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ORIGINAL PAPER

An effect of mold surface temperature on final product properties in the injection molding of high-density polyethylene materials

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Abstract

Mold surface temperature is one of the most critical process parameters in injection molding. This study aimed to determine the effect of mold surface temperature on plastic parts in injection molding of high-density polyethylene materials. Other process parameters were kept constant, and samples were prepared by changing mold surface temperatures by the injection molding method. The samples' mechanical tests, thermal tests, and gloss measurements by a gloss meter were performed, and the amount of warpage and collapses was 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, and had an effect on the melting temperature of the crystal. The microstructure investigations demonstrated that as the mold surface temperature increased, the cavity formation in the structure increased, and fibrillation decreased due to expansion and cooling time. It was determined that the amount of collapse and warpage was affected by the mold surface temperature and that the increase in the mold surface temperature decreased the amount of collapse and increased the amount of warpage and surface gloss.

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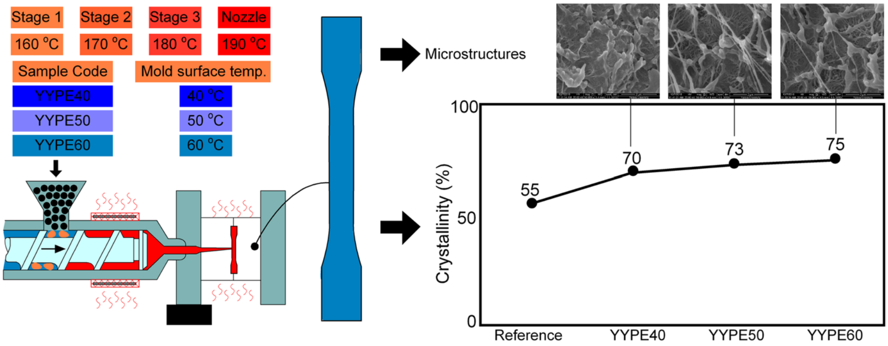
Graphic abstract



Keywords Injection · Mold surface temperature · Polyethylene · Surface gloss · Microstructure

List of symbols

T_m	Melting temperature
T_m°	Equilibrium melting temperature
X_c	Crystal percentage
δ_e	Surface energy
ΔH_m	Melting enthalpy
ΔH_m°	Enthalpy
λ	Crystal lamella thickness

Introduction

Injection molding is a polymer forming method, which is widely used for reasons such as being economical and allowing the molding of parts with complex geometry [1, 2]. The injection process is carried out in four stages, such as melting the polymer, filling the molten polymer into the mold cavity, cooling the product, and removing it from the mold [2]. Even though the molten polymer is filled into the mold cavity with high pressure, the volume of the material decreases as it becomes solid. During the cooling of the mold, shrinkages and warpages in the product occur due to this reduction in volume. The heat transfer between the temperature of the mold surface and the mold, and the plastic part is very effective on the product surface quality [3–5], dimensional stability of the product [4–6], the amount of shrinkage and warpage [5, 7], mechanical properties [6], microstructure [8], cycle time [6], and unit costs [4]. Although it varies according to the type of material, higher mold temperatures improve the impact strength, toughness, and fatigue strength of the product by forming lower stresses [6, 7]. The mold temperature is known to have a more significant effect on product gloss than the melt temperature [2, 3, 9].

Shrinkage, warpage, and gloss in the molded plastic part are tried to be solved mainly by increasing the mold surface temperature and temperature of the melt [10–12]. Increasing the temperature of the melt requires a longer cooling time, which increases the cycle time [2, 3, 10]. Uncontrolled changes in the mold temperature form stress in the molded part and, thus, cause the warpage of it [6, 11]. Such conditions, which lead to an increase in error rates and product costs, are tried to be solved in recent years through methods such as increasing the mold surface temperature in a controlled manner [13–15], rapid heat cycle molding (RHCM) technologies [3, 8, 16], heating the mold surface by using different technologies, [15–17] etc. Increasing the mold surface temperature in a controlled manner in proportion to the temperature of the melt reduces the cycle time by shortening the cooling time [12]. Oppelt et al. [15] stated that the selection of a method for heating the mold surface would vary partly depending on the shape of the mold and the size of the part. Sing and Verma [18] indicated that focusing on process parameters such as temperature (mold surface temperature, the temperature of the melt) is required in order to increase productivity without compromising product quality.

Lucchetta and Fiorotto [3] stated that high mold temperature affects the surface gloss and that it prevents solidification in runners during filling the mold cavity with melt and the formation of a connecting line at the holding pressure. Nhan et al. [10] reported that by the control of the mold surface temperature, the melt flow length was improved, and much better results were obtained in the molding of thin parts. Minh [12] stated that the product height had a significant effect on the mold surface temperature and that the mold surface temperature changed depending on the product height. Berger et al. detected that the amount of product warpage was affected by changes in mold surface temperature. To reduce the amount of warpage in the product, the researchers have determined the optimum process parameters as low nozzle temperature, high-speed heat cycle, mold surface temperature, and maximum holding pressure [16]. With mold temperature optimization, a cost saving of 10–40% can be achieved [19].

