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Effect of Process Parameters on Shear Layer Thickness in Injection Molded Short-Glass Fiber Reinforced Polypropylene

Controlling fiber orientation and fiber distribution in plastic injection of glass reinforced polymers is important due to the improvement of the properties of the material. Variation in shear layer thickness of fiber distribution affects the properties of the injection moldings. In this study, 30% glass fiber reinforced polypropylene was injected under various injection molding conditions in order to increase the shear layer thickness in which fiber orientation was parallel to the flow direction. The experimental study was carried out according to the Taguchi L9 orthogonal array. The mold temperature, nozzle temperature and injection rate were chosen as input parameters and the thickness of the shear layer was taken as output. Analysis of variance was also applied to observe the effectiveness of the process parameters on shear layer thickness. The shear layer thickness was measured over the images obtained by scanning electron microscopy. In order to investigate the dynamic mechanical behavior of the material depending on fiber distribution, dynamical mechanical analysis was applied. Storage modulus, loss modulus and tan delta values were obtained. It has been observed that higher mold temperature and nozzle temperature values increased shear layer thickness in injection molding of glass fiber reinforced polypropylene. It has been seen that 65% of increment in shear layer thickness induced approximately 50% of increment in storage modulus and loss modulus.

1 Introduction

Injection molding is the most commonly used manufacturing process for the fabrication of plastic parts. Capacity of forming fairly complex shapes at a high production rate is a main advantage of this manufacturing technique (Kim et al. 2001). Recently, there are increasing demands for superior mechanical properties. Therefore, for the production of lightweight parts with good mechanical properties, the injection molding of fiber-reinforced polymers is used widely (Lee et al., 1997). Fiber-reinforced polymers offer a number of advantages in terms of end-use performance of the products (Shokri and Bhatnagar, 2012). As superior strength, lower linear expansion coefficient and other desirable mechanical properties relative to common thermoplastics with no reinforced material, fiber-reinforced polymer products now are widely used in home appliances, automobiles, and medical equipments (Li et al., 2014). During the injection molding of fiber-reinforced polymers, fiber orientation is produced by the flow states (Kim et al., 2001). As mechanical properties depend on flow induced fiber orientation, there is considerable interest in establishing relationships between flow and orientation (Vincenta et al. 2005). Significant differences are observed in the properties of the products obtained due to the orientation of the fibers. Therefore, controlling the orientation of the fiber during flow of the material in the mold becomes necessary (Li et al., 2014). There are many researchers focused on fiber orientation of the fibers during injection molding. Li et al. (2014) investigated the mold temperature effect on fiber orientation and surface quality of the injected molded parts. Shokri and Bhatnagar (2012) studied the effect of the packing pressure on the fiber orientation. Meyer et al. (2013) reported that fiber orientation is mainly related to the initial conditions such as sprue, gate and mold. Mortazavian and Fatemi (2015) examined the distribution of fibers and their effect on tensile strength with respect to two different flow directions and part thicknesses. Minnick and Baird (2016) investigated the effect of change in injection speed on fiber orientation. Goris et al. (2016) studied the effect of fiber orientation on the mechanical properties of the parts in the injection molding process. Many studies show that holding pressure is not as effective as thermal parameters such as mold temperature. It is known that in the injection molding cycle, a large part of the material is solidified when it is transferred to the holding pressure stage. In this stage, the fibers are oriented at very small angles in the position of the matrix. Vincent et al. (2005) made a quantification of the fiber orientation in a rectangular plaque with adjustable thickness and molded with different fiber reinforcement amounts. Kim et al. (2001) investigated the distribution of fiber orientation by image processing for the injection molded products of each fiber content. They compared their results with numerical simulations (Kim et al., 2001). Thi et al. (2015) observed with 3D X-ray computed tomography in different injection molds. They analyzed the in-mold flow of the polymer by the finite element method. Peng

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et al. (2015) predicted and experimentally verified the fiber orientation in the injection molding process.

In addition to examining fiber orientation, many researchers have also worked on optimizing fiber orientation (Chen et al. 2006; Kim and Lee, 2006; Shie, 2008; Tzeng et al. 2012; Yashiro et al. 2012).

