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ScienceDirect
Materials and Design 28 (2007) 1467–1476
Materials & Design
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An experimental investigation of the effects of hot runner system on injection moulding process in comparison with conventional runner system

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Received 27 June 2005; accepted 14 March 2006
Available online 6 May 2006

Abstract

The effects of hot runner system on injection moulding process and properties of injected part have been investigated from various aspects in comparison with conventional runner system. A two-cavity mould which can be used for both of the runner systems was designed and produced so as to conduct all experiments on the same mould, and to compare the results precisely. In the experiments, acrylonitrile butadiene styrene and polypropylene materials were used as base polymers. Using the results obtained from the experiments, moulding area diagrams were plotted for both runner systems with respect to the process parameters of injection pressure and melt temperature changing within a wide range. It was observed that the required injection pressure was considerably lower to produce samples with higher weight in the case of hot runner system. The shrinkage and warpage increased with increasing process temperature, decreased with increasing injection pressure, and occurred at low level when the sample weight was high.

Keywords: Polymer (A); Moulding (C); Shrinkage (E); Runner systems

1. Introduction

The type of the runner system is one of the most influential factors on injection moulding process and the properties of the injected parts. Conventional runner systems (CRS) have some disadvantages such as high cost of energy and workmanship, high scrap ratio, low product quality of surface appearance and requirement of high injection pressure. Therefore, the mould designers are attracted to hot runner system (HRS) which is able to provide precisely adjustable process temperature, uniform filling in multi-cavity moulds, even heat distribution within the mould, improvement on mechanical properties of injected part, and reduction in injection pressure. In addition, HRS allows significant cuts in production costs by saving material as a result of eliminating sprue, shorter mould opening distance because of the absence of sprue, and shorter cycle time. Moreover, it prevents undesirable track of cavity gate [1].

Defects of the injection-moulded part, such as shrinkage, warpage, weld line, sink marks and residual stress, generated by unfavourable process conditions, have great influence on the quality and accuracy of the part. Therefore, effective control of the influential factors is a must. The effects of process conditions on the properties of injected parts have been investigated by several studies. Bushko and Stokes [2] investigated the effects of the mould and melt temperatures and packing pressure on the shrinkage. They reported that the packing pressure has an important effect on the shrinkage of the injection moulded part. They showed that the shrinkage decreases with increasing packing pressure, and increases with increasing mould temperature. Jansen et al. [3] reported the packing pressure and

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doi:10.1016/j.matdes.2006.03.015

the melt temperature as the major influential process parameters on dimensional change. Huang and Tai [4] reported that the influential process parameters on warpage are packing pressure, mould and melt temperatures, and packing time, citing in the order of importance. They regarded the filling time and gate dimension parameters as non-significant factors. Liao et al. [5] emphasized the necessity that the geometrical effect of real commercial parts on quality and interaction between the process parameters should be considered in investigating the effect of process parameters on shrinkage and warpage. They also reported that the mould temperature should be considered among the influential parameters on shrinkage and warpage because of causing the polymer inside the mould cavity to cool down in a higher temperature environment in a longer time. Jafarian and Shakeri [6] investigated the effects of packing pressure in the case of the gate freezing before complete solidification. Their research showed that the molten plastic cannot be added to compensate for shrinkage when gate freezing occurs before complete solidification. Thus, shrinkage will increase compared to a fully packed item. They also showed that higher relaxation time leads to less shrinkage and results in lower residual stress.

According the literature review, it is noticed that there have been some studies investigating the effects of process parameters on the dimensional and geometrical quality of injected parts. In this research, the effect of HRS on injection moulding process was experimentally investigated in comparison with CRS, by conducting many experiments at different process conditions on a two-cavity mould which is adaptable to both runner systems. During these experiments relating both HRS and CRS, the clear effect of the runner systems on the properties of injected part was determined by keeping the values of mould temperature, injection velocity, gate dimension and cycle time constant. The value of packing pressure was determined to be half of the injection pressure. By considering the measurements taken from the samples produced in the experiments, the process conditions (i.e., injection pressure, packing pressure and process temperature) minimizing the shrinkage and warpage, and maximizing the weight of the samples were determined.

2. Experimental setup

2.1. Part

A box-shaped part that consists of some details such as ribs, holes, large flat surface, conical surface and rounded edge was adopted, in order to observe the effects of runner systems on its dimensions and shape. The main dimensions of the part are $112 \times 78 \times 36$ mm and the thickness of the walls is 2 mm. The drawing and the general view of the part are presented in Fig. 1.

2.2. Mould

In order to examine and to precisely compare the effects of HRS and CRS, it is necessary to perform the experiments at the same conditions. Thus, a two-cavity mould which can be used with both HRS and CRS was designed and produced. The diameter of the nozzles was determined as 1.9 mm. Six resistances of 400 W for heating the nozzles and manifold, and four thermocouples for controlling the melt temperature were fitted to the mould. The determination of gate location was carried out by utilizing the Mold Flow analysis software for both HRS and CRS, as shown in Fig. 1. For each mould cavity, four cooling channels with parallel connection were generated. The core and cavity halves of the mould are assumed to have the same temperature to minimize warpage. After completion of the experiments with HRS, the mould was modified for CRS by assembling some appropriate components such as sprue pulling pin and plugs for nozzle nests. Thus, the possibility of doing all experiments with both runner systems on the same mould and comparison of the results precisely were provided.

