EXPERIMENTAL STUDY TO OPTIMIZE SHRINKAGE BEHAVIOR OF SEMI-CRYSTALLINE AND AMORPHOUS THERMOPLASTICS

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Abstract

Shrinkage is one of the most important defects of injection molded plastic parts. Injection molding processing parameters have a significant effect on shrinkage of the produced parts. In the present study, the effect of different injection parameters on volumetric shrinkage of two polymers (high-density polyethylene (HDPE) semi-crystalline thermoplastics and polycarbonate (PC) as a representative of amorphous thermoplastics) was studied. Samples under different processing conditions according to a L_{27} orthogonal array of Taguchi experimental design approach were injected. Effect of material crystallinity on the shrinkage of injected samples was investigated. Obtained results revealed that semi-crystalline thermoplastics have larger shrinkage values in comparison with amorphous thermoplastics. Shrinkages of injected samples were also studied along and across the flow directions. Results showed that the flow path can dramatically affect the shrinkage of semi-crystalline thermoplastics. However for amorphous thermoplastics, results showed an independency of obtained shrinkage to flow direction. Analysis of variance (ANOVA) results illustrated that cooling time was the most effective parameter on shrinkage for both PE and PC injected samples; followed by injection temperature as the second important parameter. The optimum conditions to minimize shrinkage of injection molded samples are also achieved using signal to noise ratio (S/N) analysis.

Keywords: *Shrinkage, Polymers, Thermoplastic, Injection molding, Optimization, Taguchi approach*

1. INTRODUCTION

Plastic injection molding is a versatile manufacturing process suitable for mass production of plastics parts with complex geometries. The quality of the parts manufactured by injection molding process depends on different factors including material properties, mold design and processing parameters [1-3].

Shrinkage as a result of defects in the dimensional stability of the injection molded parts is one of the most effective factors on the quality of products during plastic injection molding process. Shrinkage plays a critical role in the final properties of a product especially in determining the final dimensions of injected part [4, 5]. This phenomenon has attracted more attention in recent years. Furthermore, it is well known that injection molding processing parameters significantly affect the shrinkage of plastics products [6]. In other word, optimization of processing parameters could be a promising solution to minimize shrinkage. Since there are many processing conditions as variable parameters and fully experimental investigation of them would be almost impractical, the design of experiments (DOE) is an appropriate statistical method for optimization of injection molding parameters in order to minimize shrinkage. Taguchi method as one of the most practical approach could be applied for this purpose.

There are several researchers that have studied the effect of injection molding processing parameters on the shrinkage. Chang and Fasion [7] investigated the effect of injection molding processing parameters on the shrinkage of three different plastics including high-density polyethylene (HDPE), general-purpose polystyrene (GPS) and acrylonitrile butadiene styrene (ABS) using Taguchi method. The results of their study showed that for HDPE as a semi-crystalline plastic more shrinkage occurred across the flow direction compared to along the flow direction. Also, they concluded that mold and melt temperatures were the most effective parameters on shrinkage for three plastics. Liao et al. [8] investigated optimal processing conditions of shrinkage and warpage of injection molding of a cellular phone cover (PC/ABS) using Taguchi method. Their results showed that packing pressure was the most important processing parameter affecting the shrinkage and warpage of the thin-walled part. Oktem et al. [9] investigated the application of Taguchi method for optimization of shrinkage in plastic injection molding process for a thin-shell part using Moldflow analysis. The results of their study showed that warpage and shrinkage improved about 2.17% and 0.7%, respectively by optimizing processing parameters including packing time, packing pressure, injection time and cooling time. Altan [10] investigated the optimal injection molding conditions for minimum shrinkage using Taguchi, ANOVA and neural network methods for polypropylene (PP) and polystyrene (PS). He considered different processing parameters and studied the influence of them on the shrinkage of injected samples. The results of his study showed that 260 °C of melt temperature, 60 MPa of injection pressure, 50 MPa of packing pressure and 15 s of packing time were the optimal conditions for minimum shrinkage of 0.937% for PP and 1.224% for PS. Also, he concluded that packing pressure and melt temperature were significant parameters for the PP and PS molding, respectively. Wang et al. [11] investigated the effect of injection processing parameters on shrinkage of polypropylene by utilizing a combination of the artificial neural network (ANN) method and Moldflow software. The simulation results showed that packing pressure and melt temperature were the most effective parameters on shrinkage of PP. Rahimi et al. [12] studied the effect of reprocessing on shrinkage of ABS. The results of their study showed that as the reprocessing cycles increased shrinkage decreased and also the proper blend for the least shrinkage was 50% whereas the best mechanical properties were achievable by the 20% blend. Chen et al. [3] proposed a systematic optimization model of processing conditions in plastic injection molding of PBT-2100 using Taguchi method, RSM and hybrid GA-PSO.

In the present study, the shrinkage of high-density polyethylene (HDPE) and polycarbonate (PC) as semi-crystalline and amorphous thermoplastics, respectively, was studied in injection molding process. The shrinkages of PE and PC were compared. Shrinkages along and across the flow direction were also investigated and the differences between them was discussed. Also, the effect of different processing parameters on volumetric shrinkages of both considered thermoplastics was studied using Taguchi method and analysis of variance (ANOVA). The optimal conditions for minimization of shrinkages of PE and PC were achieved using the signal to noise ratio (S/N) analysis of Taguchi method and compared to the obtained experimental results.

