Materials and Design 30 (2009) 3217–3224

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

Experimental investigation of plastic injection molding: Assessment of the effects of cavity pressure and mold temperature on the quality of the final products

Mustafa Kurt *, O. Saban Kamber, Yusuf Kaynak, Gurcan Atakok, Oguz Girit

Marmara University, Technical Education Faculty, 34722 Kadikoy-İstanbul, Turkey

ARTICLE INFO

Article history:
Received 21 November 2008
Accepted 2 January 2009
Available online 10 January 2009

ABSTRACT

Today more than ever, the molding industry demands better product quality. The quality of molded parts is crucial with regard to their functional capacity, and hence a great deal of attention should be directed towards maintaining consistent tolerances and overall dimensions. As the demand for high quality final parts continues to increase, the controlling parameters of cavity pressure and mold temperature become ever more significant in the plastic injection molding process. Therefore, in this research, cavity pressure and mold surface temperature have been measured and recorded by pressure and temperature–pressure sensors using a Kistler CoMo 2869A injection-type apparatus. The influences of the measured factors on the quality of the final parts have been investigated experimentally. The results of this experimental study indicate that cavity pressure and mold temperature are the dominant factors determining the quality of the final product in plastic injection molding.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Mold making is an important supporting industry because the related products constitute more than 70% of the components in consumer products. The high demand for shorter design and manufacturing lead times, good dimensionality and overall quality, as well as rapid design changes has led to bottlenecks in mold industries [1]. Injection molding is a complex but highly efficient means of producing a large variety of thermoplastic products, including those with tight tolerances and complex shapes [2]. In addition, injection molding has many advantages, such as short production cycles, excellent surfaces of the products, and facile molding of complicated shapes, so it is the most popular molding process for making thermoplastic parts [3]. For instance, the development of communication and electronic consumer products, such as portable computers and mobile telephones, etc., has led to a trend for products to be light, thin, short, and small. The concept of product design insists on smaller and more convenient products. As a result, the shapes of products are changing and more features (i.e., the internal components) have to be packed into smaller volumes within the housing. The main means of producing plastic product housings is to use injection molding. However, as the wall thickness of plastic parts becomes thinner, the injection molding operation becomes more difficult. Hence, there is a demand in the industry for plastic injection molding techniques capable of producing plastic parts with thin wall features.

The procedure of injection molding may be described as follows. Firstly, the raw material is heated to its melting temperature. By means of high pressure, the melted polymer is injected into the cavity via a delivery system and a gate. When filling is nearly complete, the cavity is maintained at a constant pressure for the packing stage. Packing pressure is used to fill all the remaining volume of the cavity and to compensate for shrinkage during the cooling stage. After the interior of the cavity has become stable, the product is ejected from the mold [4]. The quality of the final molded part, which may be characterized in terms of dimensional stability, appearance, and mechanical properties, is highly dependent on the processing variables [5]. Defects in the products, such as warpage, shrinkage, sink marks, and residual stress, are caused by many factors during the production process. These defects are detrimental to the quality and accuracy of the products. Therefore, it is of critical importance to effectively control the influencing factors during the molding procedure [4].

Several comprehensive studies have hitherto been undertaken with a view to investigating the influences of cavity pressure and temperature on the final quality of molded parts. Postawa and Koszkul [6] presented the changes in shrinkage and weight of injection-molded parts as a function of processing conditions. Jansen et al. [7] measured the shrinkage of seven types of plastics to investigate the effects of molding conditions. The significant molding parameters were reported to be the packing pressure and the melt temperature. Kazmer and Barkan [8] investigated multi-cavity pressure control in the filling and packing stages of the injection-molding process. Their study showed cavity pressure to be a critical factor for the injection molding of high quality parts. Bushko

* Corresponding author. Tel.: +90 216 336 57 70; fax: +90 216 337 89 87.
E-mail address: mkurt@marmara.edu.tr (M. Kurt).

0261-3069/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2009.01.004

et al. [9] studied the effects of process conditions on the warpage, shrinkage, and residual stresses of thermo-viscoelastic melts between two parallel plates. Zhang et al. [10] designed a wireless sensor for cavity pressure measurement in injection molding, with which they obtained some notable results. Titomanlio et al. [11] investigated the influence of in-mold shrinkage on the dimensions and residual stress distributions of the final products. Angstadt and Coulter [12] investigated the relationship between cavity pressure and part quality in the injection molding process. According to their research, the use of cavity pressure as an indicator of part quality has significant potential.

It is clear from the above literature survey that the effects of cavity pressure and temperature on warpage and shrinkage of the produced parts have been generally investigated by researchers. However, the final part quality may not only be limited by warpage or shrinkage. To capture dimensional validity, measurements of the part must include lateral measurements. In this way, the relationship between the results of measurements and the molding parameters can be understood in depth.