2.3. Injection machine and materials

An injection moulding machine having a clamping force of 80 tonnes and a shot capacity of 170 g. was used for the experiments. In the experiments, acrylonitrile butadiene styrene (ABS) and polypropylene (PP) polymers were used. ABS is an amorphous polymer produced by GE Plastics, and PP is a semi-crystalline polymer produced by Petkim A.S. Of some major specifications, the process temperature range is 220–280 °C for ABS and 170–260 °C for PP, and the melt flow index is 3.7 g/10 min for ABS and 6 g/10 min for PP. The detailed specifications of these polymers are listed in Table 1.

3. Determination of optimal moulding area

The experimental study was carried out in a wide range of temperatures recommended by the manufacturer of the material. Within this range, both melting point and decomposition limit of the material were taken into consideration. The value of packing pressure was determined to be half of the injection pressure, and the other parameters (i.e., mould temperature, injection velocity and cycle time) were kept constant during all experiments for both runner systems. The process conditions adopted in the experiments are presented in Table 2.

Injection moulding processes were performed at three stages. In the first stage, achievable minimum and maximum values of injection pressure were determined by heating the material on the injection moulding machine to a minimum temperature at which it can be injected. Then, the same procedure was repeated for mean and maximum process temperatures. In order to determine optimal process area for HRS in comparison with CRS, moulding area diagrams (MAD) were drawn on the bases of the data obtained from the experiments. Produced samples relating to various MAD regions are shown in Fig. 2. The MADs for ABS and PP polymers are shown in Figs. 3 and 4. The lower and upper limits of the process variables used in the MADs were determined so that there would neither be a flash formation nor short shot in the injected part as well as no chemical degradation. The regions that are located to the left of and under the closed areas on these diagrams represent the short shot in the injected part at low pressure and low temperature (i.e., top in Fig. 2). The regions that are located to the right of and above the closed areas represent the flash formation in the injected part at high pressure and high temperature (i.e., middle in Fig. 2). The closed areas represent the appropriate

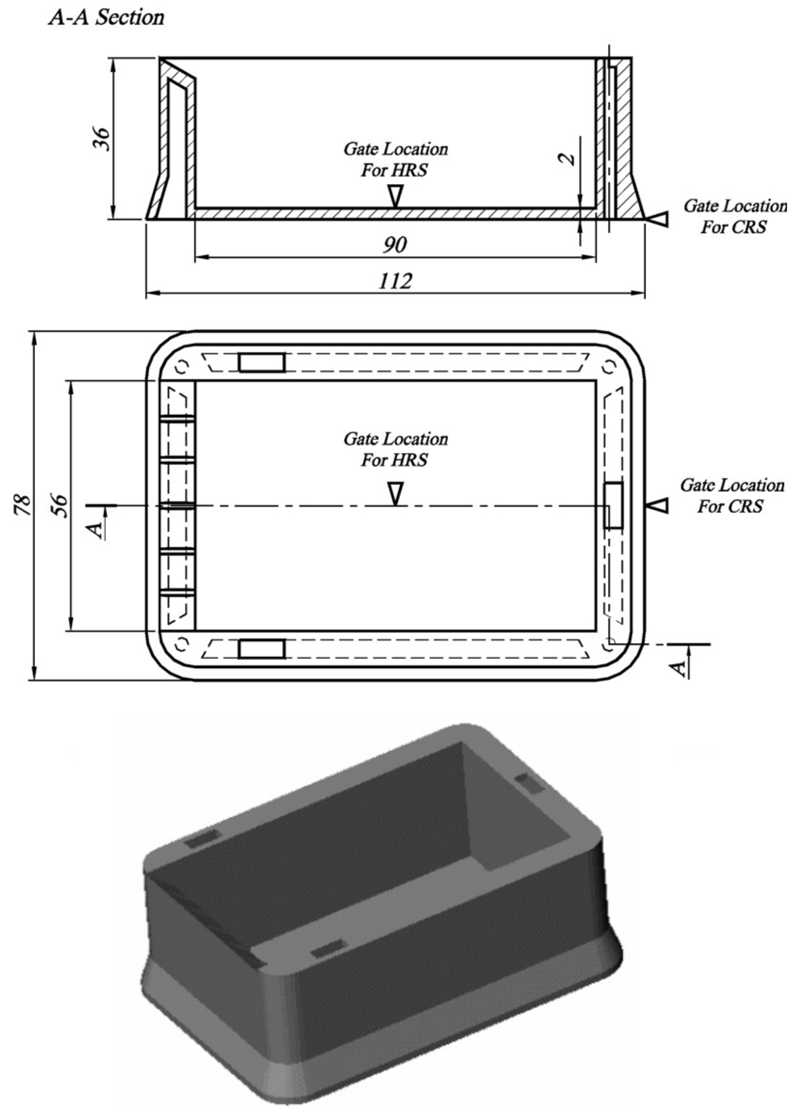

Fig. 1. The drawing and the general view of injected part adopted in the study.

Table 1
Specifications of the moulding materials

Name of material	Acrylonitrile butadiene styrene	Polyprophylene
Symbol	ABS	PP
Commercial name	Cycolac GE	Petoplen MH418
Manufacturer	GE Plastics	Petkim A.S.
Resin type	Amorphous	Semi-crystaline
Density	1.05 g/cm^3	0.91 g/cm^3
Melt flow index	3.7 g/10 min (230 °C/3.8 kg)	4–6 g/10 min (230 °C/2.16 kg)
Process temperature	220–280 °C	170–260 °C
Tensile strength	17–58 MPa	30–40 MPa
Modulus of elasticity	2800 MPa	1250 MPa

moulding area for ABS and PP when using HRS and CRS (i.e., bottom in Fig. 2).