2. MATERIALS AND METHODS

2.1. Materials

HD-52518 grade of high density polyethylene (HDPE) supplied by Bandar Imam Petrochemical Co., (with density of 0.952 g/cm^3 and melt flow index of 18 g/10min) as a semi-crystalline thermoplastic and HOPELEX PC-1100U grade of commercial polycarbonate (PC) provided by Lotte Chemical Co., (with density of 1.2 g/cm^3 and melt flow index of 10 g/10min) as an amorphous thermoplastic were used in this research study.

2.2 Mold and Injection Machine

A 128 Ton NBM HXF-128 injection molding machine with L/D = 21.1, 37 mm of screw diameter and maximum injection pressure of 196 MPa has been utilized for production of injection molding samples. A double cavity rectangular-shape mold of 175 mm × 80 mm × 3.6 mm as shown in Fig. 1 was used to inject the samples. Some PE injected samples of this research work are presented in Fig. 2.

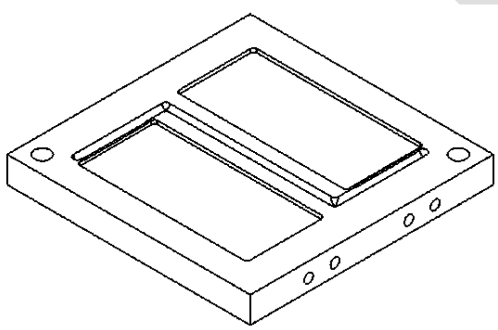

Fig. 1: Schematic view of the mold cavity used in injection molding

2.3 Design of Experiment (DOE)

Taguchi experimental design technique was selected to investigate the effect of parameters and their levels on response with the least experiments.

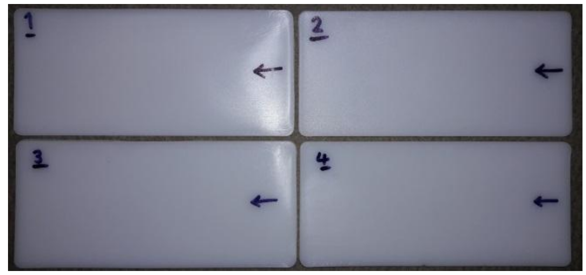

Fig. 2: The injected specimens of PE

Dr. Genichi Taguchi's approach to improve quality is currently the most widely used engineering technique in the world, recognized by virtually any engineer, though other quality efforts have gained and lost popularity in the business press [13]. The important of Taguchi design is that multiple factors can be considered at once and not only can controllable factors be measured but also noise factors could be considered. Using the Taguchi techniques, industries are able to greatly reduce product cycle time for both design and production, therefore total product cost reduces and profit will be increased. Moreover, Taguchi design allows looking into the variability caused by noise factors, which are usually ignored in the traditional DOE approaches [14].

In present study, according to related literatures [3, 7-12], the most important parameters affecting shrinkage of polymers were screened. The main processing factors selected to investigate their effect and their relevant levels for PE and PC are listed in Tables 1 and 2, respectively. According to the parameters and their levels, the selected L_{27} standard orthogonal array of this study is presented in Table 3. Data are analyzed using Minitab software.

Depending upon the objective of quality characteristic, various types of S/N ratio can be selected. In this study, the desired objective is lower values of shrinkage. So the smaller-the-better type of S/N ratio, as given below was applied for analyzing data:

$$S/N = -10\,log_{10}\left[\frac{1}{n}\sum_{i=0}^{n} x_i^2\right] \tag{1}$$

in which x_i is the value of quality characteristics for the i^{th} repetition, and n is the number of repetitions in a trial. Along with the S/N analysis, an analysis of variance (ANOVA) is required. ANOVA is a powerful technique in Taguchi method that determines meaningfulness and the contribution percent of factors affecting the response.

Table 1: Selected injection molding parameters and their levels for PE

	Variable	Level 1	Level 2	Level 3
1	Injection temperature (˚C)	175	180	185
2	Injection pressure (MPa)	80	85	90
3	Holding pressure time (s)	2	2.5	3
4	Cooling time (s)	20	30	40

Table 2: Selected injection molding parameters and their levels for PC

	Variable	Level 1	Level 2	Level 3
1	Injection temperature (˚C)	310	320	330
2	Injection pressure (MPa)	100	105	110
3	Holding pressure time (s)	2	2.5	3
4	Cooling time (s)	20	30	40

