Experimental and Numerical Investigation of Injection Molding Main Parameters' Effects on Shrinkage and Warpage of a Thin Sheet Made of HDPE

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Abstract: Injection molding is one of the common processes for producing plastic parts. In this process, the mold is filled immediately and then the part and mold will be cooled down during the packing time. In the end, the part will be ejected from the mold. In this study, the effects of the most important processing parameters such as packing time, melt and mold temperature have been investigated on shrinkage and warpage of the products experimentally and numerically. According to previous reports, a thin sheet is defined by a length to thickness ratio of at least 100. MOLDFLOW software has been utilized to obtain the numerical results. For the empirical study, 64 specimens have been produced in different production conditions. These samples have been scanned by a 3D scanner and results have been analyzed by CATIA software. The findings show that increasing melt and mold temperature decreases the warpage amount and rises the shrinkage in the specimens. Also increasing the packing time up to 2 seconds increases the warpage and decreases the shrinkage noticeably but in longer packing times the variations will be less remarkable. Moreover, findings show that the general trend in simulated and experimental results are similar in all reported values of shrinkage and warpage, in which the maximum calculated errors for both of them are approximately 10%.

Keywords: HDPE, Injection Molding, Melts and Mold Temperature, Packing Time, Shrinkage, Warpage

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Research paper

1 INTRODUCTION

Distortion and shrinkage in injected plastic parts are the most important production problems in producing thin sheet plastic parts. Prediction and control of these defects before production always get lots of attention. First Challenge is to predict the flow behavior of the polymeric melt through a thin-walled mold especially when it contains different kinds of fibers [1-2]. Shrinkage is a natural phenomenon in the injection molding process. It is happening because material's volume will change while the temperature decreases from the processing temperature to ambient temperature. During the injection molding and after the ejection of part out of mold, its dimensions are changing which will make internal stresses in the part.

Residual stress affects the product like an exterior stress. If residual stress overcomes the strength of the material during the molding, part will be twisted while it is ejecting from the mold. Shrinkage of molded plastic parts can be up to 20% of its volume [3]. Warpage is the result of residual stress which is due to different shrinkage of ingredient materials of the molded part or dissimilar cooling conditions in different surfaces of the product which also could happen because of various thicknesses in different sections of the specimen. If shrinkage be the same all over the part, there will not be a deformation or warpage in it. It means that the part simply becomes smaller without any visible defects. However low or non-uniform shrinkage in the part is inevitable based on the existence and interaction of many factors such as molecular orientation and or even fiber orientation, cooling of mold, design of part and mold and condition of the process [4-6]. The other important factor which will warp the product is the unbalance cooling condition in different parts of the mold [7].

Researches about shrinkage and warpage have been done on different materials. S.J.Liao used C-Mold software to measure effect of different parameters on shrinkage and warpage. Mold temperature, melt temperature, packing pressure and injection speed have been identified as effective parameters on shrinkage and warpage. Results showed that packing pressure had the most effect on process parameters [8]. W.H.Hsieh et al predicted warpage and shrinkage of thin walled injection parts by artificial neural network. This research was successful in prediction of shrinkage and warpage of thin walled injection parts by propagation of artificial neural network [9]. Babur Ozcelik investigated analysis of full factorial combination of three levels of process parameters by finite element method. In this case, results showed that warpage improved by 40.4% [10]. Hasan Kurtaran worked on efficient warpage optimization of thin shell plastic parts using response surface methodology and genetic algorithm. Bus ceiling lamp base was considered as thin-walled part. Results showed mold temperature, melt temperature and packing pressure, have the most effect on warpage while cooling time has minimum effect on warpage [11]. Hasan Oktem presented Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part. For this purpose, some analysis of Moldflow software was done in three levels. The signal to noise ratio and analysis of variance (ANOVA) have been used to identify the optimum levels of process parameters on shrinkage and warpage. Based on results of ANOVA analysis, packing pressure, injection time and cooling time respectively, have the most effect on warpage [12].