When using CRS, the flow of molten plastic becomes more difficult because of the heat dissipating in the runner channels. In addition, increase in flow length increases the frictional pressure losses. Using HRS provides significant pressure gain by eliminating the disadvantages of CRS. PP material was injected at temperatures of 170, 200 and 260 °C, and at pressures shown on the diagram in Fig. 4. It was observed that significant pressure gain was provided when using HRS. At mean process temperature of 200 °C, e.g., the required average injection pressure is 70 MPa for

Table 2
Experimental conditions for injection moulding process

Base polymer	Process temperature (°C)	Injection pressure (MPa)		Packing pressure (MPa)	Mould temperature (°C)	Cycle time (s)	Injection velocity (m/s)
		HRS	CRS				
ABS	225	60, 70, 75, 80, 90	70, 85, 95, 110	% 50 of injection pressure	40	50	0.012
	245	50, 65, 80	70, 100				
	260	40, 75	60, 90				
	280	30, 40, 60	50, 70, 90				
PP	170	65, 75, 80, 90, 100, 110	80, 90, 100, 110, 120		40	60	0.015
	200	40, 100	70, 100				
	260	30, 40, 60, 70	45, 60, 80				

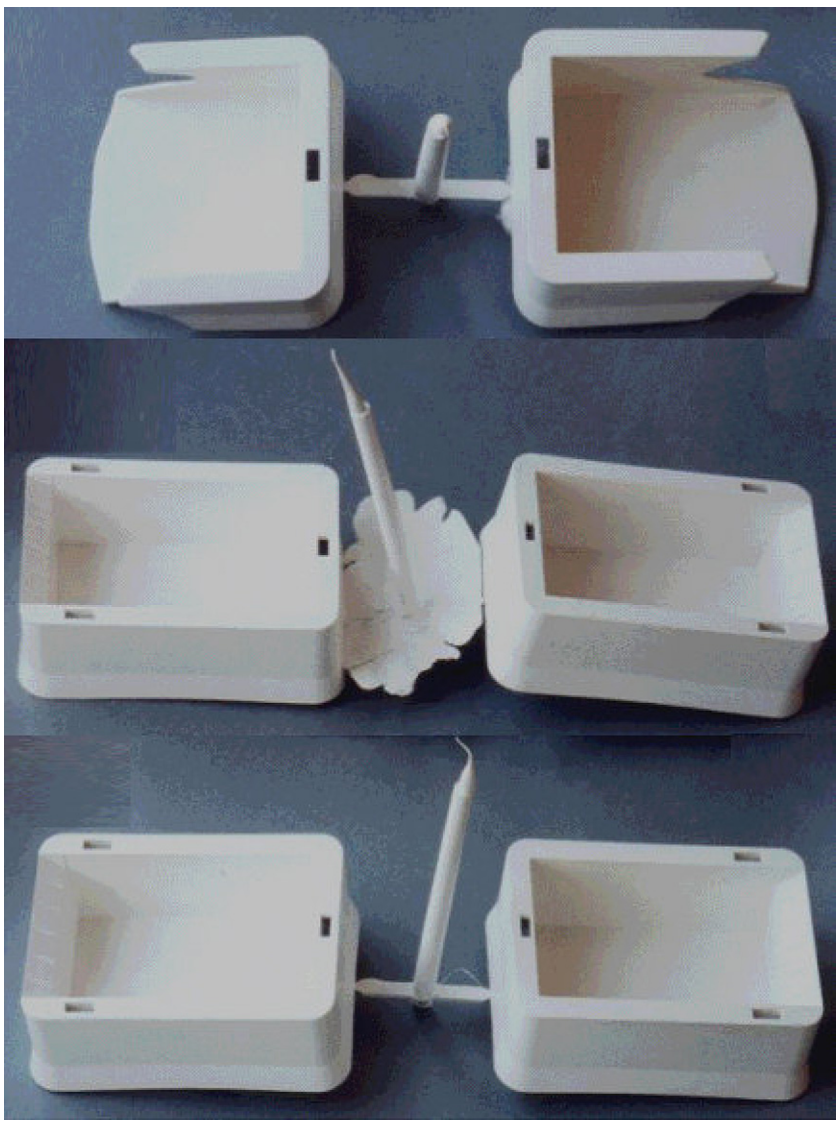

Fig. 2. Produced samples related to the various MAD regions.

HRS, instead of 85 MPa for CRS which means a pressure gain of 17.64%. The pressure gains at other process temperatures of 170 °C and 260 °C were determined as 7.5 and 20%, respectively. When considering the low peaks instead of the average values of the injection pressure, it was determined that the pressure gains rose up to 18.75%, 42.85% and 33.33% at 170, 200 and 260 °C, respectively. This reduction on injection pressure allows considerable saving in production costs and increases the lifetime of the mould and injection machine. Pressure gains obtained when using HRS for ABS and PP materials are presented in Table 3.

