded.

3.2 Deflections

The magnitude and distribution of pressures on the core vary significantly during filling and packing; therefore, deflection will also vary with time. The maximum deflection occurs during filling and packing phases when the part is inside the mold [6].



(a) (b) (c)

Fig. 4. Numerical deflections of specimens (Color figure online).

Figure 4a indicates deflection of specimen for the set of process parameters 3 (80 °C mold temperature and 210 °C melt temperature). Figure 4b also indicates deflection of specimen for the set of process parameters 7 (20 °C mold temperature and 270 °C melt temperature). Figure 4c also indicates deflection of specimen for the set of process parameters 9 (80 °C mold temperature and 270 °C melt temperature). As shown from the simulation results (Fig. 4), deflection is affected by mold and melts temperatures but mold temperature has less effect. That is why Fig. 4b and c seem similar due to the same values of melt temperatures for the two process parameters sets even if different mold temperatures. So, melt temperature has significant influence on part deflection. When melt temperature raises, the value of part deflection also increases. This can be exhibited from Fig. 4a and c which were simulated with the same mold temperature but different melt temperature.

When melt temperature increases, the viscosity of the melt decreases and allows fibers to freely rotate and develop inter-fiber internal shear stresses. These internal shear stresses produce residual deformations or deflections of parts. On the other hand, viscosity of the melt is low at high melt temperature and consequently the residual stresses and residual deformation of the part decrease [26].

3.3 Load-Displacement Curve

Ansys software (R19.2) was used for numerical simulation of applied load and displacement (extension) values. The applied loads and deformations (extensions) of the profile of the specimen (profile with inner radius of 3 mm which is the right profile sample) have been then drawn for various sets of injection molding process parameters (shown on Fig. 6). A compression load of 180.0 N was applied along the –z direction. This is illustrated on Fig. 5. As indicated on Fig. 5, the deformations (extensions) are varied along the profile in which the maximum value was found at the corner and ends of it. The deformation of the profile at the corner is maximum due to stress concentration is experienced there. The maximum deformations developed at the ends of the profile are because of the compression loading which leads to tensile deformation and in-plane shears. The profile of the specimen has been failed at 180.0 N loads. As shown on Fig. 6, the deformation (extension) of the profile at higher melt and mold temperatures is higher. As a result, the strains to failure of the profile for the various sets of process parameters are different but the loads at failure point seem the same. Hence, the strain to failure of the profile for higher melt and mold temperatures is higher due to the incremental elastic deformations. And the deformation even if depends on both the melt and mold temperatures, but the melt temperature have better influence (shown on Fig. 6). Thus, the melt temperature has more effect than the mold temperature on strain to failure.

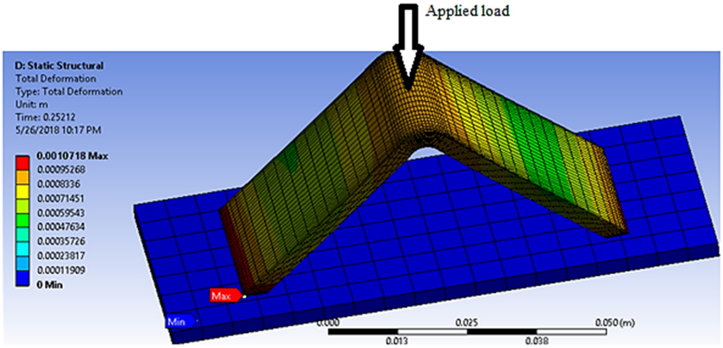


Fig. 5. Illustration on applied compression load on the profile (Color figure online).

Finally, the deformations and strains to failure of the profile of the specimen for the nine (9) sets of the process parameters have been determined and summarized in Table