Table 3: the designed L_{27} orthogonal standard array of this study

Exp.	Injection temp.	Injection pres.	Holding press. time	Cooling time	Sample Code (PE / PC)
1	1	1	1	1	PE-1 PC-1
2	1	1	1	1	PE-2 PC-2
3	1	1	1	1	PE-3 PC-3
4	1	2	2	2	PE-4 PC-4
5	1	2	2	2	PE-5 PC-5
6	1	2	2	2	PE-6 PC-6
7	1	3	3	3	PE-7 PC-7
8	1	3	3	3	PE-8 PC-8
9	1	3	3	3	PE-9 PC-9
10	2	1	2	3	PE-10 PC-10
11	2	1	2	3	PE-11 PC-11
12	2	1	2	3	PE-12 PC-12
13	2	2	3	1	PE-13 PC-13
14	2	2	3	1	PE-14 PC-14
15	2	2	3	1	PE-15 PC-15
16	2	3	1	2	PE-16 PC-16
17	2	3	1	2	PE-17 PC-17
18	2	3	1	2	PE-18 PC-18
19	3	1	3	2	PE-19 PC-19
20	3	1	3	2	PE-20 PC-20
21	3	1	3	2	PE-21 PC-21
22	3	2	1	3	PE-22 PC-22
23	3	2	1	3	PE-23 PC-23
24	3	2	1	3	PE-24 PC-24
25	3	3	2	1	PE-25 PC-25
26	3	3	2	1	PE-26 PC-26
27	3	3	2	1	PE-27 PC-27

2.4 Experimental Procedure and Shrinkage Measurements

Using the dryer unit of injection molding machine , PE and PC granules were dried before injection at 80°C for 3 h and 120°C for 24 h, respectively, . During the injection experiments, each processing condition was allowed to stabilize entirely and then, 4 parts were injected at each processing condition (2 parts in one shot). Before measuring the shrinkage, samples were kept for at least 2 weeks to relax any residual stress. Measurements were performed using a digital caliper with an accuracy of 1 μm at 3 points in both length and width for each specimen. The average results were implemented in following equations to obtain longitudinal shrinkage (S_L), latitudinal shrinkage (S_W) and volumetric shrinkage S_V.

$$S_L = \frac{L_m - L_p}{L_m} \times 100 \tag{2}$$

$$S_W = \frac{W_m - W_p}{W_m} \times 100 \tag{3}$$

$$S_V = \frac{V_m - V_p}{V_m} \times 100 \tag{4}$$

where L_m, L_p, W_m, W_p, V_m and V_p represent mold length, part length, mold width, part width, mold volume and part volume, respectively. Note that to calculate S_V, sample thickness was assumed constant due to the negligible shrinkage along the thickness.

3. RESULTS AND DISCUSSION

The measured longitudinal shrinkage (S_L), latitudinal shrinkage (S_W) and volumetric shrinkage (S_V) of PE and PC samples under different processing conditions are presented in Table 4.

Results remarkably show that both longitudinal and latitudinal shrinkage are higher for PE compared to PC. The relaxation time, λ, is a characteristic parameter used to describe the viscoelastic nature of a polymer melt. Physically, a longer λ value (i.e., higher elasticity) means that it will take longer for the accumulated stress to relax [15]. Semi-crystalline polymers have a larger λ in comparison with amorphous polymers [16] consequently, induced stresses in semi-crystalline polymers need a longer time to relax. In other words, in crystallization step, more residual stresses remain in semi-crystalline polymers, which lead to a larger shrinkage than amorphous polymers. Semi-crystalline polymers have a greater difference in specific volume between their melt phase and solid (crystalline) phase. Under glass transient temperature (T_g), the relation of specific volume with temperature is exponential for a semi-crystalline polymer while it changes linearly in an amorphous polymer. This different behavior is another reason for higher shrinkage of semi-crystalline polymers in comparison with amorphous polymers [17]. In other words, polycarbonate has a higher dimensional stability than polyethylene.

3.1 Effect of flow direction

Fig. 3 presents the shrinkage of PE and PC in two different directions: along the flow direction (AL) and across the flow direction (AC). According to Fig. 3, PE latitudinal shrinkage (AC) is considerably higher than longitudinal shrinkage (AL) as reported by Chang et al. [8] and Jansen et al. [18]. This shows high dependence of PE on flow direction. In contrast, flow direction has no significant effect on PC shrinkage as acclaimed in previous researches on ABS, PS and PBT [18]. It means that PC fluid flow is somehow isotropic in contrast with non-isotropic fluid flow of PE which demonstrates higher dimensional stability of PC.

Latitudinal shrinkage variation across the injection (CG: close to the gate and FG: far from the gate) is illustrated for both PE and PC in Fig.

4. For both samples, shrinkage is increased with an increment of distance from gate due to the changes in pressure and temperature along the injection direction. Close to the gate (CG), pressure and temperature are high and the material is dense due to injection pressure and holding pressure and thus the shrinkage is low. As the melt flows forward (areas far from the gate (FG)), because of high reduction in pressure and temperature, the material is not as dense as areas close to the gate, therefore material shrinks more. The results conspicuously indicate more dependency of semi-crystalline to the distance from the gate.