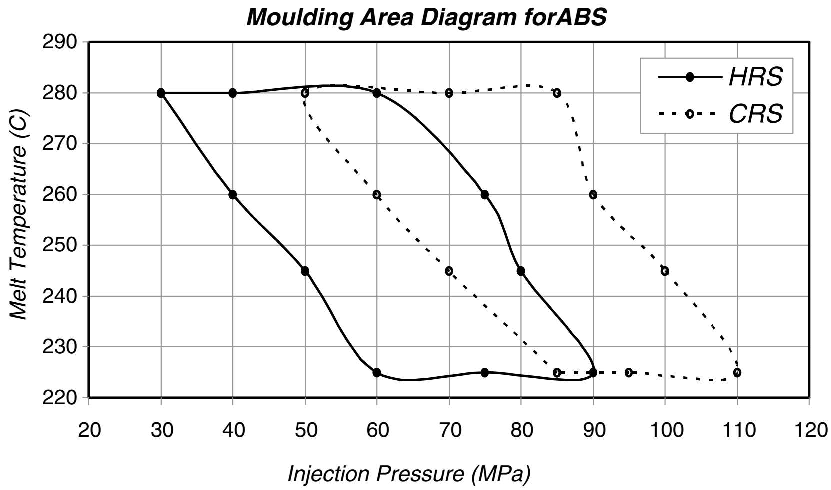

Fig. 3. Moulding area diagram for ABS material when using HRS and CRS.

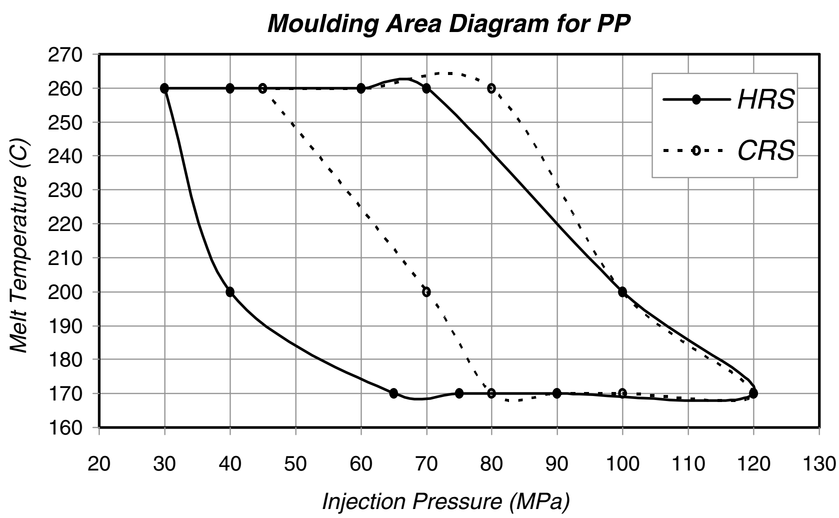

Fig. 4. Moulding area diagram for PP material when using HRS and CRS.

Table 3
Injection pressure gain with the use of HRS for ABS and PP polymers

Base polymer	Process temperature (°C)	Injection pressure gain with the use of HRS	
		(MPa)	(%)
ABS	225	20	20.51
	245	20	23.53
	260	17.5	23.33
	280	22.5	33.33
PP	170	7.5	7.5
	200	15	17.64
	260	12.5	20

4. Shrinkage evaluation

It has been reported that the primary influential factors on shrinkage of an injected part are both the magnitude and duration of exerted packing pressure. The excess shrinkage on the remote regions of the part from the sprue is largely attributed to the reduced effect of the packing pressure at the outer regions. There is a direct relationship between orientation and shrinkage due to the fact that molecular chains are oriented in line with the flow direction under the effect of friction and elongation. This effect is more pronounced at the outer zones of the part where the material sets relatively faster. Therefore, the sample produced by injection moulding experiences more shrinkage in the direction of flow [7].

The shrinkage of injected part is defined by taking its bottom surface's length and width into consideration as shown in Fig. 5. The x-direction shrinkage in length and the y-direction shrinkage in width are defined by the shrinkage of L_{p-x} and L_{p-y} segments, respectively. The thickness of the bottom surface of the part is 2 mm, and the length and width of this feature in the mould cavity are $L_{m-x} = 93.81$ mm and $L_{m-y} = 59.79$ mm, respectively. The residual stresses of the samples produced in the

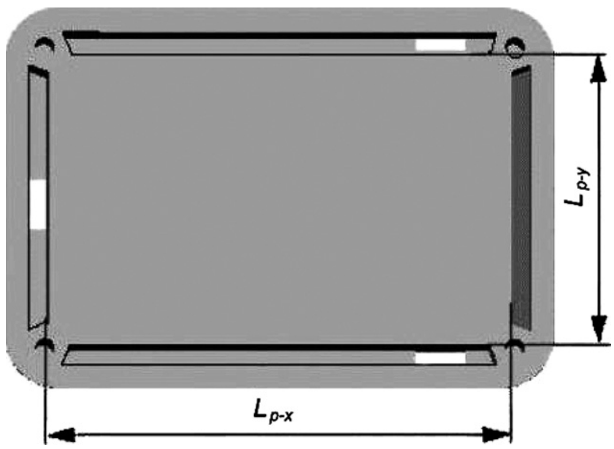

Fig. 5. Definition of shrinkage on bottom view of the injected part.

experiment were allowed to relax by keeping them in the room temperature for 10 days and then the magnitude of shrinkage was measured. The percentage of shrinkage was calculated by using the following equations:

$$\text{Length-wise shrinkage rate }(\%) = 100 \cdot (L_{m-x} - L_{p-x})/L_{m-x} \quad (1)$$

$$\text{Width-wise shrinkage rate }(\%) = 100 \cdot (L_{m-y} - L_{p-y})/L_{m-y} \quad (2)$$

The calculated shrinkage rates in length and width for both runner systems vs. injection pressure at the process temperature of 225 °C for ABS and 170 °C for PP are presented in Figs. 6 and 7, respectively. According to these figures, it was observed that the shrinkage rate decreased with increasing injection pressure for both runner systems. This point is also stated by previous researches in the literature [4–6]. Liao et. al. [5] reported that the packing pressure is the most important process parameter for shrinkage, because it becomes effective during cooling down period whereby the material starts. Under the condition that the packing pressure is high, the polymer can be squeezed into the cavity to reduce and even the shrinkage.