Mynek et al. [18] modeled the change in mold surface temperature mathematically and concluded that the mold surface temperature control for optimum process conditions in the injection process should be performed independently of the operator. Liparoti et al. investigated changes in the properties of the product molded from polypropylene (PP) depending on variable mold temperatures. They observed that changes in mold surface temperature affected morphology and that local structures, obtained depending on molecular stress, solidification, and cooling rate, differentiated the mechanical properties of the product [20]. Schwalme stated that the instantaneous control of the mold surface temperature distribution in the process helped to increase process stability by affecting the final product quality. He indicated that during the process and at the end of each molding cycle, faulty parts could be detected through performing mold surface temperature measurements [21]. Chen et al. found that the uneven temperature distribution on the mold surface created residual stress on the parts and increased the amount of warpage. They reported that in the mold decoration (IMD) process, the temperature difference of the mold increased as the temperature of the melt increased, and the film thickness used in the process decreased with increasing mold temperature [13]. Chen et al. investigated the effect of Teflon coating of mold surfaces on mold surface temperature and quality of the part. The researchers, who observed that Teflon coating prevented the weld line on the surface of the plastic part and improved the surface quality, concluded that the mold surface temperature was required to be increased depending on the coating of the mold surface [14]. Zhang et al. [8] found that the thickness of the early solidifying part on the surface decreased with the increase in the surface temperature of the mold and that the relationship between temperature and stress distribution changed the microstructure. According to Hsissou et al. [22] mastering the material behavior in injection molding provides better production and quality control.

In the literature reviews, it is observed that the studies mostly focused on the measurement and control of mold surface temperature. In the previous studies, mold surface temperatures were examined by analysis and simulation programs [14, 16, 20], and the effect of mold surface temperature on product properties was investigated in the injection process of materials such as PC [1, 6, 9], ABS [5, 14–16], POM [7, 16], PP [11, 13, 21], PC and PET film [1, 14], PC/ABS [16], and ABS/PMMA [23]. However, in injection molding of high-density polyethylene (HDPE) materials that have intensive industrial use, it has been observed that there are not enough studies on the effect of the increase in mold surface temperature on product properties.

In injection molding, the mold surface temperature is one of the parameters that are first changed to improve the quality of the part in cases such as low surface gloss of the product, misrun of the plastic material in the mold, increased amount of shrinkage and warpage in the part, etc. Although this change, which is made without controlling other molding parameters, first seems to solve the problem, it leads to major changes in final product properties, which significantly affects the quality of the part and production efficiency. This study aimed to produce injection molded parts from polyethylene material at different mold surface temperatures and to determine the change occurring in mechanical, thermal, and morphological properties of products due to the increase in mold surface temperature and to reach industrially usable results.

Materials and methods

Materials and injection molding parameters

In the studies, a widely used HDPE material with the commercial code PETILEN YY S 0464 (PETKIM, Turkey), and for stabilization purposes, a material with the commercial code Ciba Irgafos® 168 (Ciba Specialty Chemicals LTD., Sweden) at a rate of 0.01% were used. The raw material was subjected to pre-drying at 40 °C for 1 h before injection molding. The molding process was carried out with help of a Spex Victory 80 model (Engel, Germany) injection machine with a closing pressure of 800 kN in accordance with the ISO 294 standard. The samples were molded using a temperature profile of 160–170–180–190 °C for the heating zones and nozzle region and an injection pressure of 80 bar according to the tensile (ISO 527) and impact test (ISO 180) standards. In injection molding, in order to limit the variable parameters, only the mold surface temperatures were adjusted as 40 °C, 50 °C, and 60 °C while other parameters were kept constant.

The materials are designated as YYPEX where X indicates the mold surface's temperature of polyethylene material (YYPE). As an example, YYPE40 has a mold surface' temperature of 40. For mechanical properties, technical data sheet values provided by the manufacturer PETKİM and the values obtained from the tests applied to the raw material in a granular form for thermal properties and resin properties were considered as reference material values. The results obtained from the tests applied to the injection molded materials were compared with these reference values.

Characterization of materials

In order to determine changes caused by mold surface temperature in material properties, a tensile test was conducted in a Zwick Z020 device according to the ASTM D638 standard, a bending test was performed in the same device according to the TS EN ISO 178 standard, an Izod impact test was performed in an Instron Ceast 9050 device according to the ASTM D 256 standard in four different notch radii ($R=0.25/0.5/1.0/2.0$ mm), and a hardness test was conducted in a Zwick Roel device according to the ASTM D2240 standard by using a Shore D scale. Density measurements were performed according to the ISO 1183-1 standard by a Metler Toledo XS204 scale with an accuracy of 0.0001. The number of samples in all tests was at least five.