Flow of the polymer in the mold is directly related to the process parameters of the molding process. The molding conditions generate a layered structure in the solidified material. As given in Fig. 1, there is a frozen layer (skin layer) just below the mold wall and then a shear layer and a core layer, respectively. Shear layer is the layer that fiber orient parallel with flow direction while in core layer, the fibers are random. Skin layer cooled so rapidly that fibers cannot orient in such a short time. The shear layer, close to the skin layer, suffers much greater resistance due to the friction during the flowing process and large shear is generated. Depending on this, fibers can be highly oriented. On the other hand, molten material in the core layer is under less friction, shear stress is very low and only few fibers orient parallel to the flow. Most of the fibers orient randomly. If the thickness of layer including fiber oriented parallel to flow direction is high, then it is observed that mechanical strength of the material increases (Chen et al., 2006).

Although there are a number of studies in the literature concerning fiber orientation in injection of fiber reinforced polymers, no study has been found to optimize the injection conditions, taking into account the increase in the thickness of the shear layer and to relate the results to the mechanical properties of the material. In this study, the fiber orientation regions in the specimens obtained under different injection conditions were investigated and dynamic mechanical behaviors were investigated.

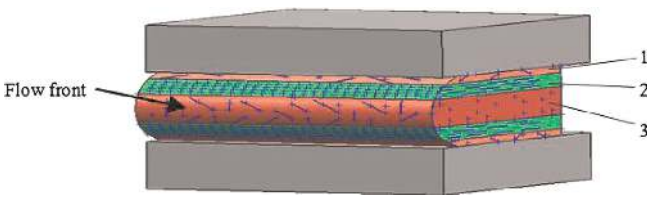


Fig. 1. Fiber orientation structure in injection part; 1) frozen layer, 2) shear layer, 3) core layer (Li et al., 2014)

Feature	Values
Density (kg/m^3)	905
Melt flow rate (g/10 min) (2.16 kg, 230 °C)	12
Elasticity modulus (MPa)	1 550
Elongation in flow (%)	9
Yield Tension (MPa)	34
Charpy impact strength (kJ/m)	3,5

Table 1. Properties of polypropylene used in the experimental work

2 Experimental Study

2.1 Material

In the experimental work, commercial polypropylene (PP) reinforced with 30 % of glass fiber (CFTP) was used. The matrix polymer was polypropylene of Borealis, Vienna, Austria (PP, HE125MO). Glass fiber used as reinforcing material was 13 μm in diameter and 4 to 6 mm in length. The properties of the material are given in Table 1.

2.2 Plastic Injection Molding

Plastic injection molding was done on a 40 t injection molding machine (Yelkenciler, Istanbul, Turkey) under different process conditions as given in Table 2. The experimental study was carried out according to Taguchi's L9 orthogonal array as shown in Table 3. The response in the study was shear layer thickness of the samples which corresponds to the layer including fiber orientation parallel to the flow direction of the polymer in the mold. "The larger – the better" was used in Taguchi method in order to determine the process conditions that could give the highest shear layer thickness. A solid model of the

No	Nozzle temperature °C	Mold temperature °C	Injection rate %
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 3. L9 OA used in the experimental study

Parameters	Level 1	Level 2	Level 3
A; Nozzle temperature (°C)	200	240	260
B; Mold temperature (°C)	20	40	60
C; Injection rate (%)	30	32	34

Table 2. Levels of the parameters

mold used in the experimental work and a photograph of the obtained part are given in Fig. 2. The dimensions of the part were 120 × 60 × 3.4 mm.

2.3 Measurement of the Shear Layer Thickness

The fracture surface of the each sample was observed with a scanning electron microscope, SEM (EVO LS 10, Zeiss, Jena, Germany). In this regard, firstly rectangular samples (1) were cut from the injected molded part as given in Fig. 3. Then, the fracture surfaces of the rectangular samples were obtained by fracture test. After obtaining SEM images of the fracture surfaces, the images were imported to Image J Software program (NIH, Maryland, USA) to measure shear layer thickness. Three measurements were done for each sample and the average of the measurements was taken. The results were reported with 1.25 of standard deviation.