Ko-Ta Chiang and Fu-Ping Chang presented analysis of shrinkage and warpage in an injection-molded part with a thin shell feature using the response surface methodology. Results show that shrinkage has declined about 37.8% and warpage has reduced about 53.9% comparing with initial condition [13]. M.C.Song et al researched on effects of injection process parameters on the molding process for ultra-thin wall plastic parts [14]. Chih-Hung Tsai presented simulation and experimental study in determining injection molding process parameters for thin-shell plastic parts via design of experiments analysis. The most important factors in simulation and experiments were discovered as melt temperature and packing pressure [15]. Chih-Cherng chen worked on analysis and modeling of effective parameters for dimension shrinkage variation of injection molded part with thin shell feature using response surface methodology [16]. Babur ozcelik and Ibrahim Sonat showed warpage and structural analysis of thin shell plastic in the plastic injection molding. They investigated the structural analysis of a mobile cover [17].

Yuh-Chyun chiang et al worked-on Warpage phenomenon of thin-wall injection molding. Based on the results, the most influential parameter on warpage of ABS and ABS+PC is mold temperature. So it has been concluded that low melt temperature, high injection speed and high injection pressure can prevent warpage during thin walled molding [18]. N.A.shuaib et al declared that packing time is the most effective parameter on warpage and the effect of other factors are moderate [19]. Daniele Annicchiarico et al offered a methodology for measurement of shrinkage in micro-injection molding for the first time and investigated the effect of processing parameters on shrinkage. The results showed that this method is capable of identifying the factors which have noticeable effects on shrinkage [20]. In continue they tried to optimize the injection process conditions in the way to minimize the shrinkage and maximize the part mass. As a corollary, they found that the melt and mold temperature beside the holding pressure are the most important factors on shrinkage in micro injecting molding [21]. Jafarian Jam et al, investigated the effect of part wall thickness on shrinkage and out of roundness in products numerically and experimentally. The results showed that by increasing the wall thickness, the shrinkage and out of roundness will also raise which is because of the higher temperature of the final product when it is ejected from the mold [22]. In another experimental study undertaken by Sobhani and Jafarian Jam, the effect of packing time and melt temperature, as the most important processing parameters in injection molding, was investigated on a thin sheet Wood-Plastic composite. It has been reported that by increasing the packing time and lowering the melt temperature, the shrinkage will reduce [23].

Davide Masato et al analyzed the shrinkage of an injection molded product with fiber-reinforced thin-wall. They also investigated the relation between the short glass fibers distribution within the part and the dimensional accuracy by utilizing X-ray computed tomography. The founding showed that melt temperature and packing pressure were the most remarkable processing parameters that affect shrinkage of a thin-wall part [24]. Manoraj Mohan et al through a comprehensive review work assessed the effects of process parameters on different specifications of the produced parts such as strength, shrinkage and warpage. Different case studies, materials and production conditions were discussed through the paper and it was reported that the mold temperature and packing pressure are the most effective parameters on the shrinkage and warpage [25].

Gurjeet Singha and Ajay Vermaa published a brief review of manufacturing process of injection molding and analyzed the term quality through their work by studying the performance parameters and different methods [26]. Yun Wang et al performed a numerical optimization of shrinkage and warpage in an injection molding process and reported the optimum conditions for melt and mold temperature, filling time, holding pressure and holding time [27]. In another study, M H N Hidayah et al, optimized the warpage on plastic parts by using Response Surface Methodology and controlling variable parameters of the process such as melt and mold temperatures, packing pressure and time. Finally they have claimed to succeed in optimizing the warpage by %34.66 [28]. Moonwoo La et al investigated the effects of some of the main processing parameters such as flow rate, melt and wall temperatures on the quality numerically and experimentally. The outcome showed that increasing these three parameters improves the transcription quality of micro-pillar arrays [29].

M. Abbasalizadeh et al, in a research work studied the effect of different injection parameters on volumetric shrinkage of two polymers; high-density polyethylene and polycarbonate. 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 [30]. Sreedharan and Jeevanantham through an optimization process, tried to investigate the effects of some processing parameters such as injection pressure, gate size and cooling system on final shrinkage of the injection molding parts used in automobile applications. The results showed that the cooling time has the most important role on shrinkage of the parts [31]. Yue Wu et al, in a study investigated the effect of microscopic structures on the shrinkage of macroscopic product. Flat specimens with and without microstructures were injection molded and the distribution of in-plane shrinkage was measured using an optical method. In the case without microstructures, anisotropic shrinkage is observed and the shrinkage magnitude increases with the distance from the gate. By applying the microstructures, the shrinkage could be reduced significantly, and the effect is especially noticeable when lower packing pressure was applied in the injection molding process [32].