In order to determine the effect of mold surface temperature on the thermal properties of the material, a DSC test was performed in a Seiko DSC 7020 device according to the ASTM D3417 standard, and a VICAT test was performed in an Instron Ceast HV3 device according to the ASTM D1525 standard. From the fractured surface of the impact test specimens, microstructures were imaged by an Inspect S50 scanning electron microscope (SEM). With the analysis of DSC curves, crystal percentages (X_c) were calculated by using Eq. 1, and the crystal lamella thicknesses (λ) were calculated by using the Gibbs–Thomson correlation given in Eq. 2. For PE, enthalpy (ΔH_m°) in a 100% crystalline state was taken as 293 J/g, the equilibrium melting temperature (T_m°) as 146 °C, and the free surface energy (δ_e) of crystals as 90 mJ/m^2 [24]. In the equations, ΔH_m represents the melting enthalpy, and T_m represents the melting peak temperature.

$$X_c = \frac{\Delta H_m}{\Delta H_m^\circ} \times 100 \tag{1}$$

$$\frac{T_m}{T_m^\circ} = 1 - \frac{2\delta_e}{\Delta H_m} \tag{2}$$

Collapse and warpage and density measurements

Collapses and warpages formed in the materials depending on the mold surface temperature were measured by using a video measuring system (SmartScope ZIP Advance 250/OGP) and a comparator with a sensitivity of ± 0.001 (Mitutoya). The collapse depth was determined by the auto-focus feature on the *Z*-axis of the video measuring system, and the warpage amount was calculated by defining measurements from different points.

Plastic parts' surface quality measurement

Surface roughness measurements were performed in accordance with the ISO Class 3 in a Mitech MR200 (Onalkon) surface roughness measuring device with an R_z measurement range of 0.1–50 µm, by using 1.0 mm/s feed rate, 0.4 mN load, and a diamond detector tip with a diameter of 5 µm. Surface gloss measurements were performed in an Elcometer micro-gloss device at a 60° projection angle. The obtained numerical results were compared with each other, and the effect of mold surface temperature on surface roughness and surface gloss was tried to be determined.

Results and discussion

Mechanical test results

The tensile test results of the materials and the bending test results were presented in Table 1. The graphical comparison of the bending and tensile test results was demonstrated in Fig. 1. The highest tensile strength was obtained in the sample with a mold surface temperature of 50 °C. At mold surface temperatures above and below 50 °C, lower tensile strength values were obtained. Tensile strength and modulus of elasticity increased with increasing temperature. Chen et al. [14] reported in their study that the increase in the mold surface temperature increased the tensile strength and that providing more homogeneous heat distribution on the surface by coating the mold surface increased the tensile strength significantly. In the tensile test, it is observed that the tensile strength and tensile modulus of elasticity first increase and then decrease again, with the increase in mold surface temperature. This situation is

Table 1 Mechanical test results of the materials

Sample code	Tensile strength (MPa)	Tensile modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Standard deviation	
					Tensile strength	Flexural strength
Referance	31.00	1200	27.50	1150	–	–
YYPE40	27.80	1190	28.50	1210	0.20	0.17
YYPE50	30.17	1290	29.80	1290	0.11	0.19
YYPE60	28.15	1250	29.30	1220	0.26	0.14