2.4 Dynamic Mechanical Analysis

Dynamic Mechanical Analysis (DMA 8000, Perkin Elmer, Massachusetts, USA) was applied at a frequency of 1 Hz with a heating rate of 5 °C/min and a temperature range of –50 to 100 °C in a single cantilever mode. DMA and SEM samples were cut from the same location of the injected molded part in separate shots. DMA samples had the dimensions of 60 × 10 × 3.4 mm, numbered as (1) in Fig. 3. SEM samples were prepared similar to DMA samples but their fracture surface were investigated as numbered (2) in Fig. 3.

3 Results and Discussion

3.1 Effect of Parameters on Shear Layer Thickness

The Taguchi method was used to identify the optimal setting conditions that could maximize the shear layer thickness in injection molded short fiber reinforced polypropylene. It is known that gate geometry, its location, and material type are effective in fiber orientation (Meyer et al., 2013). The main injection factors affecting fiber orientation are nozzle temperature, mold temperature and injection speed (Chen et al., 2006;

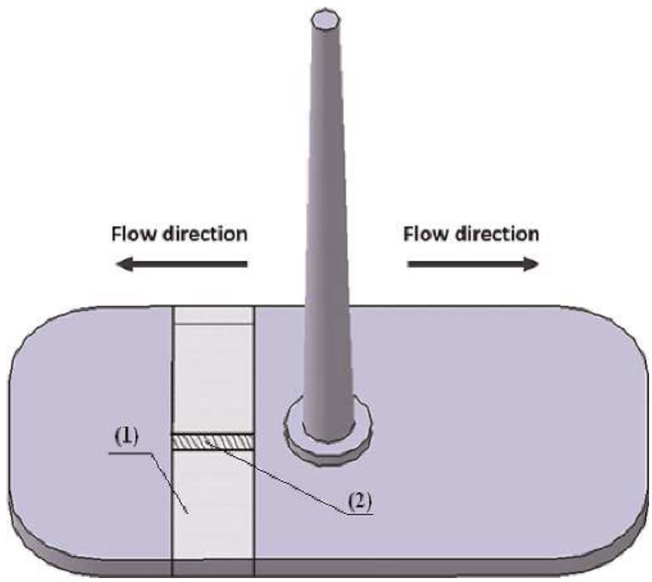
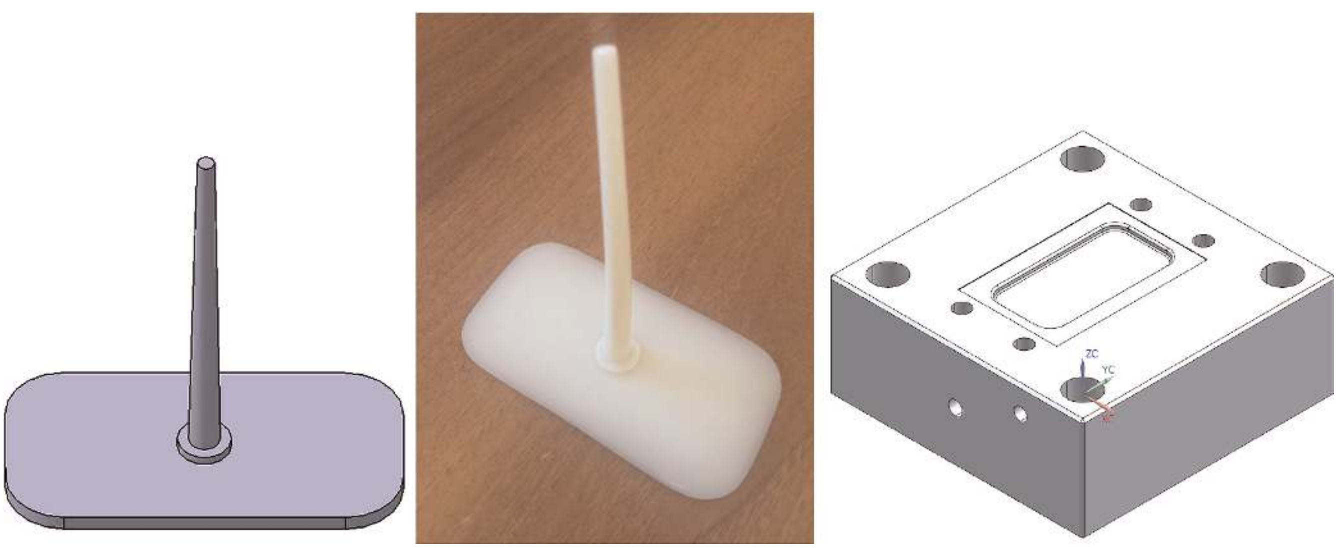