For HRS and CRS, the average shrinkage rates in length and width for ABS and PP polymers are presented in Table 4. These results showed that using HRS decreases the shrinkage rates for both of the polymers in comparison with CRS. It is interpreted that this shrinkage-decreasing effect of HRS is resulted from more influential packing stage due to late solidification of the gates, lower heat losses and better fluidity of the molten plastic. In addition, using HRS makes the adaptation of central gate location possible in multi-cavity moulds. This shortens flow length, decreases pressure loss and contributes to achieving more influential packing stage.

In the case of using CRS, reduction in shrinkage rates requires impractically high working pressures. For example, CRS results in low shrinkage rate at 170 °C for PP polymer, but it requires 120 MPa injection pressure. Same shrinkage rate can be provided at much lower injection pressures when compared with HRS.

5. Warpage evaluation

In general, it can be said that the warpage is caused mainly by residual stresses inside the part and uneven thickness in various directions. Progressive narrowing of the cross-sectional area caused by setting of melt as layer on cold cavity surfaces leads to increasing stresses in the direction of the flow, thus causing different shrinkage rates. Consequently, higher shear stresses on the material and more molecular orientation will be expected, which may contribute to warpage. The mould and melt temperatures, design of the injection moulded part and cooling system, the higher ratio of the length to the thickness in an injected part, packing pressure and time, and gate type, dimension and location can be listed as the most influential factors on the warpage occurrence [4,8].

The cavity is maintained at a constant pressure for packing stage when filling is nearly completed. Packing pressure

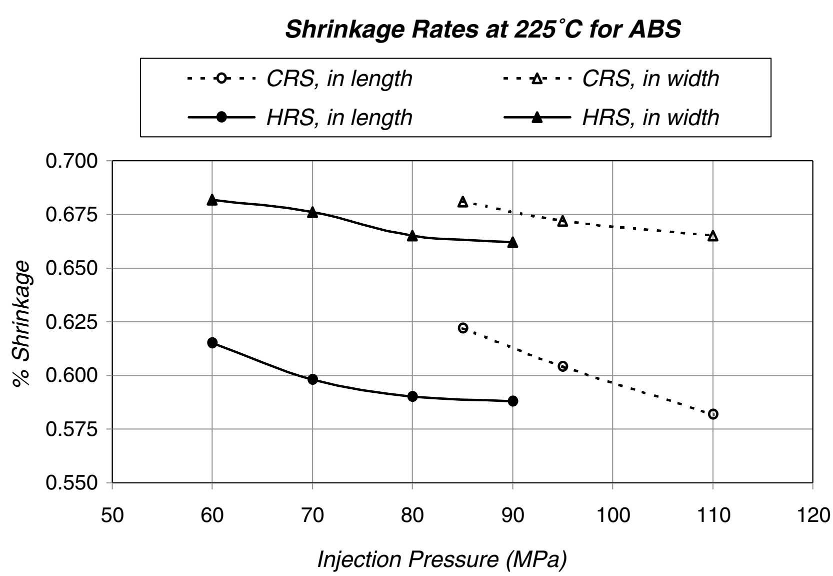

Fig. 6. Shrinkage rates in length and width vs. injection pressure at 225 °C for ABS polymer.

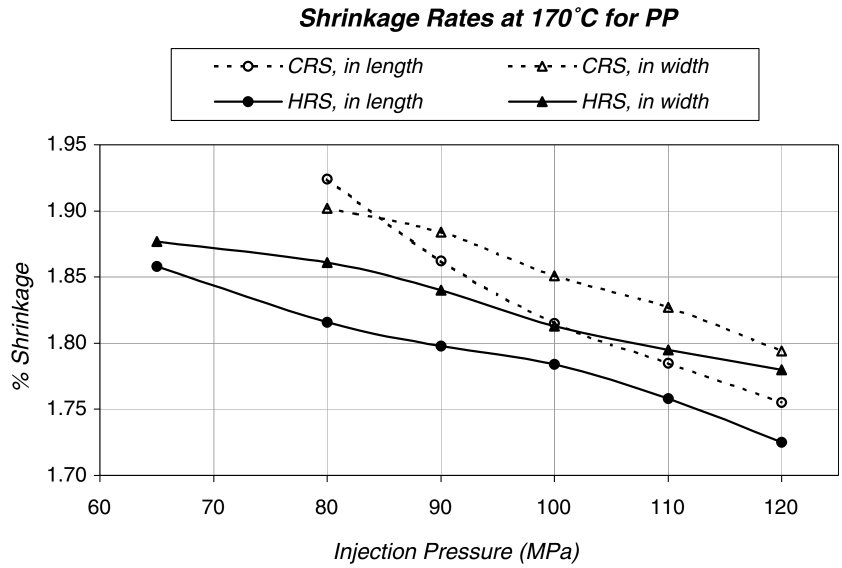

Fig. 7. Shrinkage rates in length and width vs. injection pressure at 170 °C for PP polymer.