Erdal Öztürk et al, in a paper designed a mold and molding process and selected high-density polyethylene for gear material. Firstly, they determined shrinkage factor in a preliminary circular mold. Next, based on the experimentally verified shrinkage factor a gear cavity was cut by EDM and injection process was used to produce plastic test gears. After visual inspections of the molded plastic gears, tip diameter like preliminary measurements were accomplished on the plastic gears [33]. Khosravani and Nasiri utilized case-based reasoning (CBR) system as an artificial intelligence (AI) approach for knowledge representation and manipulation which uses successful solutions of past problems as a candidate solution for a given problem in injection molding manufacturing process [34].

Zhiyuan Song et al, like many other researchers, considered the shrinkage and warpage as the most important indicators of the quality in thin-walled parts in injection molding process. They investigated the effects of some of the main parameters in this process such as mold and melt temperature, injection time, holding time and cooling time based on neural network. The results showed that the melt temperature, holding time and cooling time are the most important factors on the warpage and volume shrinkage [35]. Bikram Solanki et al, carried out an analysis using Autodesk Moldflow Insight 2019.05 to find the best gate locations and flow resistance along with a polypropylene (PP). The numerical and experimental study was conducted to evaluate the effect of packing pressure, packing time, and melt temperature on diametric shrinkage, mass, and sink marks of PP gear. The results show that by increasing packing pressure and packing time, the diametric shrinkage decreased but mass increased. However, as the melt temperature increased the diametric shrinkage also increased but the mass decreased [36].

M. Ramesh and K. Panneerselvam, investigated the manufacturing parameters in order to improve the quality characteristics of the injection molding of HDPE-PBI composite samples. The quality aspects controlled were shrinkage and warpage and the parameters considered as factors were melting temperature, Injection pressure and cooling time. Using the Taguchi Optimization method, the injection molding process was performed and the optimum injection pressure and temperature were found. The influence of parameters was studied through this research using analysis of variance [37]. İdris Karagöz in a study determined the effect of mold surface temperature on plastic parts in injection molding of high-density polyethylene materials. The mechanical tests, thermal tests, and gloss measurements by a gloss meter were performed on samples and the amount of warpage and collapses were measured by a video measuring system. Microstructures were examined under a scanning electron microscope. It was observed that the mold surface temperature increased the crystallization rate, tensile and bending strength of the materials decreased the thicknesses of the crystal lamella, and impact strength had an effect on the melting temperature of the crystal [38].

İdris Karagöz1 and Özlem Tuna in a reseach work focused on the effect of melt temperature on as-injection molded product made of high-density polyethylene samples and examined their mechanical, thermal, and morphological and surface quality properties. The results showed that higher melting temperature lowered crystallization rate and decreased the strength of tensile and bending; however, it increased crystal lamellar thickness and impact strength [39]. César Leyva-Porras et al, determined, the effect of processing variables on the microstructure and crystallinity of injection-molded LDPE specimens. The polymer was injected at different temperature conditions in the barrel and the mold. The specimens were characterized by scanning electron microscopy and X-ray diffraction. With the data obtained, an analysis of variance was carried out. The results showed that the interaction of the two temperatures has the greatest effect on the size of the spherulite, while the temperature of the mold affects the crystallinity [40]. Norshahira Roslan et al, in a study work utilized an optimisation method to optimise processing parameters of molded parts using recycled materials. In this study, Response Surface Methodology (RSM) and Particle Swarm Optimisation (PSO) methods were conducted on thick plate parts moulded using virgin and recycled low-density polyethylene (LDPE) materials. They showed that shrinkage in the x and y directions increased in correlation with the recycled ratio, compared to virgin material.

Meanwhile, the tensile strength of the thick plate part continued to decrease when the recycled ratio increased [41]. Chidambara Kuttalam Kailasanathan et al, in research, studied the warpage of thin-walled parts made of polyoxymethylene-talc composite in injection-molding process. Samples were prepared with various weight fractions of talc to investigate the reduction in warpage and its effect on mechanical properties such as tensile, compressive, impact, and thermal properties like Vicat softening point and heat deflection temperature (HDT). The uniform distribution of talc fillers is confirmed in Fourier transform infrared (FTIR) examinations. The talc is found to act as a nucleation agent and affect the crystallinity of POM. It is found from differential scanning calorimetry (DSC) analysis that the percentage of crystallinity is increased with respect to the weight percent of talc fillers [42].