Table 4: The results of longitudinal, latitudinal and volumetric shrinkages for PE and PC samples

Sample code	S_L (%)	S_W (%)	S_V (%)	Sample code	S_L (%)	S_W (%)	S_V (%)
PE-1	3.001	3.354	6.255	PC-1	0.810	0.740	1.544
PE-2	3.119	3.260	6.277	PC-2	0.784	0.740	1.518
PE-3	2.964	2.984	5.860	PC-3	0.797	0.746	1.537
PE-4	2.478	2.677	5.089	PC-4	0.790	0.683	1.468
PE-5	2.529	2.671	5.133	PC-5	0.804	0.671	1.469
PE-6	2.489	2.621	5.045	PC-6	0.797	0.677	1.469
PE-7	2.020	2.746	4.711	PC-7	0.770	0.639	1.404
PE-8	2.066	2.727	4.737	PC-8	0.767	0.702	1.464
PE-9	2.043	2.746	4.733	PC-9	0.768	0.671	1.434
PE-10	2.544	3.135	5.599	PC-10	0.790	0.746	1.530
PE-11	2.272	3.016	5.219	PC-11	0.758	0.765	1.517
PE-12	2.724	3.016	5.657	PC-12	0.774	0.755	1.524
PE-13	2.907	3.116	5.932	PC-13	0.781	0.715	1.490
PE-14	3.102	3.144	6.148	PC-14	0.781	0.715	1.491
PE-15	2.793	2.984	5.694	PC-15	0.785	0.714	1.490
PE-16	2.770	2.846	5.537	PC-16	0.675	0.646	1.317
PE-17	2.495	3.022	5.442	PC-17	0.672	0.690	1.357
PE-18	3.062	2.972	5.942	PC-18	0.672	0.668	1.337
PE-19	2.867	3.154	5.930	PC-19	0.707	0.665	1.367
PE-20	2.712	2.978	5.610	PC-20	0.710	0.602	1.307
PE-21	2.712	2.978	5.610	PC-21	0.685	0.712	1.392
PE-22	3.153	3.034	6.092	PC-22	0.724	0.652	1.371
PE-23	2.278	3.003	5.212	PC-23	0.732	0.652	1.380
PE-24	2.278	3.003	5.212	PC-24	0.727	0.654	1.374
PE-25	2.959	3.028	5.897	PC-25	0.712	0.746	1.453
PE-26	2.981	3.125	6.014	PC-26	0.724	0.715	1.433
PE-27	2.890	3.085	5.885	PC-27	0.718	0.730	1.443

3.2 Analysis of variance (ANOVA)

Analysis of Variance (ANOVA) method was carried out to investigate the effect of processing parameters on volumetric shrinkage. Fig. 5 describes the normal probability of data in the vicinity of diagonal line. As demonstrated, analyzed P-value is higher than 0.05 from which it can be deduced that all the obtained data follow a normal distribution. It is noteworthy that following the normal distribution is the prerequisite to be able to utilize ANOVA for different purposes.

ANOVA results for PE and PC are tabulated in Tables 5 and 6, respectively. Considering each parameter degree of freedom (DF) of 2 and 26 total DF, $F_{0.05, 2, 26}$ is calculated as 3.37 which is lower than F-value calculated for each parameter indicating the effectiveness of all parameters on PE and PC shrinkage.

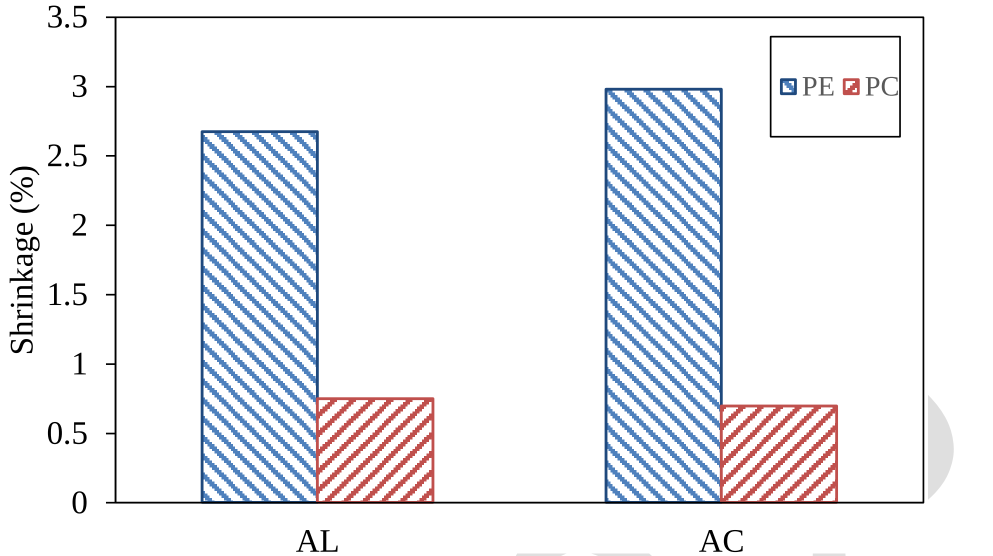

Fig. 3: Comparison between shrinkage of PE and PC along (AL) and across (AC) the flow direction