Table 4
Average shrinkage rates in length and width for ABS and PP polymers

	Shrinkage rates (%)	
	ABS (at 225 °C)	PP (at 170 °C)
CRS, in length	0.603	1.828
CRS, in width	0.673	1.852
HRS, in length	0.598	1.790
HRS, in width	0.671	1.827

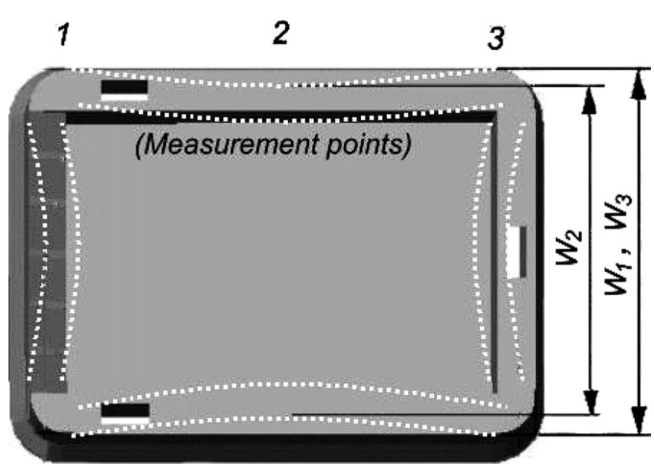

Fig. 8. Definition of warpage on top view of the injected part.

is used to fill the remaining volume of the cavity and to compensate for shrinkage in cooling stage. An appropriate packing pressure and time can reduce the shrinkage of the injected part and warpage caused by uneven shrinkage. Therefore, the packing pressure and the packing time are the most important process parameters for reducing the shrinkage and warpage. This point is highlighted by some other researchers [2–5]. When using HRS on multi-cavity moulds, nozzle-gate can be located symmetrically for each cavity, and weakening tendency of packing pressure on outer regions from the gate can be reduced by decreasing the ratio of flow length to the thickness.

In the experiments performed in this research, it is noticed that warpage generally occurs on long-side wall of the injected part, after taking it out from the mould. Therefore, the warpage definition is described by taking length-wise warpage into consideration, as shown in Fig. 8. Ten days after the experiments, the related measurements were performed at three points of the part and the amount of single-side warpage was calculated by using the following equation:

$$\text{Single-side warpage}: W = [(W_1 + W_3)/2 - W_2]/2 \qquad (3)$$

A comparison of the minimum warpage rates for ABS and PP polymers in the case of using both runner systems vs. pressure at the stages of process temperature is presented in Figs. 9 and 10. In these figures, the measurement points are presented on the horizontal axis, and the values of single-side warpage were presented on the vertical axis. These figures show that increasing process temperature leads to increasing warpage generally. The process temperature and injection pressure providing minimum warpage occurrence were realized at 260 °C/60 MPa for CRS and 225 °C/90 MPa for HRS when using ABS polymer, and 170 °C/120 MPa for CRS and 200 °C/40 MPa for HRS when using PP polymer.

6. Effect of runner system on sample weight

Saint-Martin et al. [9] studied the effect of holding pressure, mould and melt temperatures and injection speed on the density of the injection-moulded part and the voids rate inside the part. They found that the hydraulic holding pressure level is the most relevant parameter. When the hydraulic pressure level increases, the polymer pressure inside the

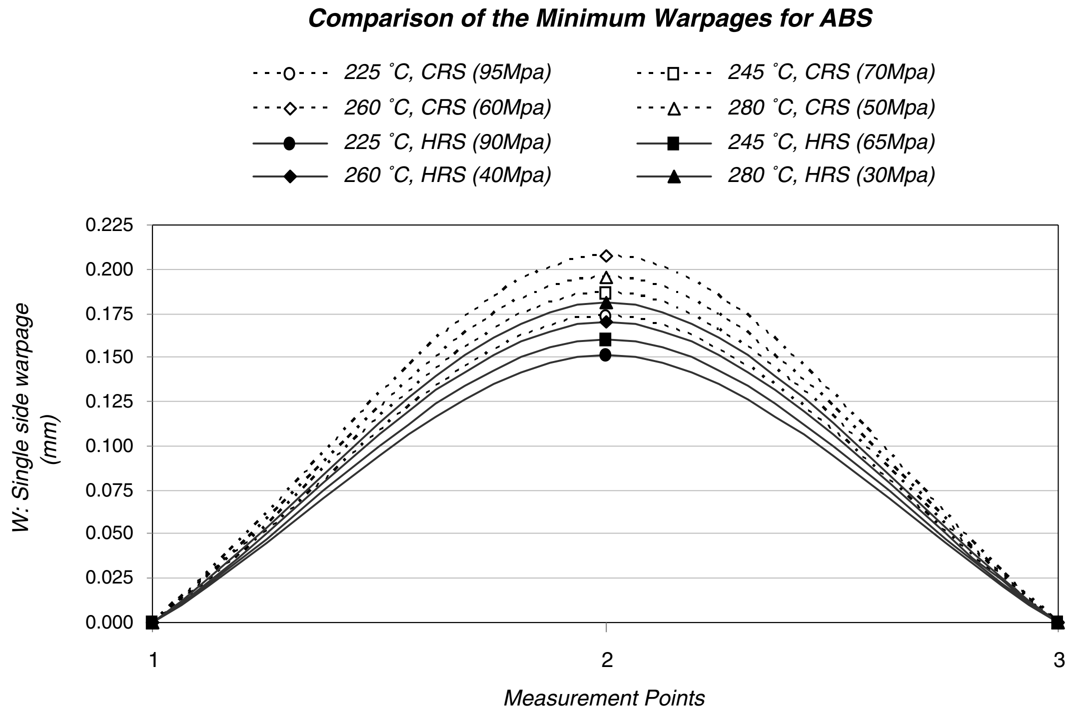

Fig. 9. Comparison of the minimum single side warpages for ABS vs. temperature and pressure when using both HRS and CRS.