Fig. 3. Samples for DMA (1) and SEM (2)



A) B) C)

Fig. 2. Solid model (A) of the mold, solid model of the part (B) and sample part (C)

Li et al., 2014; Tzeng et al., 2012), but selecting the correct parametric combination of these parameters is important in increasing the shear layer thickness.

The SEM images given in Fig. 4 show the layer thickness determined by Image J software program where each image corresponds to a set of injection molding parameters given in Table 3. The measured shear layer thicknesses are reported in Table 4. The signal-to-noise ratios (S/N) for each experiment were determined by Eq. 1, where n is the number of experiments, which is equal to 9, and y_i is the shear layer thickness for the value for the data set.

$$S/N = -10.\log\left(\frac{1}{n}\sum_{i=1}^{n} 1/y_i^2\right), \quad (1)$$

SN response data diagrams were obtained by the Minitab program as in Fig. 5. According to the larger – the better phenomena, the optimal process condition for shear layer thickness is A3B3C2 which is the 9th set of experiments in Table 3.

It has been seen that an increment of mold temperature and nozzle temperature were effective in increasing the shear layer thickness. Injection speed increased the shear layer thickness in its medium value.

Analysis of variance (ANOVA) was applied to the parametric contribution of the control factors in increasing the shear layer thickness. As shown in Table 5, the percentage contribution of nozzle temperature (48.30 %) is higher than that of the mold temperature (41.78 %). When the nozzle temperature increased, the viscosity of the polymer decreased and this increased the motion ability of the fibers. Mold temperature has the second degree importance in increasing the shear layer thickness with 41.78 of contribution. The increment in mold temperature reduced the surface tension between the melt and the mold and fibers orient freely. It could be clearly seen that the highest shear thickness was obtained when the melt and mold temperature were at their highest values at the same time. This corresponds to the third level of these two parameters in Fig. 5. Higher values in mold temperature and nozzle temperature induced a reduction in temperature difference between the molten polymer and the mold surface. As a result, the skin layer of the melt in contact with the mold surface could be frozen in a longer time. This allowed fibers to