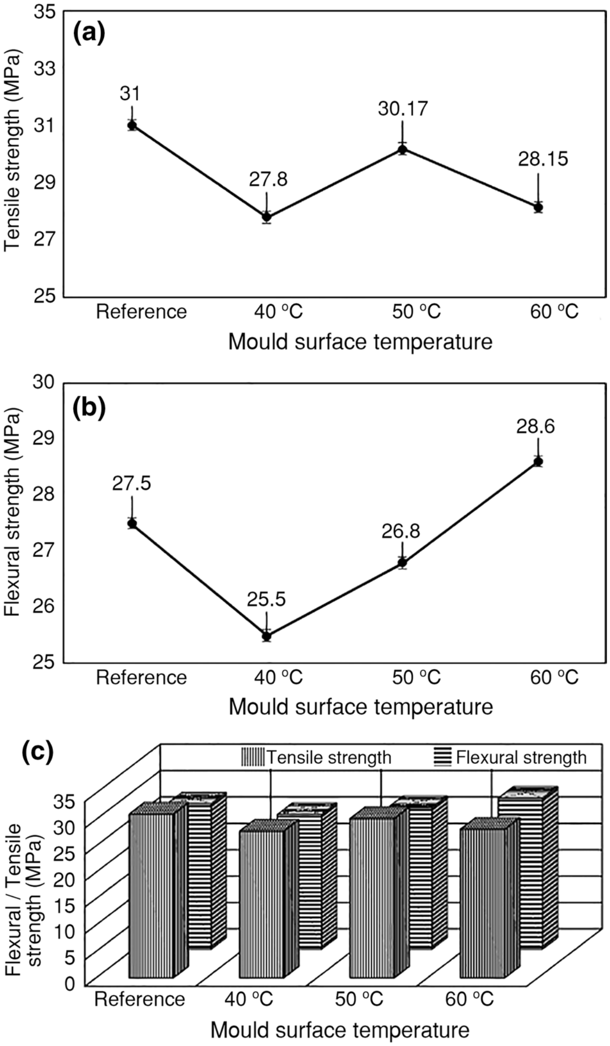


Fig. 1 Result of tensile and flexural test, **a** tensile strength, **b** flexural strength, **c** comparison of the tensile and flexural strength

thought to be due to the increase in the amount of crystallization and formed microstructure depending on the increase in mold surface temperature. Liparoti et al. [20] stated that the fibril structure in the structure, lamella thicknesses, and spherulite dimensions affect the tensile strength and tensile modulus of elasticity.

In the bending test, no fracture occurred in the samples. Bending strengths and flexural modulus of elasticity were obtained to be higher compared to the reference material. As the mold surface temperature increased, the bending strength also increased. In general, it is estimated that the formed strength differences in the bending and tensile tests are due to the spherulite structure and molecular chains, which expand volumetrically more with increasing temperature and which are formed in cooling after solidification. The increase in mold surface temperatures is known to increase molecular mobility. Since the cooling time was kept constant, it was observed that the molecular mobility in the materials exiting the mold at different temperatures created residual stresses by continuing in different ways and affected the strength of the parts. Such a result was expected because the mold surface temperature was changed. It is thought that changing the nozzle outlet temperatures or cooling time in parallel with this at different mold surface temperatures may be effective in preventing the strength-induced defects that occur during production. Similar studies have reported results that are similar to those expressed here by the researchers [16, 25].

When the graphs given in Fig. 1 are examined, it is clear that the results vary depending on the mold surface temperature. This situation is thought to be caused by features of parts after molding that change depending on the molding parameters such as the density of the material, the amount of crystallization, etc. [16]. The mold surface temperature was observed to significantly affect the mechanical properties of the material, such as tensile and bending strength.

The reference hardness value is 65 Shore D. Depending on the mold surface temperature, the hardness measurement results are 68, 66, and 65 Shore D, respectively. The hardness measurement results were observed to be close to each other. The highest hardness value was measured as 68 Shore D in samples with a mold surface temperature of 40 °C. It is thought that this is due to the upper surface, which comes into contact with the mold surface and which solidifies in the form of a layer by rapid cooling [2, 6]. However, it is predicted that depending on the microstructure and the amount of crystallization, the hardness will vary with the progression toward the inner parts, and similar hardness values will be obtained for all samples [24, 26]. When the hardness measurement results and DSC and microstructure investigations are evaluated together, it is possible to obtain more meaningful data and change the process parameters accordingly.

In Fig. 2, the impact test results were demonstrated graphically. Upon examining Fig. 2, the impact strength was observed to decrease as the notch radius increased. Since the notch effect is known to reduce impact strength [6], it was predicted that the results would be similar. When the impact test results were compared, the highest impact strength was obtained from the samples with a mold surface temperature of 50 °C. The results obtained in the molding process performed at 40 °C and 60 °C mold surface temperatures were measured to be lower compared to the reference sample. It is estimated that this situation is caused by residual stresses and that these problems can be prevented by process parameters such as mold surface temperature, ironing pressure, and holding time [6, 27]. In general, it is expected that products with the desired quality and strength will be obtained in the productions performed without significant changes in the molding processes and production environment, in which standard deviations give similar results [5, 26, 28]. Sustainable process and product quality are of great importance in production with injection [4, 5]. Therefore, it is thought that impact strength can be used as a parameter in measuring the efficiency of the injection molding process [5, 6].