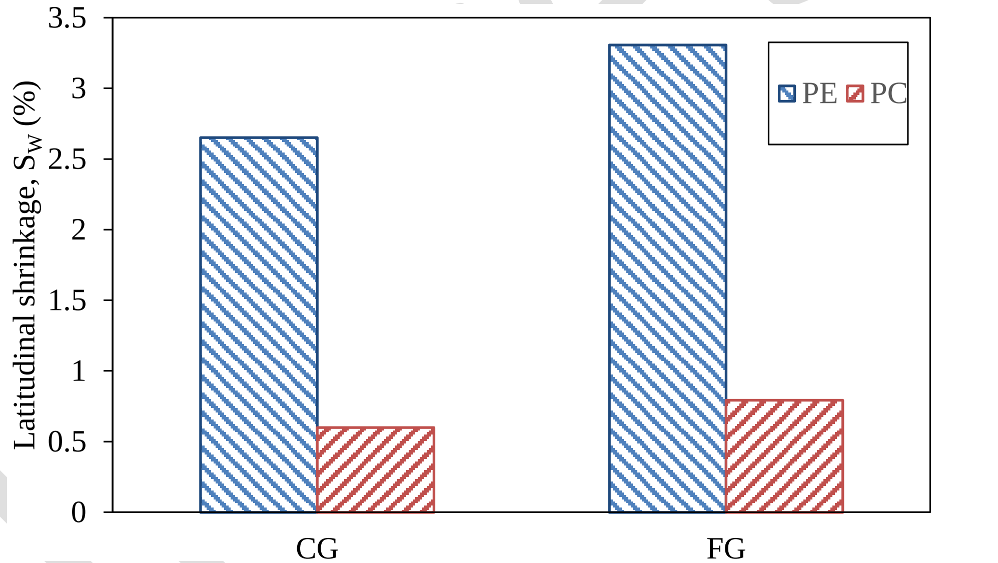

Fig. 4: Comparison between shrinkage in areas close to gate (CG) and far from the gate (FG)

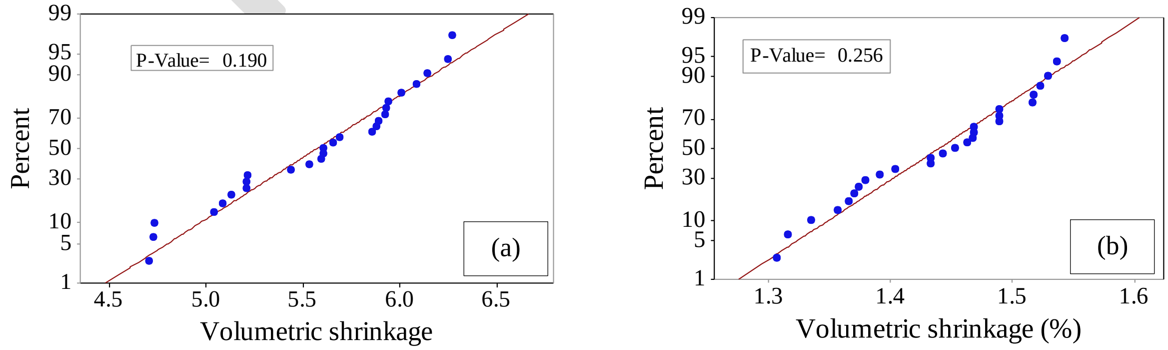

Fig. 5: Normal probability plot for a) PE and b) PC volumetric shrinkage

Table 5: ANOVA results for shrinkage of PE samples

Source	DF	SS	F-value	P-value	Contribution (%)
Injection temperature (°C)	2	0.9006	7.60	0.004	15.75
Injection pressure (MPa)	2	0.6007	5.07	0.018	10.50
Holding pressure time (s)	2	0.4768	4.02	0.036	8.34
Cooling time (s)	2	2.6741	22.56	0.000	46.76
Error	18	1.0668			18.65
Total	26	5.7191			100

Table 6: ANOVA results for shrinkage of PC samples

Source	D.F.	SS	F-value	P-value	Contribution (%)
Injection temperature (°C)	2	0.035666	45.54	0.000	27.36
Injection pressure (MPa)	2	0.019875	25.38	0.000	15.25
Holding pressure time (s)	2	0.020700	26.43	0.000	15.88
Cooling time (s)	2	0.047076	60.11	0.000	36.11
Error	18	0.007048			5.40
Total	26	0.130366			100

P-values also confirmed this outcome as it is less than 0.05 for all parameters. A P-value less than 0.05 indicate an intense overall influence on the response value. According to the ANOVA results, cooling time is the most effective parameter influencing PE and PC shrinkage with the contribution percentage of 47% and 36%, respectively. After that, injection temperature is the next most effective parameter affecting shrinkage of both PE and PC. For PE, injection pressure and holding pressure time are the other effective parameters, respectively, whereas this trend is contrariwise for PC. PE and PC error contribution percentage of 18.65% and 5.4% respectively is owing to the unconsidered processing parameters such as mold temperature and holding pressure.

3.3. Effect of processing parameters

Main effects of parameters on volumetric shrinkage of PE and PC samples are graphed in Figs. 6 and 7, respectively.