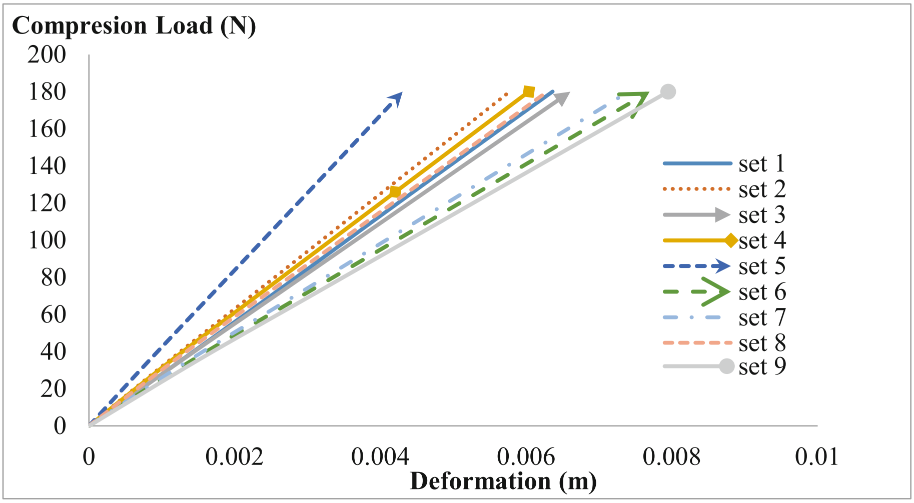


Fig. 6. Compression load versus deformation graph (Color figure online).

2. Table 2 shows that the strains to failure of settings 3 (low melt temperature and high mold temperature) and 6 (moderate melt temperature and high mold temperature) are the highest and lowest values, respectively. This seems very logical that the specimen molded by injection molding process with low melt temperature and high mold temperature has the maximum strain to failure which is tough. The specimen molded by moderate melt temperature and high mold temperature has the minimum strain to failure which is less tough but stiff one. So it is possible to conclude that the part molded by injection molding of moderate melt temperature and high mold temperatures performs the highest mechanical properties except the lowest strain to failure characteristics. Indeed, this conclusion was also aligned with the optimum conclusion of experimental results (shown

Table 2. Deformations and strains to failure of the profile of specimen for process sets.

Set of process parameters	Compression load (N)	Deformation (mm)	Strain to failure (%)
Set 1	180.0	6.3634	4.4252
Set 2	180.0	5.7753	4.4253
Set 3	180.0	6.6065	4.4266
Set 4	180.0	6.0356	4.4234
Set 5	180.0	4.3046	4.4246
Set 6	180.0	7.6924	4.4207
Set 7	180.0	7.4078	4.4224
Set 8	180.0	6.2909	4.4239
Set 9	180.0	7.9483	4.4248

in Sect. 4). It is therefore that the numerical simulation has predicted good results of strain to failure of the specimens.

4 Experimental Analysis

The different specimens with various sets of process parameters given in table 1 were tested by the compression loading. The compression testing was used for the experimental analysis because the design of the profiles of the specimen was appropriate for compression only. As discussed in Sect. 2.2.1, each specimen consists of three corner profiles with different radii. Each corner profile has been tested five times and the mean value was taken to obtain a homogeneous result. The machine used for the compression testing is the Instron 5567 equipped with a load cell of 1 kN. The deflection rate is tuned at 3 mm/min. The compression test was used to give the relation between the applied load and deformation (extension) of the corner profiles of the specimen. The results from the three different corner profiles of the specimen were compared to each other as shown on Fig. 7. For this comparison, the melt temperature was fixed at 210 °C and the mold temperature was fixed at 20 °C. As shown on Fig. 7, the inner (internal) radius of the corner of the profile sample has great impact on the load carrying capacity. The bigger the inner radius, the larger compression load the profile of the specimen can sustain. This is because sharp corners will lead to the stress concentrations. These stress concentrations will lead to a premature failure of parts. Therefore, a good design rule is to make the inner radius of the part as large as possible. Accordingly, the middle profile (sample) not only failed at a load lower than the others two but it also failed under a smaller extension (shown on Fig. 7).

The effect of sets of the different mold temperatures was also examined. For this analysis, the profile of the specimen with the inner radius equal to half of the thickness (left profile sample) was used and the melt temperature was fixed at 210 °C. The results indicated that the effect of changing the mold temperature is less though the higher mold temperature has delivered slightly higher load carrying capacity which is better mechanical properties (shown on Fig. 8). Theoretically, a higher mold temperature improves the