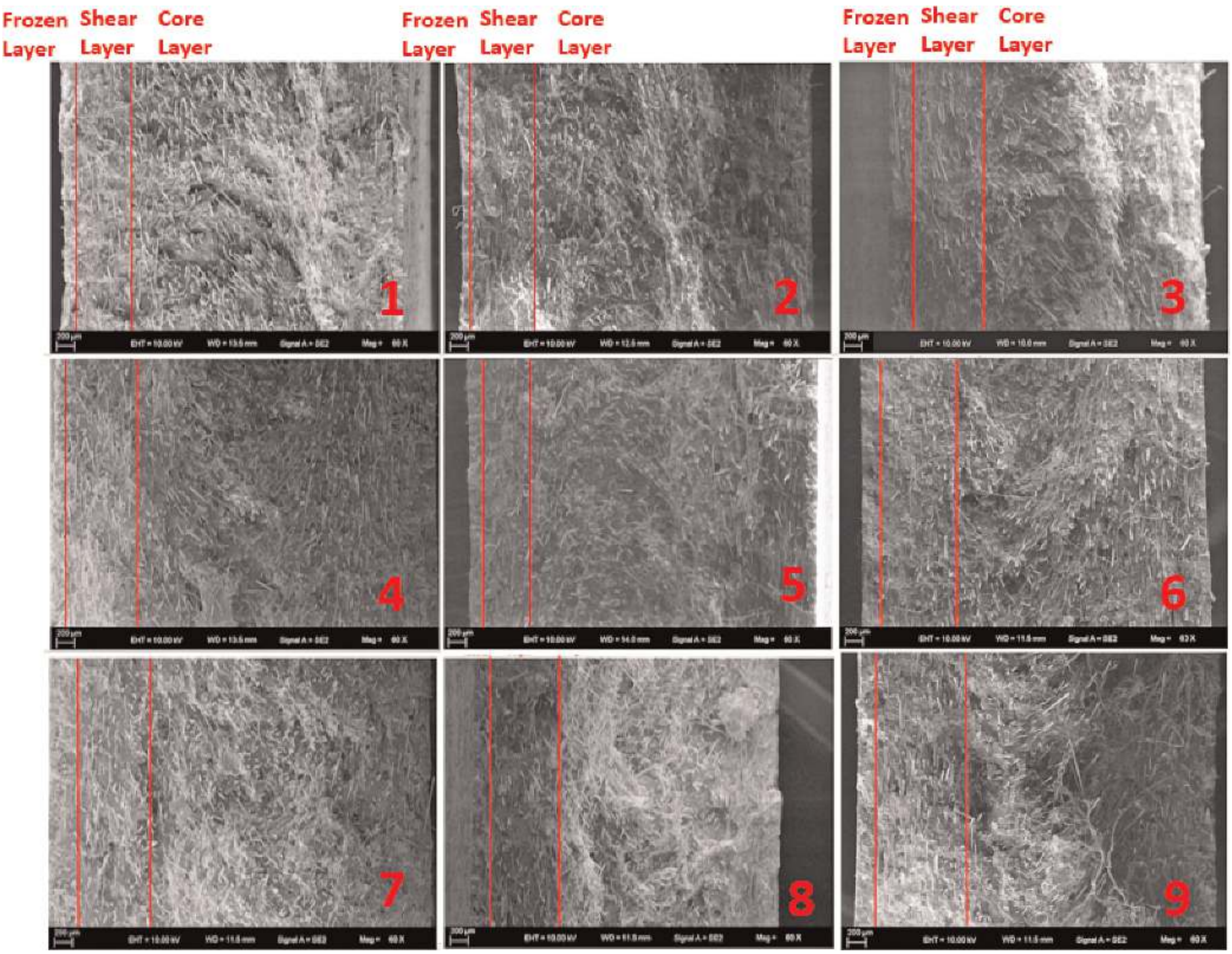


Fig. 4. Shear layer thickness of the samples

relax and orient in the flow direction. When the mold temperature was kept lower, such as 20 °C, it has been observed that the thickness of the core region of the injection moldings were higher where the fibers oriented randomly in this region. The reason for this was due to the rapid cooling of the frozen layer and this generated a small distance between "skin layer" and "shear layer".

3.2 *Effect of Shear Layer Thickness on Dynamic Mechanical Analysis*

Dynamic mechanical analysis of the injected molded parts was performed in order to see the effect of shear layer thickness on the mechanical behavior of the material. Among the experiments, the highest (9th) 910 μm- the lowest (1st) 550 μm and the medium (4th) 786 μm shear thickness values were considered in determining the effect of the shear thickness on the dynamic mechanical behavior of the material. The storage modulus (E′) is given in Fig. 6A. The sample of 1 gave the lowest storage modulus which corresponds to the lowest shear thickness. The samples of 7th and 9th had higher storage modulus. The higher shear thickness had the higher amount of fibers with parallel orientation to the flow direction and this increased the stiffness of the material. A similar behavior was observed for loss modulus given in Fig. 6B. The temperature at the tan δ peak corresponds to the glass transition temperature (Tg). The damping in the glass transition region represented the energy dissipated for the deformation or irreversible intermolecular movement inside the materials (Amash and Zugenmajer, 1997; Jacob et al., 2006). In this study, the glass fiber concentration was constant for all samples, therefore an apparent difference in loss factor was not determined. Tan delta values are given in Fig. 6C. It has been known that tan δ value gives information about the strong interfacial fiber–matrix interaction (Karsli and Aytac, 2013; Liu et al., 2015). However, in this study, the interaction behavior for the three samples is the same due to the