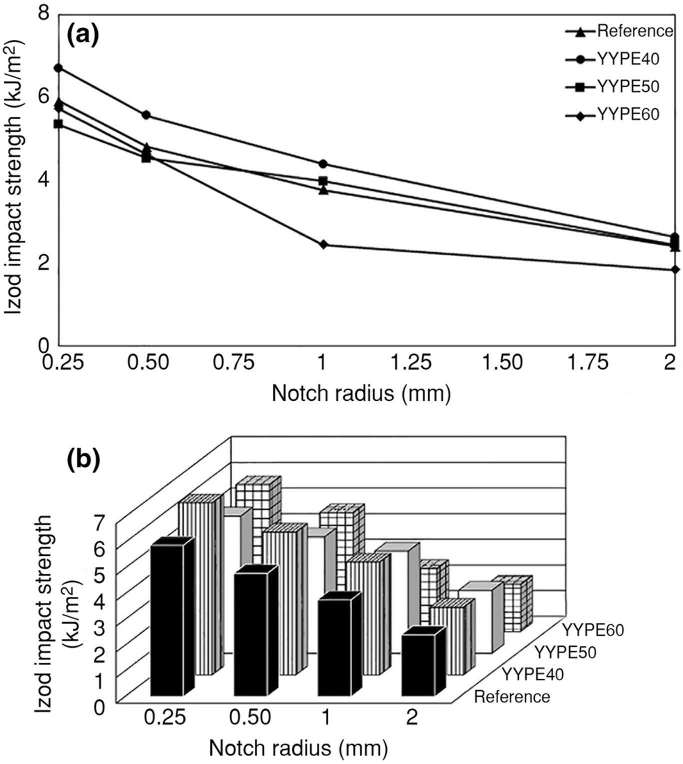


Fig. 2 Results of impact test, **a** effect of notch radius on impact strength, **b** comparison of result of impact test

Result of the thermal analysis

The DSC curves of the samples are given in Fig. 3, and the comparison of crystal lamellar thicknesses (Fig. 4b) and crystallization percentages (Fig. 4a) calculated according to the data obtained from the curves is given in Fig. 4. The increase in mold surface temperatures increased the melting temperatures (T_m) and the amount of crystallization. The highest percentage of crystallization was obtained as 75% from samples with a mold surface temperature of 60 °C. This situation is thought to be caused by the tendency of being in the order of molecular chains during cooling after molding with the increased mold surface temperature. The obtained crystallization rates confirm this situation. As can be seen in Fig. 4b, the mold surface temperatures had an effect on the crystal lamella thicknesses. It is known from the literature that lamella thicknesses will decrease as crystallization increases [13, 24]. However, an exactly opposite situation is true for samples molded at a mold surface temperature of 60 °C. It is estimated that this situation is caused by different cooling curves that are formed from the surface to the inner

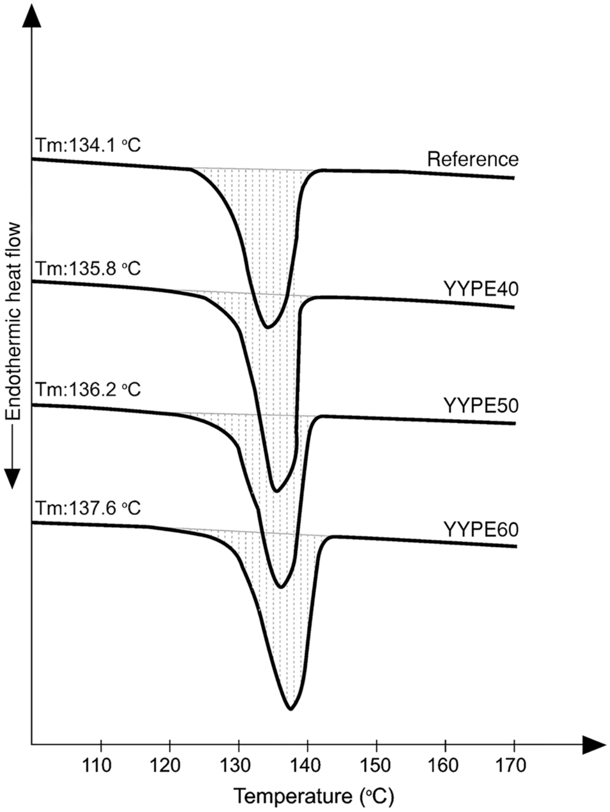


Fig. 3 DSC curves

parts by high mold surface temperatures, and by the tendency of stratification occurring depending on the temperature difference.

In Fig. 4c, it is observed that no significant difference occurred between crystallization onset and peak temperatures for the mold surface temperature YYPE40 and YYPE50 coded materials. It is considered that the solidification kinetics in both materials ran similarly, which caused the lamella thicknesses to be close. Mohammadi [29] indicated that solidification kinetics that changed with temperature and microstructure were effective on lamella thicknesses and that close values could be obtained in materials with similar solidification kinetics. The rate of heat transfer between the mold and material also affects the crystallization ratio, crystal lamella thicknesses, and microstructure [29–32]. Chalid et al. [33] determined that there was a relationship between the crystallization temperature and crystallization properties, and Kuzmanović et al. [34] determined that the crystallization ratio was higher at higher temperatures. Rastogi et al. [35] stated that the cooling behavior of the molten material might affect the lamella thickness. The results obtained with regard to the crystallization ratio and lamella thicknesses, and the results obtained when increased mold surface temperature and