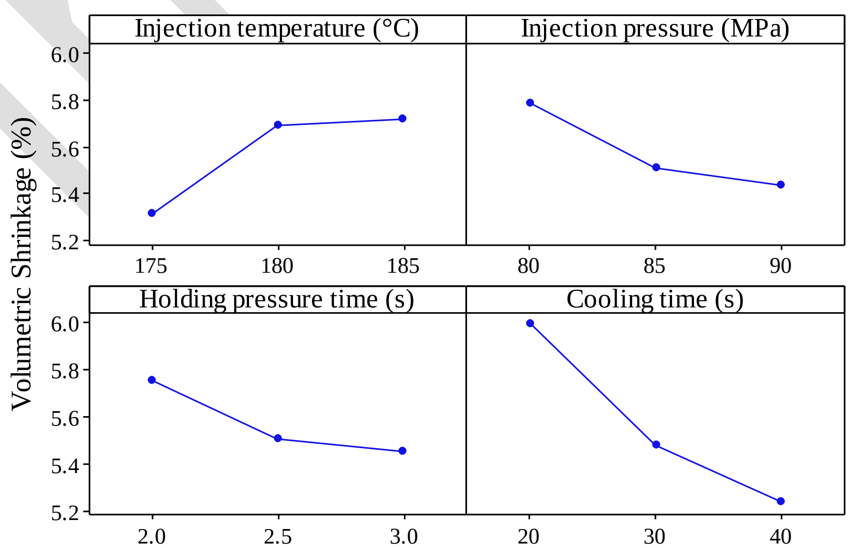

Fig. 6: Main effects of parameters on PE volumetric shrinkage

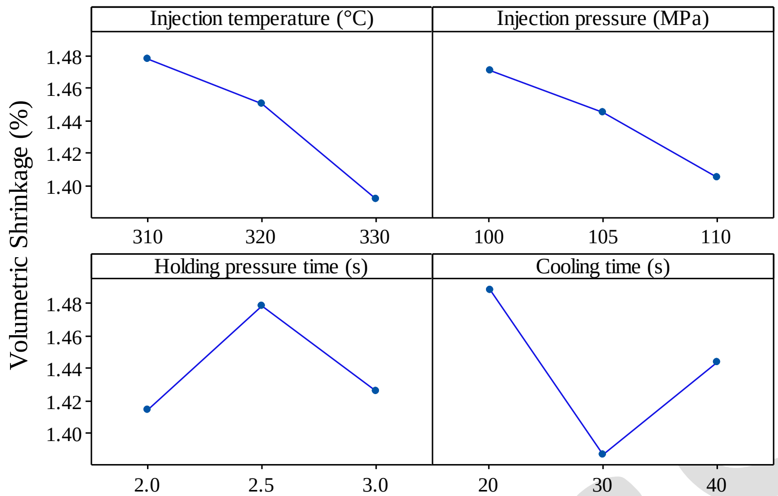

Fig.7: Main effects of parameters on PC volumetric shrinkage

As the results show, increasing injection temperature causes a rise in volumetric shrinkage of PE while PC volumetric shrinkage decreases. Increasing temperature in semi-crystalline PE leads to more disentanglement of molecular chains and while solidification occurs, shrinkage increases. On the other hand, with an increase in temperature, during cooling stage, the external layer of sample solidifies whereas the core melt is still hot and this causes more shrinkage of PE samples. However increasing temperature from 180 to 185 has no significant effect on PE volumetric shrinkage. Chang et al. [7] stated the same trend for ABS and HDPE.

Due to the amorphous nature of PC, temperature variations do not generate a noticeable effect on chains structure, only the melt viscosity decreases leading to easier mold filling and decreasing shrinkage due to material compacted in the mold, as has been previously stated for PS [10] and ABS [19].

Results extracted from Figs. 6 and 7, illustrate shrinkage descend by increasing injection pressure. Higher injection pressure results in higher material compression through the mold and as detailed before, shrinkage decreases. A similar procedure is reported by Wang [11] and Altan [10] for PP and PS, respectively.

According to the Fig. 6, PE shrinkage decreases by increasing holding pressure time and cooling time. Higher holding pressure time compensates the lack of material caused by densification and consequently shrinkage decreases. Previous researches declared similar results for PP [10, 11], PS [10] and ABS [7]. As same as holding pressure time, higher cooling time leads to lower shrinkage attributable to more time given to the sample for thermal and pressure stresses relaxation as reported for HDPE shrinkage in [7]. For amorphous polymers such as ABS [7] and PP [11], increasing cooling time increases shrinkage. This phenomenon is based on the arranged molecular chains in lower cooling rate [20]. Similar behavior is expected for PC, for which increasing cooling time from 30 s to 40 s, increases shrinkage. But in lower cooling times, from 20 s to 30 s, shrinkage decreases abnormally. Inverse behavior was observed for holding pressure time where shrinkage increased by increasing holding pressure time from 2 s to 2.5 s. Results of Table 3 clarifies that PC-25, PC-26, and PC-27 are samples processed in 2.5 s holding pressure time and 20 s cooling time with an injection temperature of 330°C (lowest viscosity) and an injection pressure of 110MPa (highest pressure). Formation of pleated material (see Fig. 9) is observed in these samples which lead to increase in shrinkage.