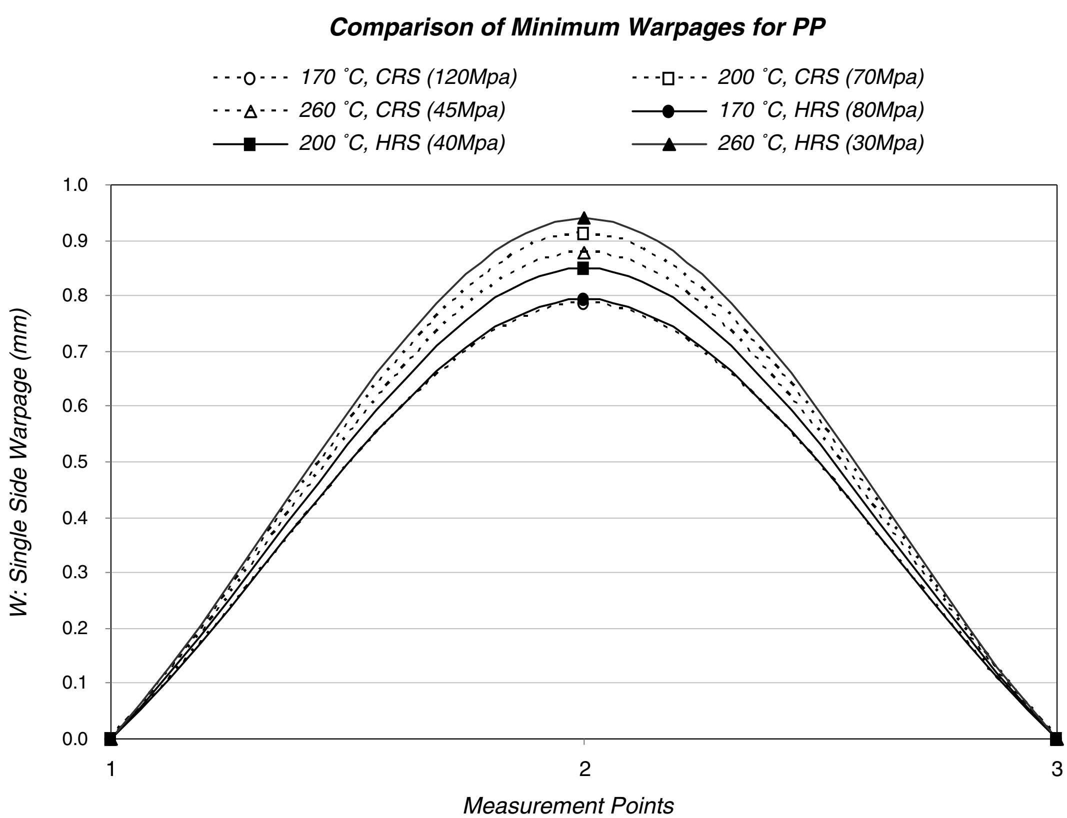

Fig. 10. Comparison of the minimum single side warpages for PP material vs. temperature and pressure when using both HRS and CRS.

cavity decreases more slowly, the shrinkage compensation becomes more efficient, and the voids rate goes to zero level. They reported that the mould and melt temperatures also affect parameters, while the injection speed is non-significant. As voids can lead to stress concentrations and early failure of the part, decreasing the void rate in injection-moulded part (i.e., increasing the density and weight of the part) is crucial. In the case of using HRS, the dis-

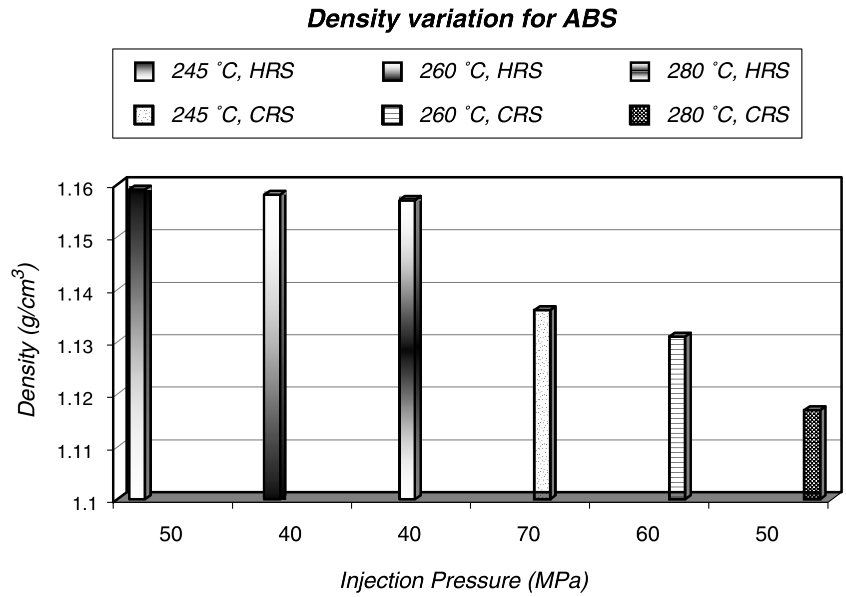

Fig. 11. Density variation of the injected parts vs. process temperature and injection pressure for ABS polymer when using both HRS and CRS.