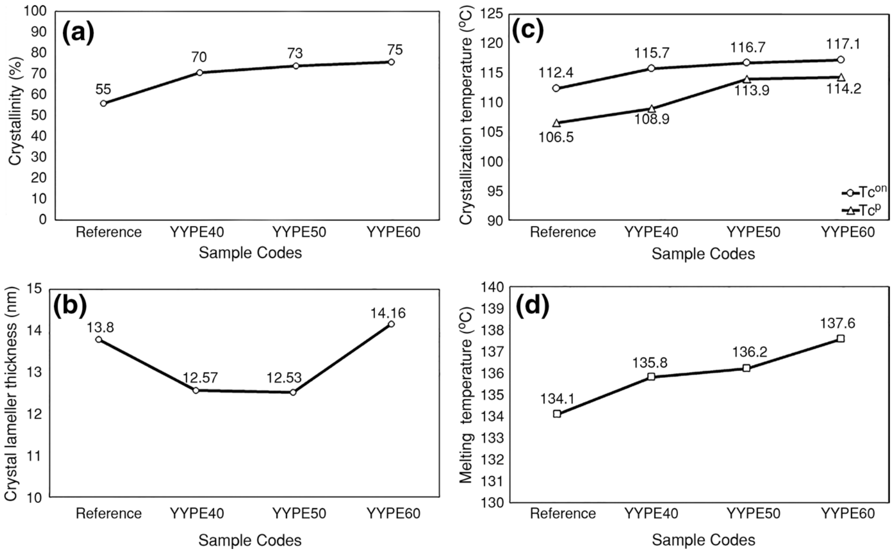


Fig. 4 Crystallization properties of materials **a** crystallization percentages, **b** crystal lamellar thickness, **c** crystallization temperatures, **d** melting temperatures

crystallization onset and peak temperatures are considered are similar to other studies [30–35].

In injection molding, the mold surface temperature was determined to be effective on the crystallization ratio, crystal lamella thicknesses, and crystallization onset and peak temperatures. In Fig. 4, crystallization onset and peak temperatures (Fig. 4c) and crystal melting temperatures (Fig. 4d), which vary depending on mold surface temperature, were compared. Crystallization onset and peak temperatures were observed to increase as the mold surface temperatures increased. When the mold surface temperature is ≥ 50 °C, the temperature difference between crystallization onset and peak temperatures is observed to be less. It is estimated that this situation will create a density difference in materials. When all the results were examined, crystallization ratio, crystal lamella thicknesses, and melting temperature values obtained from the DSC data were observed to be consistent with other test results and the literature [13].

Vicat softening point and density measurement results are presented in Table 2. It is thought that the mold surface temperature has an effect on the Vicat softening temperature of the molded product [4, 25] and that this effect will gain more importance with increasing temperature difference. It is predicted that this difference in Vicat temperature is caused by the crystallization ratio and the crystal lamella thicknesses [24] and that the strength will vary depending on this also under thermal loads. The increase in mold surface temperature has a significant effect on material density. It is thought that this density difference may be clearly observed as the part sizes to be produced increase. Zhou et al. [4] detected in their study that the density varied depending on the mold surface temperature and that it could be used to determine the stability of the process.

Table 2 Vicat softening point and density values of the materials

Sample code	Mold surface temperature (°C)	Vicat softening point (°C)	Density (g/cm^3)	Increase rate	
				Vicat (%)	Density (‰)
Referance	–	124.0	0.961	–	–
YYPE40	40	126.2	0.958	+ 1.77	− 3.12
YYPE50	50	126.8	0.972	+ 2.26	+ 11
YYPE60	60	125.7	0.978	+ 1.37	+ 18

Microstructure investigation results

Photographs, obtained with scanning electron microscopy (SEM) investigations, are given in Fig. 5a for the YYPE40 coded material, in Fig. 5b for the YYPE50 coded material, and in Fig. 5c for the YYPE60 coded material. As can be seen in Fig. 5, the microstructures formed in the material at different mold surface temperatures