As it mentioned above, there are plenty of research works on this field but there is lack of information about empirical results especially on thin products which are more vulnerable to warpage and shrinkage and our main scope in this study is to better understand the main specifications of this process, with the aim of producing the high-quality products with the least possible wastage. The main goal of this study, in continue of the previous research works of the authors, is to investigate the effect of mold temperature, melt temperature and packing time on shrinkage and warpage of thin-walled high density polyethylene (HDPE) parts both experimentally and numerically. These parameters have been chosen based on above mentioned literature review and are believed to be the most effective parameters on shrinkage and warpage of a thin sheet HDPE product through injection molding process.

2 EXPERIMENTATIONS

2.1. Materials

High density polyethylene (HDPE), grade I3, with MFI of 8.23 g/10min (190ºC / 2.16 kg) produced by Arak Petrochemical Co. was used as the polymeric material. More details about this polymeric matrix are shown in “Table 1”.

2.2. Design of Experiments

Based on the material specifications, melt temperature, mold temperature and packing time are considered to be as “Table 2”.

Table 1 Typical properties of HDPE, grade I3

Property	Unit	Typical Value	Test Method
Physical			
Melt Flow Rate (190 °C /2.16 Kg)	g/10 min	8.23	ISO 1133
Density	g/cm^3	0.957	ISO 1183
Mechanical			
Tensile strength @ yield	MPa	29	ISO 527
Tensile strength @ break	MPa	30	ISO 527
Elongation @ break	%	>1000	ISO 527
Hardness Shore D	-	64	ISO 868
ESCR (FNCT) @ 2.5 MPa	h	1.5	ISO CD 16770
Charpy Notch Impact Strength	Kj/m^2	3	ISO 179
Thermal			
Vicat Softening Temperature	°C	72	ISO 306
Melting Point	°C	138	ISO 3146

Table 2 Details of designing of experiments

Variable	Sign	Levels			
		1	2	3	4
Mold Temperature, °C	A	30	35	40	45
Melt Temperature, °C	B	190	200	210	220
Packing Time, Sec	C	1	2	3	4
Total Experiments		4×4×4 = 64			

In “Table 2”, A is mold temperature, B is melted temperature and C refers to packing time. Each number from 1 to 4 refers to one level for each parameter. It means there are 4 levels for each parameter. Design of experiments has been done based on full factorial method and all 64 experiments have been done and results of simulations and assessment of produced specimens have been analyzed and compared with each other. “Table 3” shows the specimens’ numbers and codes.

Table 3 Specimens’ numbers and codes

Specimen Number	Specimen Code	Specimen Number	Specimen Code
1	A1B1C1	33	A3B1C1
2	A1B1C2	34	A3B1C2
3	A1B1C3	35	A3B1C3
4	A1B1C4	36	A3B1C4
5	A1B2C1	37	A3B2C1
6	A1B2C2	38	A3B2C2
7	A1B2C3	39	A3B2C3
8	A1B2C4	40	A3B2C4
9	A1B3C1	41	A3B3C1
10	A1B3C2	42	A3B3C2
11	A1B3C3	43	A3B3C3
12	A1B3C4	44	A3B3C4
13	A1B4C1	45	A3B4C1
14	A1B4C2	46	A3B4C2
15	A1B4C3	47	A3B4C3
16	A1B4C4	48	A3B4C4
17	A2B1C1	49	A4B1C1
18	A2B1C2	50	A4B1C2
19	A2B1C3	51	A4B1C3
20	A2B1C4	52	A4B1C4
21	A2B2C1	53	A4B2C1
22	A2B2C2	54	A4B2C2
23	A2B2C3	55	A4B2C3
24	A2B2C4	56	A4B2C4
25	A2B3C1	57	A4B3C1
26	A2B3C2	58	A4B3C2
27	A2B3C3	59	A4B3C3
28	A2B3C4	60	A4B3C4
29	A2B4C1	61	A4B4C1
30	A2B4C2	62	A4B4C2
31	A2B4C3	63	A4B4C3
32	A2B4C4	64	A4B4C4

2.3. Mold and Injection Molding Equipment

To produce thin sheet specimens, an injection mold with two cavities has been designed and made for the experimental study of this research work. The mold is made of ST37 steel and all the fixed and moving parts are made of MO40 steel. Figure 1 shows the injection mold and its cavities.

Fig. 1 The injection mold used for producing the specimens.