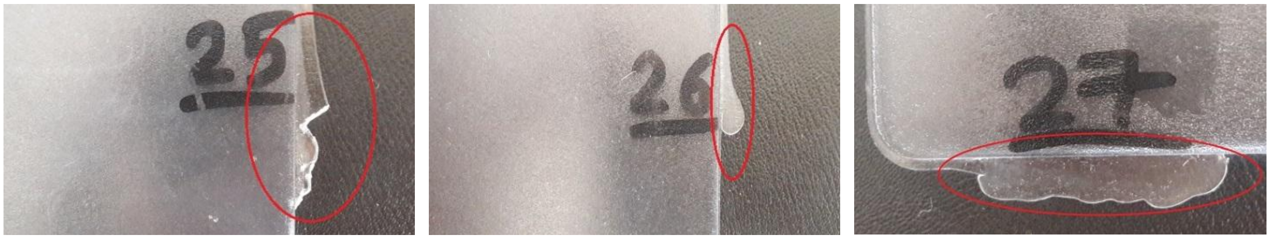

Fig. 9: The pleated PC samples with holding pressure time of 2.5 s and cooling time of 20 s

3.4. Signal to noise ratio (S/N) analysis

As previously stated, since the goal is minimizing the shrinkage, the signal to noise ratio (S/N) analysis was used in the smaller-better state. The results of S/N for PE and PC were shown in Tables 7 and 8, respectively. The higher difference between the values of S/N for parameter levels is a factor indicating that the output is changed significantly by changing the levels of that parameter. In other words, this fact illuminates that the parameter with larger delta (difference between maximum and minimum amount of S/N) is more effective on the response value [21]. The results of S/N analysis demonstrate that cooling time has the highest effect on shrinkages of both thermoplastics i.e. PE and PC similar to the obtained results of ANOVA. Also, injection temperature was the second parameter influencing the shrinkage of PE and PC. But the most important aim of the signal-to-noise analysis is obtaining optimal conditions for the best response which is the minimal shrinkage in the present study. The best level of a parameter for optimization of the output is the level with largest S/N value [22]. Therefore, in order to achieve the minimum PE shrinkage the levels of injection temperature, injection pressure, holding pressure time and cooling time must adjust on 1st, 3rd, 3rd and 3rd levels, respectively. Whiles this sequence is 3rd, 3rd, 1st and 2nd levels, respectively for minimum shrinkage of PC. Table 3 shows that the optimal conditions for PE are same with the processing conditions of PE-7, PE-8, and PE-9 samples while predicted optimum settings for PC are not included in the produced samples. One of the capabilities of Minitab software is predicting the response value in the optimum conditions. The predicted optimal shrinkage for PE and PC in the aforementioned conditions using Taguchi approach is 4.727% and 1.278%, respectively. Comparing between the predicted value for PE with results of Table 4 for PE-7, PE-8 and PE-9 emphasize that the Taguchi approach can optimize the shrinkage value with a high level of confidence.

Table 7: Signal to noise ratio analysis for shrinkage of PE

Level	Injection temperature	Injection pressure	Holding pressure time	Cooling time
1	-14.46	-15.23	-15.21	-15.56
2	-15.10	-14.81	-14.80	-14.77
3	-15.15	-14.66	-14.70	-14.38
Delta	0.69	0.57	0.51	1.18
Rank	2	3	4	1

Table 8: Signal to noise ratio analysis for shrinkage of PC

Level	Injection temperature	Injection pressure	Holding pressure time	Cooling time
1	-3.393	-3.337	-2.999	-3.454
2	-3.214	-3.190	-3.394	-2.834
3	-2.866	-2.947	-3.080	-3.185
Delta	0.528	0.390	0.395	0.620
Rank	2	4	3	1

5. CONCLUSIONS

In the present study, longitudinal, latitudinal and volumetric shrinkages of semi-crystalline and amorphous polymers were investigated in injection molding process. For this purpose, different PE and PC samples were produced under various processing parameters according to L_{27} orthogonal array of Taguchi approach. As a conclusion, the results demonstrated that semi-crystalline polymers significantly shrink more than amorphous polymers. Also, the flow direction had a meaningful influence on PE shrinkage in contrast to PC. For both polymers, the shrinkage of area which are far from the gate was greater than those that are close to the gate. The sensitivity of semi-crystalline polymers shrinkage to the distance from the gate was higher compared to amorphous polymers. Analysis of variance (ANOVA) results indicated that cooling time was the most effective parameter on shrinkage of both polymers following by injection temperature. By increasing cooling time, volumetric shrinkage of PE decreases while shrinkage of PC increases. In order to minimize shrinkage optimization of processing parameters was carried out using the signal to noise ratio (S/N) analysis. 175 °C of injection temperature, 90 MPa of injection pressure, 3 s of holding pressure time and 40 s of cooling time are the optimum conditions to minimize shrinkage of PE. These conditions were 330 °C of injection temperature, 110 MPa of injection pressure, 2 s of holding pressure time and 30 s of cooling time for PC. The results lightened Taguchi approach as an appropriate optimization method in injection molding process.