On the other hand, most of the studies performed to date have relied solely on computer-based simulation results [13–16]. Generally speaking, the presented results of this kind of study are acceptable, but under some circumstances there may be differences between the simulation and experimental results. Although the cost of experimental study is high, it is necessary in order to obtain more accurate results. For such experimental study, in order to completely understand the effects of variable parameters on the quality of the obtained parts, it is necessary to use sensitive measurement devices. In this way, trustworthy results can be obtained from the experimental research.

In this study, the plastic injection molding process has been comprehensively investigated by considering the influence of process parameters on the quality of the final parts. Values of cavity pressure and mold temperature were taken from sensors placed inside the molds rather than from measuring devices within the injection machine. It is hoped that the results obtained from this study may be beneficial to both researchers and manufacturers.

2. Experimental study

2.1. Mold design and fabrication

To produce suitable specimens (Fig. 1), a mold was modeled (Fig. 2) and fabricated in the laboratory (Fig. 3). As shown in Fig. 3, four cavity inserts were used in this research. A dimmer cover is used for some kinds of home appliances. For assembly of such parts, the dimensional and positional tolerance is tight. The tolerance of the part during the plastic injection molding process has therefore been considered.

2.2. Molding procedures

This experiment was conducted on a Haitian type HTW58 injection molding machine with 244 MPa injection pressure, 25 mm screw diameter, and 2.43 ton ejector tonnage. The initial molding parameters for the experimental study were determined by consulting the literature and considering industrial application. The experiments were performed with varying packing pressures ranging from 850 bar to 1000 bar and melt temperatures ranging from 185 °C to 225 °C; in all cases, the cooling time was 25 s. The material used in the experiments was acrylonitrile–butadiene–styrene copolymer (ABS). ABS thermoplastic resins are made with a wide range of properties, and are suitable for injection molding to produce products of exceptional dimensional stability and secondary

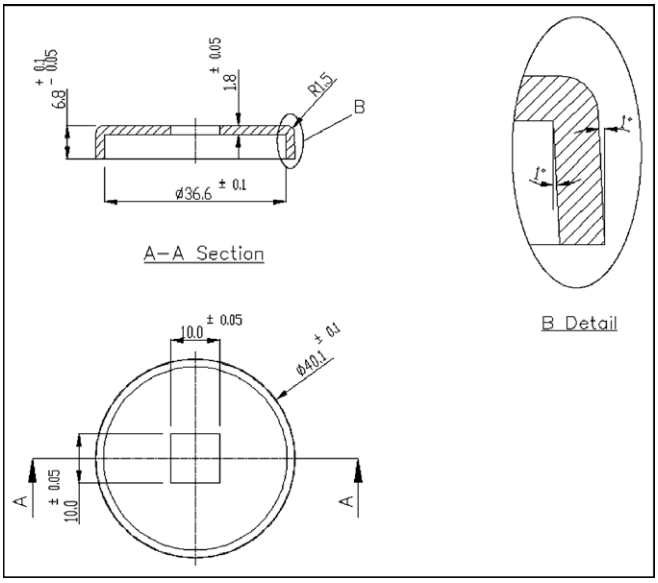


Fig. 1. Geometry and dimensions of the specimen.

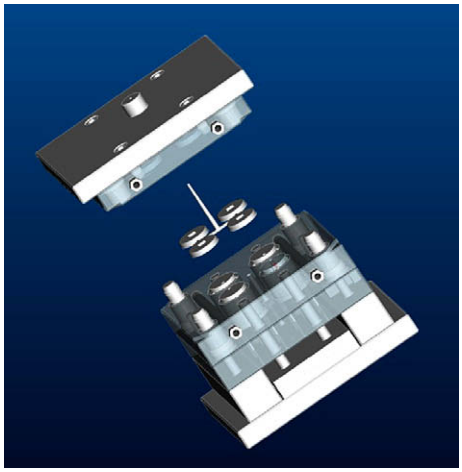


Fig. 2. Modeling of plastic injection mold.



Fig. 3. Layout of cavities and runner system in the plastic injection mold.

Table 1
Mechanical properties of ABS.

Properties	Tensile strength	Elongation	Flexural strength	Impact trength	Rockwell hardness
Condition	23 °C	23 °C	23 °C	6.1 mm	
Method (ASTM 750)	D 638	D 638	D 790	D 256	D 785
Unit	kg/cm^2	%	kg/cm^2	kg cm/cm	R-scale
General purpose	500	30	600	21	104

processability for plating, painting, etc. The properties of the ABS used in this study are summarized in Table 1.