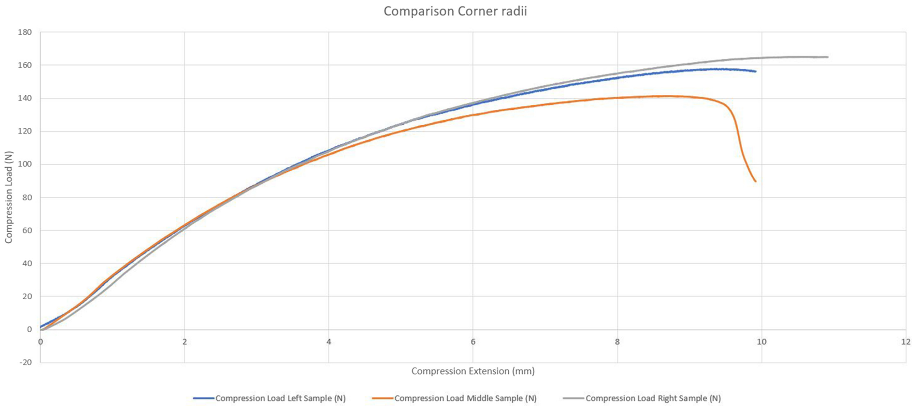


Fig. 7. Comparison of the three profiles of the specimen (Color figure online).

flow behavior of a melt and reduces the internal stresses but can make part demolding more difficult [5, 27].

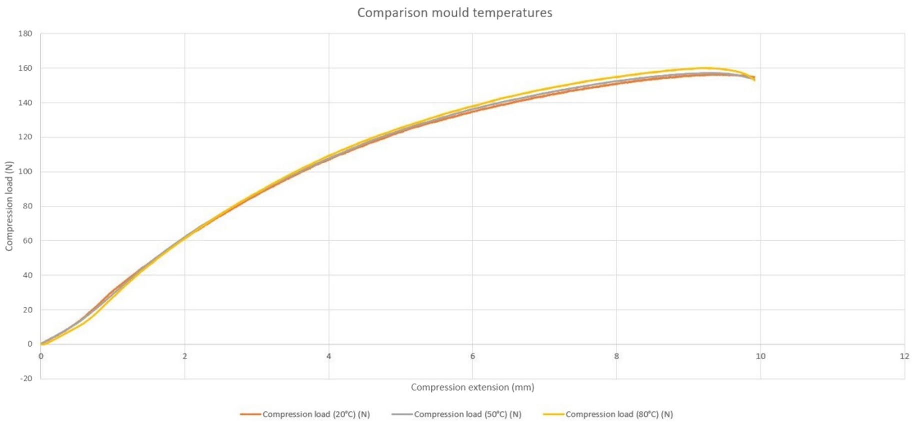


Fig. 8. Comparison of different Mold temperatures and fixed melt temperature (Color figure online).

The effect of changing the melt temperature was also investigated. Again the test profile of the specimen subject to this analysis was with the inner radius equal to halve of the thickness (left profile sample). The fixed mold temperature and various melt temperatures were used for the analysis. It is shown on Fig. 9 that the profile of the specimen performs different due to the change of the melt temperatures. This is because of the fact that the fiber orientation is one of the factors affecting the properties of composite parts. It is know that fiber orientation highly depends on melt temperature and geometry of the profile of the specimen. A higher melt temperature results higher orientation of fibers which also leads to an improved part performance.

Changing the melt temperatures has a larger effect than the mold temperatures on the mechanical properties of the profile of the specimen. This conclusion is evident just by looking the Figs. 8 and 9. The reason behind the larger effect of melt temperature on the composites is that the viscosity of the melt will be lower when increasing the melt temperature. The effect of lower viscosity will induce less residual stress but higher fiber orientation in the injection molded profile of the specimen. This means that the profile of the specimen manufactured by injection molding with higher melt temperatures can withstand a higher compression load (shown on Fig. 9). Though the profile of the specimen manufactured injection molding with higher melt temperature can withstand larger compression load, the profile of the specimen fails at lower compression extension (strain). This means that the profile of the specimen manufactured by injection molding at higher melt temperature is stiffer but less tough.

The three different setups were studied independently. The general comparison had been then done about the influence of the inner radii of the corner profiles of the specimen, melt temperatures and mold temperatures. In total, 27 load-extension (deformation) relationships were obtained for the various nine (9) sets of injection molding process