By using a 120 tons injection molding machine, the HDPE granules were injected into the mold to produce parts. The machine is a HBL which is made in Germany and has a PORHCHESON controller with the model number of PS800AM. Figure 2 shows a schematic design of the part. Also, a sample picture from one of the produced specimens has been shown in “Fig. 3”

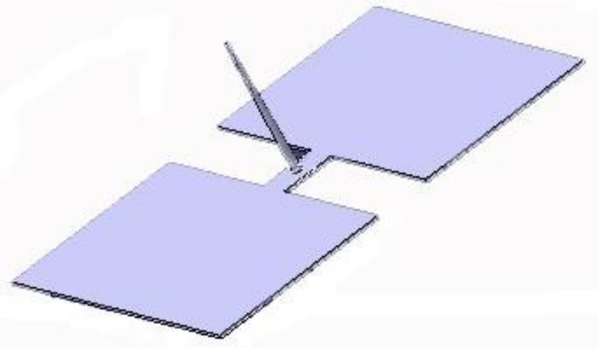

Fig. 2 Schematic design of the part.

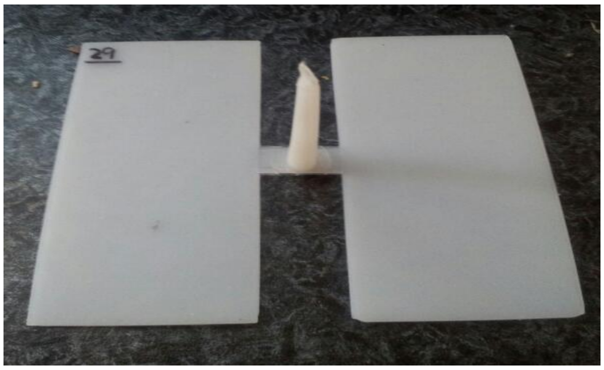

Fig. 3 A sample picture from one of the produced specimens

2.4. 3D Scanning

In order to 3D scanning, the specimens were placed on a white surface (Using this surface is for better accuracy). Then some round tags were stuck on the specimens. Finally, the specimens were covered by dioxide titanium spray to make communications between the cameras and tags, the tags should be cleaned. By using REXCAN CS+, a 3D scanner made by Solutionix, the cloud of points was generated and exported to a CAD drawing file and the values and dimensions were measured. Figure 4 shows the 3D scanner which has been used for scanning the specimens. The scanner uses two industrial cameras and one light source which can scan the specimens from different views. Figure 5 shows the 3D scanning of some specimens.

After obtaining cloud points file and transferring them into CATIA software, all dimensions and measured samples are in cloud points format and then warpage that is shown in “Fig. 5” will be obtained. Shrinkage can be calculated by Equation (1).

$$S = \left(\frac{L_{cavity} - L_{part}}{L_{cavity}}\right) \times 100 \tag{1}$$

Where L_{cavity} is cavity length and L_{part} means the longer length of the part [43].

Fig. 4 3D Scanner used for scanning the specimens.

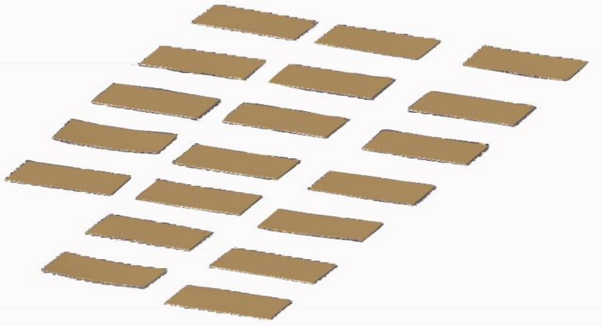

Fig. 5 Exported CAD file showing the 3D scanning of some specimens.

2.5. Numerical Simulation

After doing the experimental study on the specimens, simulation has been done. Software simulation was performed by MOLDFLOW software. Figure 6 shows the simulated specimen and the cooling system of the mold which have been modeled in MOLDFLOW software.