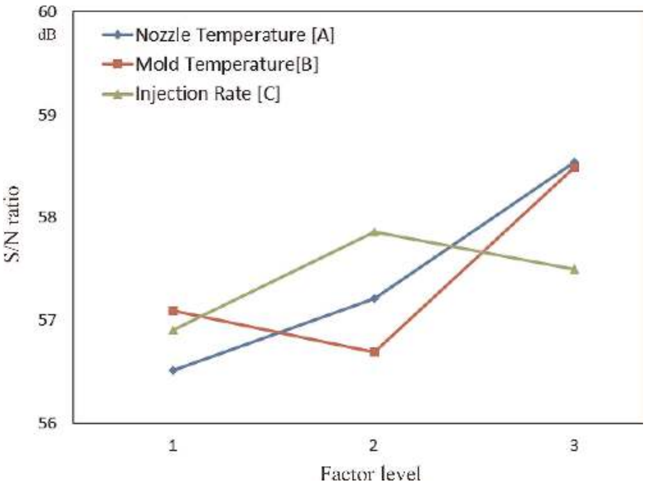


Fig. 5. Response diagram of SN ratio

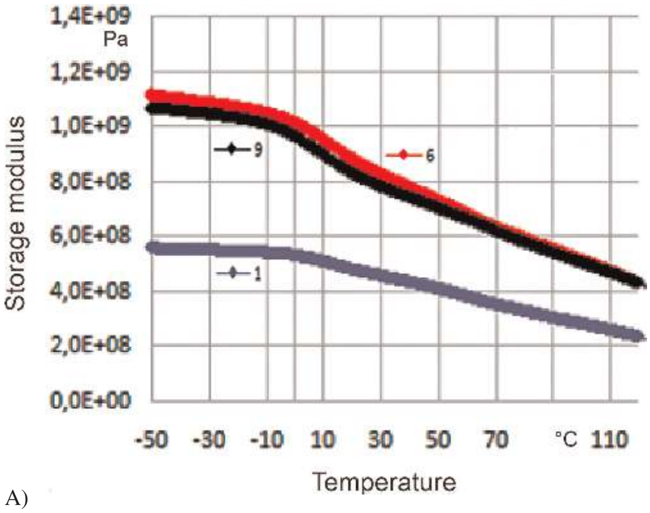
No	Nozzle temperature °C	Mold temperature °C	Injection rate %	Shear layer thickness μm	S/N ratio dB
1	200	20	30	550	54,80
2	200	40	32	668	56,49
3	200	60	34	816	58,23
4	240	20	32	786	57,90
5	240	40	34	608	55,67
6	240	60	30	798	58,04
7	260	20	34	847	58,55
8	260	40	30	783	57,87
9	260	60	32	910	59,18

Table 4. Shear layer thickness values

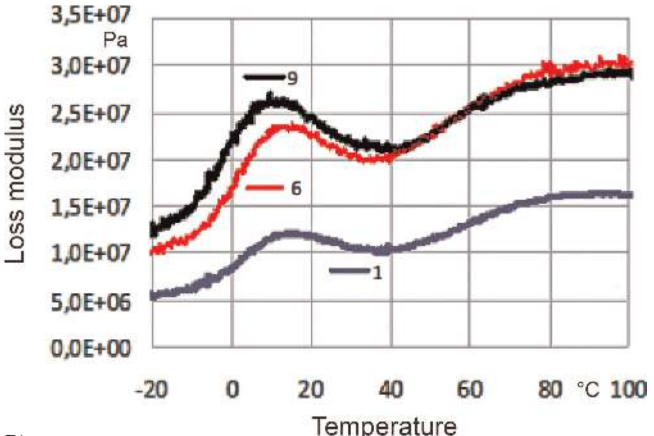
Symbol	Factors	DF	Sum of squares	Mean square	F-ratio	P-value	Percentage contribution %
A	Nozzle temperature (°C)	2	44 678,2	22 339,1	2,43	0,2918	48,300
B	Mold temperature (°C)	2	38 653,6	19 326,8	2,10	0,3226	41,786
C	Injection rate (%)	2	9 170,89	4 585,44	0,50	0,6675	9,914
Residual		2	18 410,9	9 205,44			

Table 5. ANOVA results

constant concentrations of the glass fiber in the matrix. Therefore, an apparent difference in tan delta value could not be observed.