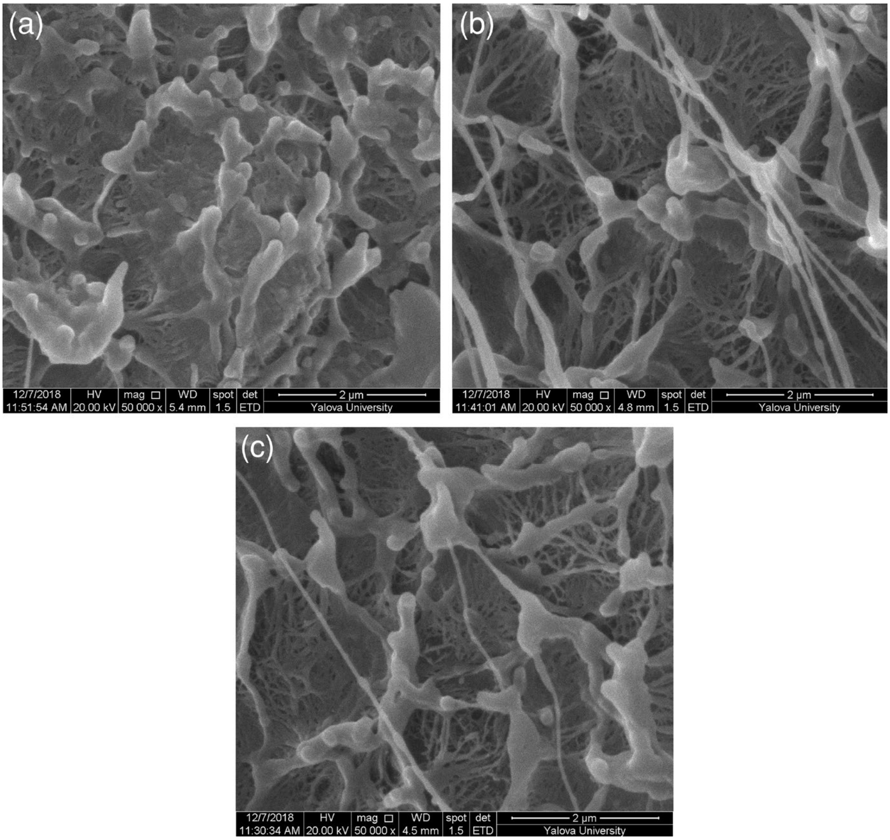


Fig. 5 SEM photos **a** YYPE40, **b** YYPE50, **c** YYPE60

are entirely different from each other. In the material molded at a mold surface temperature of 40 °C (Fig. 5a), there were few but longer fibrillations compared to the others. In molding at 50 °C, fibrillation increased, but fibril lengths became shorter. In the molding process performed at 60 °C (Fig. 5b), it is observed that the fibril structure was replaced with a more hollow structure in the form of Lattice mesh.

While few and long fibrillation in the structure increases flexibility, a short and hollow structure reduces flexibility. A hollow structure and crystallization are known to reduce impact strength [4, 24]. Since the raw material is subjected to the predrying process before the injection process, it is thought that this hollow structure is caused by the bubble expansion formed due to high temperatures while the channels of the melt are still open, or by the difference in shrinkage and cooling between the upper surface and the inner zone during solidification depending on the mold surface temperature. It is foreseen that this hollow structure can be prevented by increasing the holding pressure or duration. When the data obtained from the impact test and DSC results are evaluated together with microstructure investigations, the results are observed to support each other and to be compatible with each other. It was found that the mold surface temperature is effective on the microstructure in injection molding [8, 20] and that it is an important parameter that must be taken into consideration during molding in order to obtain the desired microstructures and mechanical properties.

Results of warpage and collapse measurements

The results of collapse and warpage measurements are presented in Table 3. According to the results obtained, the warpage ratios in the parts were mapped in Fig. 6 by meshing. By checking the amount of warpage by the comparator, the accuracy of the results was checked manually. It was found out that with the increase in mold surface temperatures, the amount of collapse and warpage decreased, and the amount of shrinkage increased. Similar studies reported that errors such as warpage, shrinkage, residual stress, etc. would be formed in the piece if the optimum conditions in molding could not be adjusted correctly [5, 27, 36]. It is known that the material structure, which expands more with the increase in the mold surface temperature and solidifies more lately, will increase the amount of shrinkage by affecting fluidity [11, 17]. The correct adjustment of process parameters, especially in parts with sensitive tolerances, will be important in terms of process efficiency, shrinkage amount, and product quality [5, 28, 37]. Chen et al. [1] stated that the increase in the

Table 3 Collapse and warpage rates of the materials

Sample code	Collapse rate (%)	Warpage rate (%)	Warpege rates according to axes (mm)		
			x	*y*	*z*
YYPE40	+6	+0.4	+0.021	+0.018	+0.019
YYPE50	+4	+0.6	+0.018	+0.016	+0.017
YYPE60	+3	+1.0	+0.010	+0.008	+0.011

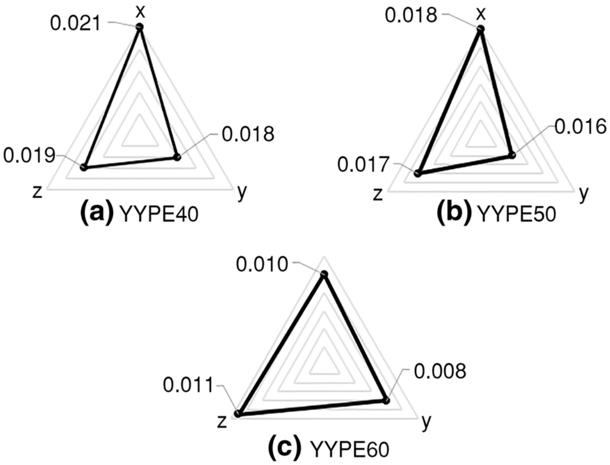


Fig. 6 Mapping of the amount of warpage according to axes

temperature of the melt increases warpage by creating residual stresses and affects the product quality, and therefore, it should be focused on mold surface temperature and heat transfer in the mold for less warpage and better product quality.