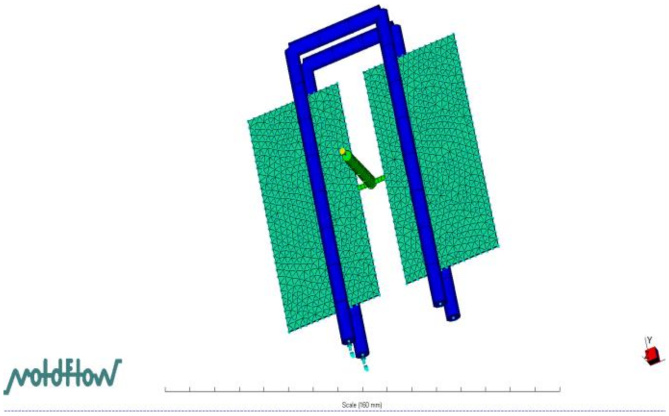

Fig. 6 Cooling system of the mold used in injection molding process.

3 RESULTS AND DISCUSSION

As it can be seen in the following diagrams in Figure 7, the effects of changing three important processing parameters such as packing time, melt and mold temperatures on shrinkage of resulted products in an injection process have been reported experimentally and also by simulating the process. Figure 7 shows the results for shrinkage.

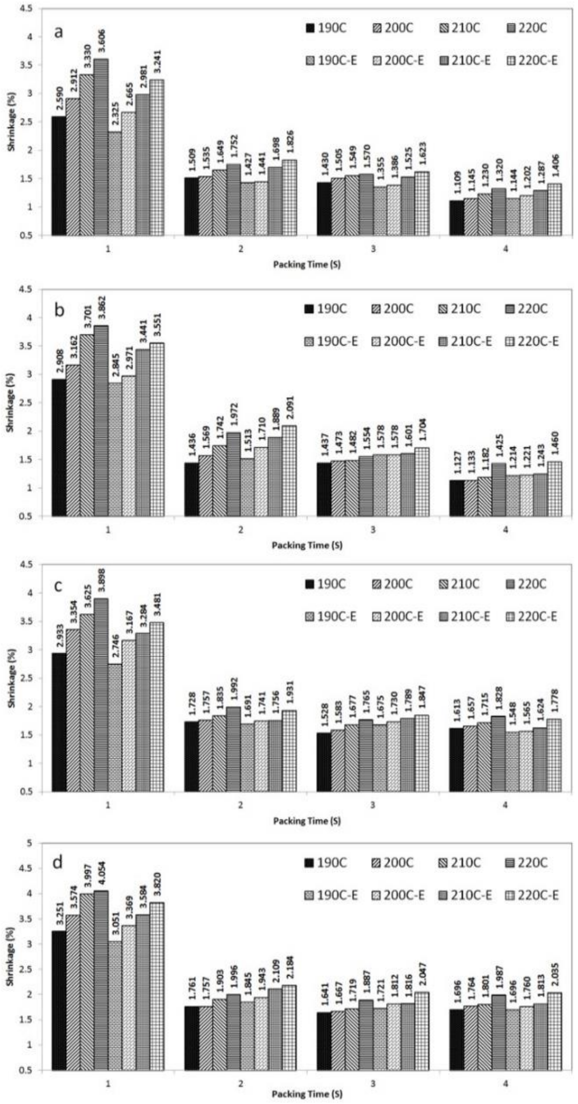

Fig. 7 Effect of packing time on shrinkage in different Melt and Mold temperatures: (a): Mold temperature 30°C, (b): Mold temperature 35°C, (c): Mold temperature 40°C, and (d): Mold temperature 45°C.

There are four diagrams labeled with a, b, c and d which are related to 4 different mold temperatures (30°C, 35°C, 40°C and 45°C respectively). In each diagram, the shrinkage percentage has been reported for 4 different packing times from 1sec up to 4sec. There are also 8 reported values in each packing time in which the first 4 values represent the results originated from the simulation with different melt temperatures varied from 190°C up to 220°C and the rest values belong to the experimental results measured from the produced specimens in the same range of melt temperatures mentioned above.

It should be mentioned that the experimental results have been specified with the letter “E” at the end of their series’ name in the legends of the diagrams. As it can be seen in Figure 7, the maximum amount of shrinkage can be detected in 1sec packing time which is noticeably higher than other packing times. In other words, by increasing the packing time from 1sec to 2sec, the amount of shrinkage will be decreased dramatically and this reduction will continue with a much milder slope from 2sec up to 4sec. The reason is that the difference between melt and mold temperature is very high in the first seconds after filling the mold cavity, so the mold body and cooling system of the mold are absorbing more thermal energy from the specimen and will cause a more rapid reduction in temperature which will cause a noticeable decrease in shrinkage of the product. After a 2sec packing time, this phenomenon will be much weaker and so its effect on the final shrinkage will be less remarkable.