REFERENCES

1. Rosato, D.V. and Rosato, M.G., *Injection molding handbook*. 2012, Springer Science & Business Media.
2. Guo, W., Hua, L., Mao, H. and Meng, Z., *Prediction of warpage in plastic injection molding based on design of experiments. Journal of Mechanical Science and Technology*, 2012, 26(4), 1133-1139.
3. Chen, W.C., Nguyen, M.H., Chiu, W.H., Chen, T.N. and Tai, P.H., *Optimization of the plastic injection molding process using the Taguchi method, RSM, and hybrid GA-PSO. The International Journal of Advanced Manufacturing Technology*, 2016, 83, 1873-1886.
4. Kc, B., Faruk, O., Agnelli, J.A.M., Leao, A.L., Tjong, J. and Sain, M., *Sisal-glass fiber hybrid biocomposite: Optimization of injection molding parameters using Taguchi method for reducing shrinkage. Composites Part A: Applied Science and Manufacturing*, 2016, 83, 152-159.
5. Mohan, M., Ansari, M.N.M. and Shanks, R.A., *Review on the Effects of Process Parameters on Strength, Shrinkage, and Warpage of Injection Molding Plastic Component. Polymer-Plastics Technology and Engineering*, 2017, 56(1), 1-12.
6. Kramschuster, A., Cavitt, R., Ermer, D., Chen, Z.B. and Turng, L.S., *Effect of processing conditions on shrinkage and warpage and morphology of injection moulded parts using microcellular injection moulding. Plastics, rubber and composites*, 2006, 35, 198-209.

7. Chang, T. C., and Faison, E., *Shrinkage behavior and optimization of injection molded parts studied by the Taguchi method. Polymer Engineering & Science*, 2001, 41, 703-710.
8. Liao, S.J., Chang, D.Y., Chen, H.J., Tsou, L.S., Ho, J.R., Yau, H.T., Hsieh, W.H., Wang, J.T. and Su, Y.C., *Optimal process conditions of shrinkage and warpage of thin-wall parts. Polymer Engineering & Science*, 2004, 44, 917-928.
9. Oktem, H., Erzurumlu, T. and Uzman, I., *Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part. Materials & design*, 2007, 28, 1271-1278.
10. Altan, M., *Reducing shrinkage in injection moldings via the Taguchi, ANOVA and neural network methods. Materials & Design*, 2010, 31, 599-604.
11. Wang, R., Zeng, J., Feng, X. and Xia, Y., *Evaluation of effect of plastic injection molding process parameters on shrinkage based on neural network simulation. Journal of Macromolecular Science, Part B*, 2013, 52, 206-221.
12. Rahimi, M., Esfahanian, M. and Moradi, M., *Effect of reprocessing on shrinkage and mechanical properties of ABS and investigating the proper blend of virgin and recycled ABS in injection molding. Journal of Materials Processing Technology*, 2014, 214, 2359-2365.
13. Taguchi, G., Chowdhury, S. and Wu, Y., *Taguchi's quality engineering handbook*. 2005, Wiley.
14. Phadke, M.S., *Quality engineering using robust design*. 1995, Prentice Hall PTR.
15. Leung, S.N., Park, C.B., Xu, D., Li, H. and Fenton, R.G., *Computer simulation of bubble-growth phenomena in foaming. Industrial & engineering chemistry research*, 2006, 45, 7823-7831.
16. Yan, W., Fang, L., Heuchel, M., Kratz, K. and Lendlein, A., *Modeling of stress relaxation of a semi-crystalline multiblock copolymer and its deformation behavior. Clinical hemorheology and microcirculation*, 2015, 60, 109-120.
17. Sun, J., Liao, X., Minor, A.M., Balsara, N.P. and Zuckermann, R.N., *Morphology-Conductivity Relationship in Crystalline and Amorphous Sequence-Defined Peptoid Block Copolymer Electrolytes. Journal of the American Chemical Society*, 2014, 136, 14990-14997.
18. Jansen, K.M.B., Van Dijk, D.J. and Husselman, M.H., *Effect of processing conditions on shrinkage in injection molding. Polymer Engineering & Science*, 1998, 38, 838-846.
19. Kurt, M., Kaynak, Y., Kamber, O.S., Mutlu, B., Bakir, B. and Koklu, U., *Influence of molding conditions on the shrinkage and roundness of injection molded parts. The International Journal of Advanced Manufacturing Technology*, 2010, 46, 571-578.
20. Berkery, D.J., *Process monitoring for plastics injection molding* (Doctoral dissertation, Massachusetts Institute of Technology), 1993.
21. Azdast, T., Hasanzadeh, R. and Moradian, M., *Optimization of process parameters in FSW of polymeric nanocomposites to improve impact strength using step wise tool selection. Materials and Manufacturing Processes*, 2017, 33(3), 343-349.
22. Doniavi, A., Babazadeh, S., Azdast, T. and Hasanzadeh, R., *An investigation on the mechanical properties of friction stir welded polycarbonate/aluminium oxide nanocomposite sheets. Journal of Elastomers & Plastics*, 2016, 49(6), 498-512.