When the results are examined, it is observed that the amount of shrinkage is higher in the regions with larger values dimensionally, collapse is concentrated in the middle sections and thin sections, and warpage is concentrated at the endpoints of the part, and that with the increase in mold surface temperature, superficial shrinkage starts to be formed in every section of the part. It should be considered that in the design of plastic parts and the design of molds, there will be more collapse, warpage, and shrinkage, especially in regions with cross-sectional differences or with more wall thicknesses. Similar studies conducted by other researchers [16, 28, 36] indicated that mold surface temperature had a significant effect on warpage, shrinkage, and collapse like all other process parameters.

Plastic parts' surface quality measurement results

Surface gloss and surface roughness measurement results are presented in Table 4. In physical controls, it was observed that flash burr formation in the parts increased as the mold surface temperature increased. It is estimated that burr formation is caused by the material overflowing to the mold joining surface before ironing pressure. It is observed that increasing the time at the holding pressure applied just before the ironing pressure prevents burr formation. When the surface gloss measurement results given in Table 4 were examined, the surface gloss of all materials was found to be at the medium gloss level. According to the measurement values, the surface gloss class obtained at 40 °C and 60 °C was determined to be satin-like finish and the surface gloss class at 50 °C to be semi-gloss. As the mold surface temperatures increased, the density of the material increased, and better surface quality was obtained. Lucchetta and Fiorotto [3] stated that as the mold surface temperature

Table 4 Surface roughness and surface gloss improved efficiency under different mold surface temperature

Sample code	Mold surface temperature (°C)	Surface roughness (R_z, μm)	Roughness improved. efficiency (%)	Surface gloss (GU 60°)	Gloss improved. efficiency (%)
YYPE40	40	25.0	–	22–23	–
YYPE50	50	10.3	+58.8	40–43	+82
YYPE60	60	15.6	+37.6	30–31	+36

increased, the gloss of materials also increased. This situation is estimated to be caused by material fluidity that varies with mold surface temperatures [10]. Chen et al. [9] found that high mold temperatures improved surface quality, but that surface roughness and surface gloss decreased rapidly when the temperature reached a particular value. Berger et al. [16] stated that changes in nozzle temperature and mold surface temperatures significantly affected the part's surface quality and gloss. Chen et al. [14] observed that by coating the mold surface, much better product surface properties were obtained in comparison with uncoated mold surfaces. The results obtained are consistent with the literature [9, 14, 16].

Conclusions

In this study, an experimental study was conducted to determine the effect of mold surface temperature on the mechanical, thermal, and microstructure properties of the molded product. The overall results obtained from the study are as follows:

1. When mold surface temperature is selected as the single parameter which varies, while the tensile strength and bending strength of the molded product increase, its impact strength will decrease. In the impact test, the notch effect can be used as a parameter in measuring the injection molding process efficiency and stability.
2. Depending on the mold surface temperature, the crystallization ratio, crystal lamella thicknesses, and crystal peak temperatures of materials differ. The mold surface temperature is effective on the crystal melting temperature of the molded product. The mold surface temperature parameter should be taken into consideration, especially in the production of parts subjected to thermal loads.
3. As the mold surface temperature increases, the cavity formation in the structure increases, and fibrillation decreases depending on materials' expansion and cooling time. In the structure, the formation of fibrillation that is few in amount and longer increases the flexibility of materials. The microstructure formed depending on the mold surface temperature change has an effect on mechanical properties.
4. There is a relationship between the collapse and warpage amounts and the mold surface temperature. As the mold surface temperature increases, the amount of collapse decreases, and the amount of warpage increases. An increase of + 10 °C

in mold surface temperature decreases the amount of collapse by 1% and increases the amount of warpage by 2‰.

5. The surface gloss of products is affected by mold surface temperature. As the mold surface temperature increases, the gloss of materials also increases. However, the gloss value decreases when the critical temperature is exceeded. For products in which gloss is important, the critical temperature value for the mold surface temperature should be determined according to the type of the material used.
6. When other process parameters are kept constant, the mold surface temperature has a significant effect on material properties. Increasing the number of variable process parameters will limit this effect. For materials, the process parameters given by manufacturers must be definitely considered. As lower and upper values are approached, it should be taken into consideration that there will be significant changes in the product properties and that it will be more challenging to obtain the desired properties.

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