It can be concluded from “Fig. 7” that by increasing the mold temperature, the amount of shrinkage will be increased. It seems that this trend is stronger in lower packing time and mold temperature. In other words, increasing the mold temperature from 30°C to 35°C in 1sec packing time will increase the shrinkage more rapidly than raising mold temperature from 40°C to 45°C in 4sec packing time. The main reason for this occurrence is that by increasing the mold temperature, forming of the crystalline structure in the specimen will be put off and so the shrinkage will be increased. Moreover, adding 5°C to the mold temperature of 30°C means raising the temperature by %16.7 which is much remarkable than increasing the mold temperature from 40°C to 45°C which is equal to an augmentation of %12.5.

So, it is reasonable to expect more shrinkage in the former condition. Figure 7 also shows that by increasing the melt temperature, the amount of shrinkage will be increased. Again, this movement is stronger in lower packing times. In other words, the effect of melt temperature on shrinkage is less noticeable in higher amount of packing times. The reason for this observation is similar to what has been explained for the mold temperature. As it can be expected, the effect of increasing melt temperature in higher packing times is less noticeable than lower ones, and the reason is that in higher packing times, the specimen has more time to cool down in the mold cavity which will compensate the effect of higher melt temperature.

The other finding from Figure 7 is the difference between simulated and experimental results. As it can be seen, the general trend is same in all reported values. It can also be seen that the shrinkage values from simulation are higher than experimental values in 1sec packing time, but in higher packing times this will be vice versa, which means that the experimental shrinkage values are higher than simulated results. The maximum amount of error between experimental and simulated values is equal to %10.82 and is calculated for the specimen with the melt and mold temperature of 210°C and 45°C respectively, with the packing time of 2sec (specimen number 58).

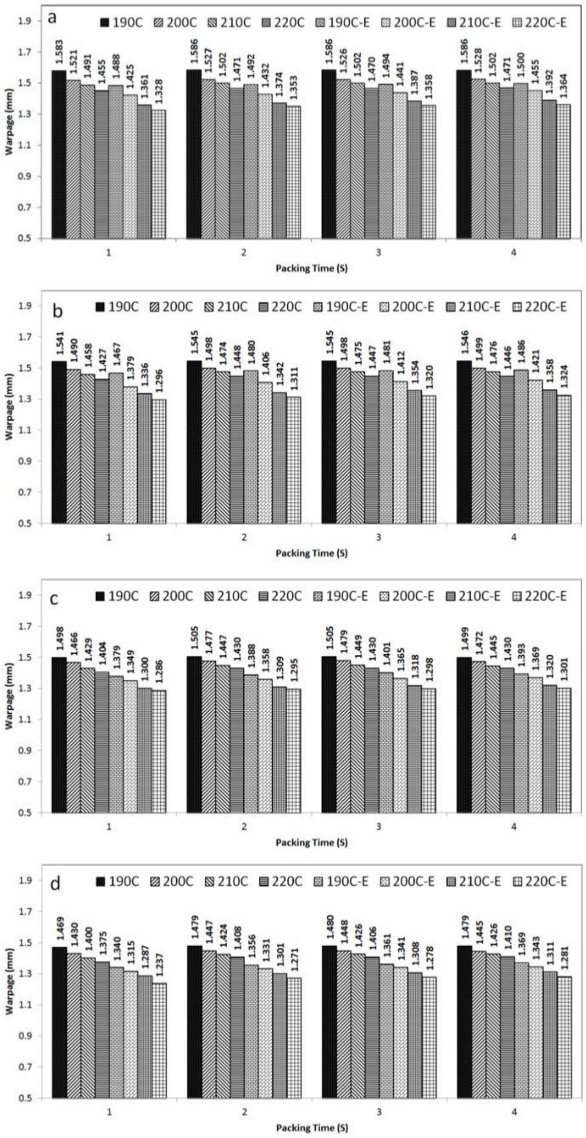

Fig. 8 Effect of packing time on warpage in different Melt and Mold temperatures: (a): Mold temperature 30°C, (b): Mold temperature 35°C, (c): Mold temperature 40°C, and (d): Mold temperature 45°C.

The same investigation has been done on studying warpage experimentally and by simulating the process and the results are presented through the following diagrams in Figure 8.