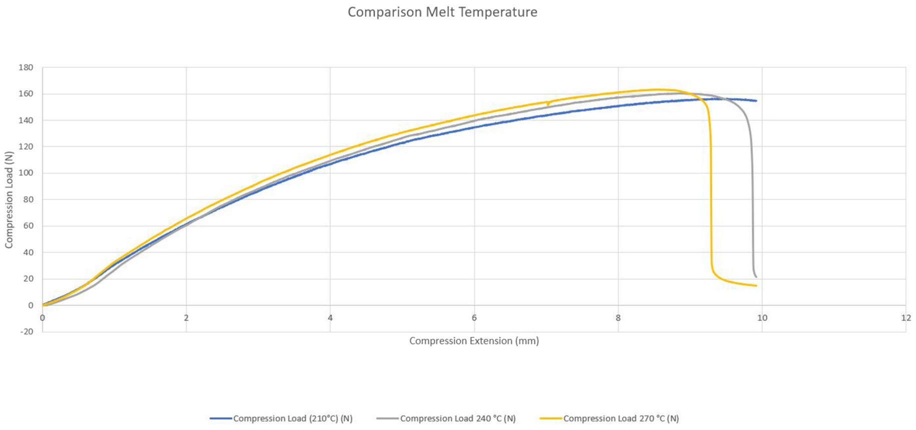


Fig. 9. Comparison different melt temperatures and fixed mold temperature (Color figure online).

parameters and three profiles of the specimen. Because a graphical representation with 27 lines would be varying chaotic, the authors of this paper have chosen to compare the maximum compression loads the specimens sustain and extensions (deformations) at which they occur due to the loadings (shown in Table 3).

Table 3. Comparison of load versus extension for profiles of the specimens.

Set of process parameters	Load versus extension of the three profiles of specimens		
	Left profile	Middle profile	Right profile
	N (mm)	N (mm)	N (mm)
Set 1	156.6 (9.37)	141.5 (8.70)	164.9 (10.62)
Set 2	157.3 (9.31)	141.5 (8.59)	168.0 (11.01)
Set 3	159.9 (9.21)	141.7 (8.11)	169.2 (10.18)
Set 4	160.2 (8.87)	142.9 (7.98)	169.0 (9.93)
Set 5	164.9 (8.81)	139.9 (7.88)	172.4 (9.48)
Set 6	163.6 (8.19)	134.4 (7.06)	174.0 (9.32)
Set 7	160.2 (8.55)	141.4 (8.17)	172.8 (9.74)
Set 8	161.4 (8.84)	138.6 (7.85)	174.7 (9.71)
Set 9	164.6 (8.58)	126.3 (6.15)	175.0 (9.36)

When the maximum compression loads (shown in Table 3) are compared, some interesting facts are found. The geometry of profile of the specimen is the most important parameter for load carrying capacity. As said previously, the inner radius should be as large as possible to diminish the stress concentration. The right profile of the specimen has the largest inner radius and thus can withstand the largest compression loads (shown in Table 3). And as expected, the maximum load is proportional to the melt temperature and mold temperature. The inner radius of the left profile of the specimen is only half of the inner radius of the right profile of the specimen that leads the alignment of fibers in the left profile corner is more difficult. The left profile of the specimen shows that it is important to match the mold temperature and the melt temperature. A too large temperature difference between the melt and mold results in a larger frozen layer in which fibers will be orientated randomly and thus lower mechanical properties. The properties of the middle profile of the specimen seem to decrease with increasing mold temperature which can be explained by the transverse alignment of the fibers during the packaging stage. The small increasing properties with melt temperature could be due to a mismatch between melt and mold temperatures.

5 Conclusion

This paper contains a numerical and experimental analysis of three profiles of each specimen of the short glass fiber reinforced polypropylene (Sabic PP Compound G3220A) composite using various sets of injection molding process parameters. Following both the numerical simulations and experimental analysis of the profiles of specimens, the following conclusions have been drawn:

- The load carrying capacity of the specimen highly depends on the geometry of the profiled specimen. When the inner radius of the profile of the specimen is larger (less sharp at its corner), it sustains the maximum applied compression load.
- The extensions (deformations) values of the numerical analyses are less predicted than the extensions (deformations) values of the experimental extensions for the same profile (right profile sample). However, the numerical simulations of the right profile sample have predicted higher extensions (deformations) than the experimental extensions of the middle profile sample for sets of process parameters 6 and 9 (as shown in Tables 2 and 3).
- The mechanical properties of the specimens of the composite are slightly higher at high melt temperatures. This is because fiber orientation is higher at high melt temperatures whereas the residual stresses inside the injection molded part decreases as a result of viscosity reduction at higher melt temperatures.
- Melt temperature has more influence on the overall properties of injection molded parts when compared with other injection molding process parameters.

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