A)



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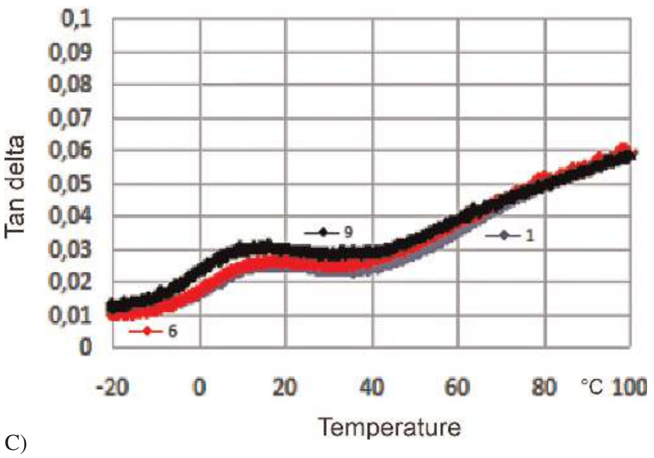

C)

Fig. 6. Dynamic mechanical analysis curves, storage modulus (A), loss modulus (B) and tan delta (C)

4 Conclusions

The fiber orientation and fiber distribution in glass fiber reinforced polypropylene were examined. Optimal process condition for increasing shear layer thickness were determined. The obtained results were as follows:

- According to the Taguchi and ANOVA methods, nozzle temperature was found to be the most critical parameter in increasing the shear layer thickness while mold temperature had the second degree importance. The increment of mold and nozzle temperature simultaneously decreased the temperature difference between the polymer and the mold surface. Therefore, fibers had time to orient and distribute. Injection speed was effective in its medium values. On the contrary, when the mold temperature was kept cold at 20 °C, the frozen layer and the core layer were high in thickness but shear layer was less. The fibers in the core region oriented randomly, which reduced the total amount of fiber orientation parallel to the polymer flow direction in the structure.
- When shear layer thickness reduced, the thickness of the core region increased and this reduced storage modulus and loss modulus of the material due to highly randomly oriented fibers. Random orientation of the fibers decreased the stiffness of the material. On the other hand, when the shear thickness increased from 550 µm to 910 µm, the storage modulus and loss modulus showed a 50 % increment.

As a result, higher mold and nozzle temperature were successful in increasing the "shear layer thickness" but it should be noted that higher temperatures bring higher cooling time and this increases the cycle time in injection molding which is not preferable in industrial applications. Therefore, an optimization is always necessary for keeping the shear thickness high with acceptable cycle times.

References

Amash, A., Zugenmajer, P., "Thermal and Dynamic Mechanical Investigations on Fiber Reinforced Polypropylene Composites", J. Appl. Polym. Sci., **63**, 1143 – 1154 (1997), DOI:10.1002/(SICI)1097-4628(19970228)63:9<1143::AID-APP6>3.0.CO;2-H

Chen, C. S., Chen, T. J., Chen, S. C. and Chien, R. D., "Optimization of the Injection Molding Process for Short-Fiber-Reinforced Composites", Mech. Compos. Mater., **47**, 359 – 368 (2006), DOI:10.1007/s11029-011-9214-x

Goris, S., Gandhi, U., Song, Y. Y. and Osswald, T. A., "Analysis of the Process-Induced Microstructure in Injection Molding of Long Glass Fiber-Reinforced Thermoplastics", SPE ANTEC Tech. Papers, 318 – 326 (2016)

Jacob, M., Francis, B., Thomas, S. and Varughese, K. T., "Dynamical mechanical Analysis of Sisal/Oil Palm Hybrid Fiber-Reinforced Natural Rubber Composites", Polym. Compos., **27**, 671 – 680 (2006), DOI:10.1002/pc.20250

Karsli, N. G., Aytac, A., "Tensile and Thermomechanical Properties of Short Carbon Fiber Reinforced Polyamide 6 Composites", Composites Part B, **51**, 270 – 275 (2013), DOI:10.1016/j.compositesb.2013.03.023

Kim, E. G., Park, J. K. and Jo, S. H., "A Study on Fiber Reinforced Orientation during the Injection Molding of Fiber Reinforced Polymeric Composites", J. Mater. Process. Technol., **111**, 225 – 232 (2001), DOI:10.1016/S0924-0136(01)00521-0