So, the effects of packing time, melt and mold temperatures are studied on warpage of the products in an injection process. There are four diagrams in Figure 8 , which are labeled with a, b, c and d that are related to 4 different mold temperatures (30°C, 35°C, 40°C and 45°C respectively).

In each diagram the warpage amount has been reported for 4 different packing times from 1sec up to 4sec. There are also 8 reported values in each packing time, in which the first 4 values represent the results originated from the simulating of the injection process with different melt temperatures varied from 190°C up to 220°C, and the rest values belong to the experimental results measured directly from the produced specimens in the same range of melt temperatures mentioned above. It should be mentioned that the experimental results have been specified with the letter “E” at the end of their series’ name in the legends of the diagrams.

As it can be seen in Figure 8, by increasing the packing time from 1sec into 2sec, a significant rise in warpage amount will take place and beyond 2sec mostly the variations are not remarkable. In other words, by increasing the packing time from 2sec up to 4sec, the amount of warpage will not change noticeably in the specimens.

The most probable reason for this occurrence is that the difference between the mold and melt temperature is high and in the first 2 seconds the specimen will be cooled down rapidly and the crystalline structure forms and so increasing the packing time beyond 2 seconds will not change the warpage notably. It can be concluded from Figure 8 that by increasing the mold temperature the amount of warpage will be decreased. It is because of the reduction in difference between melt and mold temperature which will lower the thermal shock in the melt flow front and the resulted residual stress and lessen the total warpage in the specimens.

It seems that this trend is the same in different packing times. It should be noted that overheating the mold to higher amounts with the hope of decreasing the thermal shock of the hot material during the injection of polymer melt into the mold cavity, is not a rational method for decreasing the residual stress in the specimens. On the other hand, it exacerbates the condition and causes a dramatic decrease in the effect of packing time on the warpage of the final products.

Figure 8 also shows that increasing the melt temperature decreases the amount of warpage. The main reason for this occurrence is that by increasing the melt temperature, formation of the crystalline structure will be delayed and so the stresses in the specimen will be relieved and the final warpage declines. Moreover, this reducing trend is stronger in lower mold temperatures. In other words, the effect of melt temperature on warpage is less noticeable in higher mold temperatures. The other finding from "Fig. 8" is the difference between simulated and experimental results. As it can be seen, the general trend is same in all reported values. It can also be seen that the warpage values from simulation are higher than experimental values in all packing times. The maximum amount of error between experimental and simulated values is equal to %10.03 and is calculated for the specimen with the melt and mold temperature of 220°C and 45°C, respectively, with the packing time of 1sec (specimen number 61).

4 CONCLUSIONS

In this study, a large number of specimens were produced to evaluate the effect of packing time, melt and mold temperature on shrinkage and warpage of the products and the results concluded the followings:

- By increasing the packing time from 1sec to 2sec the amount of shrinkage will be decreased dramatically and this reduction will continue with a much milder slope from 2sec up to 4sec. It can be concluded that after a 2sec packing time, its effect on the final shrinkage will be less remarkable.
- By increasing the mold temperature, the amount of shrinkage will be increased. This trend is stronger in lower packing time and mold temperatures. The main reason is that by increasing the mold temperature, forming of the crystalline structure in the specimen will be put off and so the shrinkage will be increased.
- By increasing the melt temperature, the amount of shrinkage will be increased. The effect of increasing melt temperature in higher packing times is less noticeable than lower ones, and the reason is that in higher packing times, the specimen has more time to cool down in the mold cavity which will compensate the effect of higher melt temperature.
- Finding shows that the general trend in simulated and experimental result is similar in all reported values of shrinkage and the maximum calculated error is %10.82.
- By increasing the packing time from 1sec into 2sec, a significant rise in warpage amount will take place and beyond 2sec mostly the variations are not remarkable. The reason is that the difference between the mold and melt temperature is high and in the first 2 seconds the specimen will be cooled down rapidly and the crystalline structure forms and so increasing the packing time beyond 2 seconds will not change the warpage notably.
- By increasing the mold temperature, the amount of warpage decreases as the reduction in difference between melt and mold temperature which will lower the thermal shock and the resulted residual stress and lessen the total warpage.
- By increasing the melt temperature, the amount of warpage decreases. The main reason for is that by increasing the melt temperature, formation of the crystalline structure will be delayed and so the stresses in the specimen will be relieved and the final warpage declines.
- Finding shows that the general trend in simulated and experimental result is similar in all reported values of warpage and the maximum calculated error is %10.03.

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