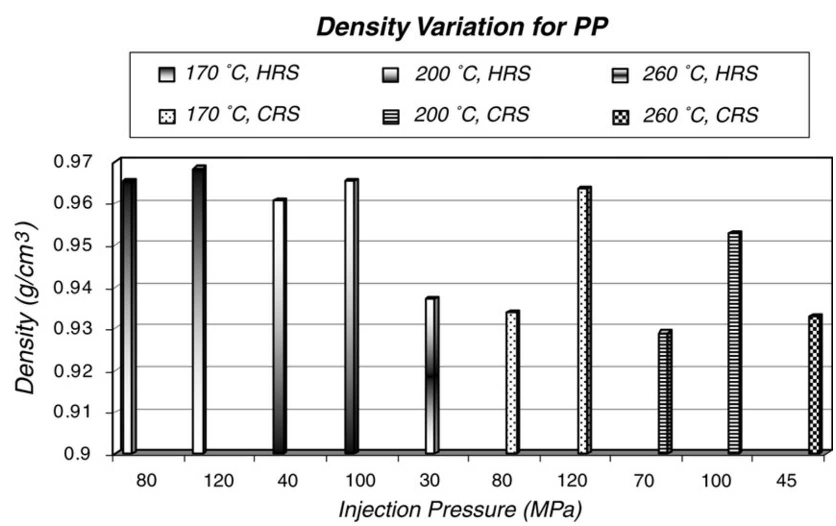

Fig. 12. Density variation of the injected parts vs. process temperature and injection pressure for PP polymer when using both HRS and CRS.

Table 5
Density variation of the injected parts vs. process temperature and injection pressure for base polymers when using both HRS and CRS

Base polymer	Process temperature (°C)	HRS		CRS	
		Injection pressure (MPa)	Density (g/cm^3)	Injection pressure (MPa)	Density (g/cm^3)
ABS	245	50	1.159	70	1.136
	260	40	1.158	60	1.131
	280	40	1.157	50	1.117
PP	170	80	0.9652	80	0.9337
		120	0.9683	120	0.9636
	200	40	0.9605	70	0.9290
		100	0.9655	100	0.9258
	260	30	0.9370	45	0.9330

tance between the outermost edge of the part and the gate is smaller due to the nozzle location, and the pressure and heat losses are also lower due to the eliminating sprue. Thus, the packing pressure and the melt temperature, which are the most influential process parameters on the void generation as mentioned above, can be controlled more easily and accurately, so higher sample weights are achievable [10].

The weights of the parts produced in the experiments were measured after 30 days. Figs. 11 and 12 show the variations in densities of the injected parts vs. injection pressure for the experimented temperatures. According to these figures, the density of the injected parts is higher at low temperatures than that of high temperatures. The increasing effect of injection pressure on density is also noticeable from the figures. It was observed that the densities of the samples increased with the increasing injection pressure. Determined sample densities vs. process temperature and injection pressure are presented in Table 5.

Since the polymer can be compressed, high pressure results in a high density product. Minimizing the pressure and heat losses is possible by shortening flow length due to absence of the sprue, and the central gate location in the moulds using HRS. Therefore, the same pressure level is more influential in the cavity of the mould using HRS than the mould using CRS. When investigating both runner systems comparatively, it can be seen that higher weights of injected parts are achievable at the same process temperature in the case of HRS. The increase of density varies between 2.02% and 3.58% for ABS polymer, and 0.43 and 3.39% for PP polymer.

7. Conclusion

In this experimental study, optimal process conditions, variations in length-wise and width-wise shrinkage rates, warpage rates and densities of samples produced of ABS and PP polymers were determined with respect to the changes in process temperature and injection pressure when using HRS, in comparison with CRS. It was observed that the required injection pressure in HRS was considerably lower. When using HRS, injection moulding process can be performed at lower process temperature and injection pressure than the case of using CRS. It was noted that the pressure gain can reach up to 33.33% for ABS and 42.85% for PP. Such a saving in required power results in accordingly less energy consumption by the injection moulding machine and hence smaller machines with less power can be utilized for producing relatively large components. This gain reduces the requirement for mould clamping force, increases the lifetime of the mould and injection machine, and allows the significant cuts in production costs.

It was observed that the shrinkage rate decreased with increasing injection pressure for both runner systems. Results showed that the usage of HRS decreases the shrinkage rates for both of the polymers in comparison with CRS. This shrinkage-decreasing effect of HRS results from more influential packing stage due to late solidification of the gates, lower heat and pressure losses and better fluidity of molten plastic.

When using HRS on multi-cavity moulds, nozzle-gate can be located symmetrically for each cavity. Thus, weakening tendency of packing pressure on outer regions from the gate can be reduced by decreasing the ratio of flow length to thickness. This provides decrease in pressure losses, contributes to achieving more influential packing stage and reduction in shrinkage and warpage.

It was observed that the shrinkage and warpage rates generally increase with the increase of process temperature. It was noted that the shrinkage rates in length and width were not the same. This diversity caused by cooling conditions and flow direction of melt in the cavity is decreased with using HRS.

It is found that higher sample densities are achievable when using HRS than in the case of using CRS. It is noted that the increase in density can reach up to 3.58% and 3.39% for ABS and PP polymers, respectively. Increase in weight and density of injected parts implies that their mechanical properties become better due to denser structure. Another interesting point is that low rates of shrinkage and warpage occur when the weight is high. In order to produce the sample having dimensional stability and low rate of shrinkage and warpage, the injection pressure providing the highest sample weight can be adopted by experimenting different values of pressure at defined temperature.

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