Kim, J. W., Lee, D. G., "Fiber Orientation State Depending on Injection Mold Gate Variations during FRP Injection Molding", Key Eng. Mate., **321,** 938–941 (2006), DOI:10.4028/www.scientific.net/KEM.321-323.938

Lee, S. C., Yang, D. Y., Ko, J. and Youn, J. R., "Effect of Compressibility on Flow Field and Fiber Orientation during the Filling Stage of Injection Molding", J. Mater. Process. Technol., **70**, 83–92 (1997), DOI:10.1016/S0924-0136(97)00041-1

Li, X. P., Zhao, G. Q. and Yang, C., "Effect of Mold Temperature on Motion Behaviour of Short Glass Fibers in Injection Molding Process", J. Adv. Manuf. Technol., **73**, 639–645 (2014), DOI:10.1007/s00170-014-5874-8

Liu, Y., Zhang, X., Song, C., Zhang, Y., Fang, Y., Yang, B. and Wang, X., "An Effective Surface Modification of Carbon Fiber for Improving the Interfacial Adhesion of Polypropylene Composites", Mater. Des., **88**, 810–819 (2015), DOI:10.1016/j.matdes.2015.09.100

Meyer, K. J., Hofmann, J. T. and Baird, D. G., "Initial Conditions for Simulating Glass Fiber Orientation in the Filling of Center-Gated Disks", Compos. Appl. Sci. Manuf., **49**, 192–202 (2013), DOI:10.1016/j.compositesa.2013.03.004

Minnick, R. A., Baird, D. G., "Effects of Injection Molding Processing Parameters on Experimental Fiber Length Distribution of Glass Fiber-Reinforced Composites", SPE ANTEC Tech. Papers, 368–372 (2016)

Mortazavian, S., Fatemi, A., "Effects of Fiber Orientation and Anisotropy on Tensile Strength and Elastic Modulus of Short Fiber Reinforced Polymer Composites", Composites Part B, **72**, 116–129 (2015), DOI:10.1016/j.compositesb.2014.11.041

Peng, X., Qin, J. and Jiang, Y., "An Approach for Predicting Fiber Orientation Distribution in Plastic Injection Molding of Composites", British Journal of Applied Science & Technology, **7**, 186–194 (2015), DOI:10.9734/BJAST/2015/15765

Shie, J. R., "Optimization of Injection Molding Process for Contour Distortions of Polypropylene Composite Components by a Radial Basis Neural Network", Int. J. Adv. Manuf. Technol., **36**, 1091–1103 (2008), DOI:10.1007/s00170-007-0940-0

Shokri, P., Bhatnagar, N., "Effect of the Post-Filling Stage on Fiber Orientation at the Mid-Plane in Injection Molding of Reinforced Thermoplastics", Phys. Procedia, **25**, 79–85 (2012), DOI:10.1016/j.phpro.2012.03.053

Thi, T. B. N., Morioka, M., Yokoyama, A., Hamanaka, S., Yamashita, K. and Nonomura, C., "Measurement of Fiber Orientation Distribution in Injection-Molded Short-Glass-Fiber Composites Using X-Ray Computed Tomography", J. Mater. Process. Technol., **219**, 1–9 (2015), DOI:10.1016/j.jmatprotec.2014.11.048

Tzeng, C. J., Yang, Y. K., Lin, Y. H. and Tsai, C. H., "A Study of Optimization of Injection Molding Process Parameters for SGF and PTFE Reinforced PC Composites Using Neural Network and Response Surface Methodology", Int. J. Adv. Manuf. Technol., **63**, 691–704 (2012), DOI:10.1007/s00170-012-3933-6

Vincenta, M., Girouda, T., Clarke, A. and Eberhardt, C., "Description and Modeling of Fiber Orientation in Injection Molding of Fiber Reinforced Thermoplastics", Polymer, **46**, 6719–6725 (2005), DOI:10.1016/j.polymer.2005.05.026

Yashiro, S., Sasaki, H. and Sakaida, Y., "Particle Simulation for Predicting Fiber Motion in Injection Molding of Short-Fiber Reinforced Composites", Compos. Appl. Sci. Manuf., **43**, 754–1764 (2012), DOI:10.1016/j.compositesa.2012.05.002

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Bibliography
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