2.3. Measurements of injection pressure and temperature

As the demand for high-quality plastic injection molding continues to increase, controlling the injection pressure and temperature for plastic injection molding machines becomes ever more crucial. To control these parameters, sensors capable of detecting pressures and temperatures during processes, so as to implement a feedback control for the injection molding machine, can be used. Although the sensing of pressure can increase the cost of experimental study, this research can be expected to improve the accuracy of scientific studies. In such studies, a significant aspect of implementing process controls is the proper placement of these sensors. The most reliable measurements can only be made by using properly placed sensors.

In this study, cavity pressure and temperature have been monitored by means of an instrumentation system employing three Kistler 6157BA piezoelectric pressure transducers in the cavity and a 6190BAG temperature–pressure combined transducer. A Kistler CoMo 2869A injection-type apparatus has been used for cavity pressure-based optimization, control, monitoring, and documentation of the injection molding process. The CoMo injection-type apparatus has eight channels and is supplemented by a database system with statistical functions and reporting. This all-in-one unit

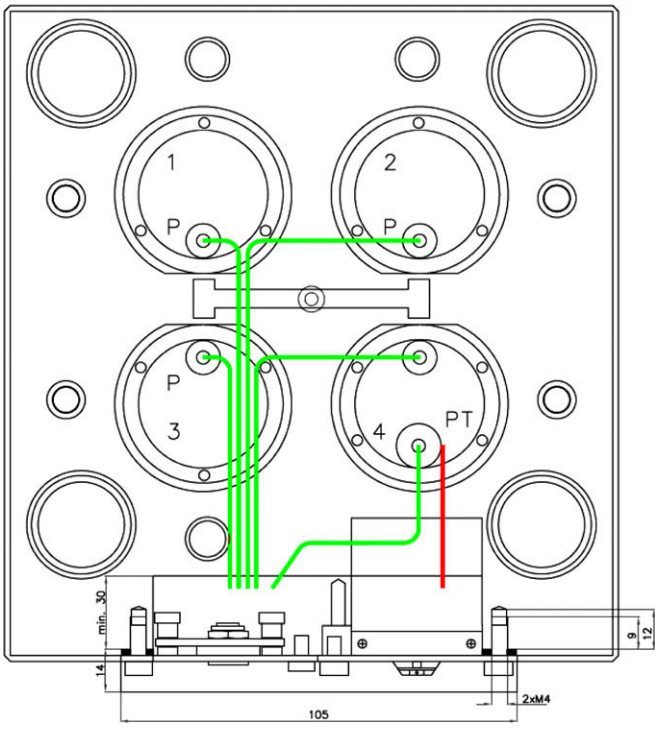


Fig. 4. Locations of sensors in the mold.

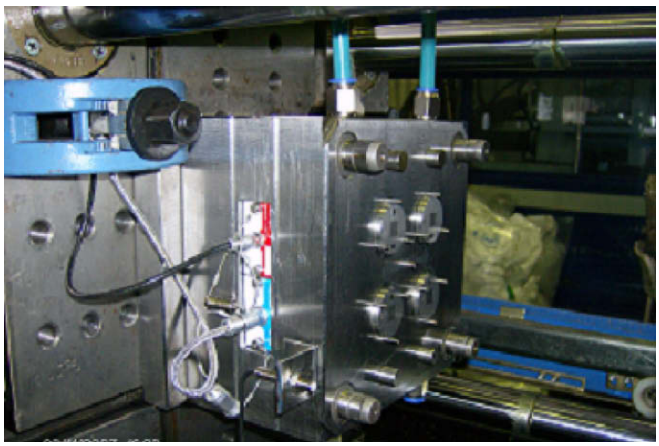


Fig. 5. The location of the pressure and temperature connectors.

contains all the functions needed for evaluating the injection molding process. Signals can be directly acquired and evaluated from the injection molding machine as well as from piezoelectric cavity pressure sensors. The charge amplifiers have a measuring range of 2000–50,000 pC. The voltage inputs have a measuring range of 0–10 V [17]. Hence, these sensors are suitable for direct pressure and temperature measurements from the cavities of the mold. The locations of these sensors are shown schematically and photographically in Figs. 4 and 5, respectively. The pressure sensors were placed at one-third of the distance from the gate in the first three cavities. The pressure–temperature combined sensor, however, was placed at the other side of the fourth cavity.

2.4. Measurements of deflections

In order to determine the deflections of parts, an ATOS system was used. The automated ATOS So system (three-dimensional optical scanner) scanned the produced parts without the need for special fixtures or reference markers on the part. Then, the ATOS system automatically created the final mesh after scanning. Additionally, the CAD data (obtained using Pro/Eng software) were imported into the ATOS system. Finally, the scanned data were registered into the CAD data to calculate and display the deviations of the two data sets by using GOM software (Fig. 6).

The following quality attributes were measured: (1) y-direction shrinkage, (2) x-direction shrinkage, and (3) cyclicity of the part (see Fig. 7). A sample of the products is shown in Fig. 8.

3. Results and discussion

3.1. Evaluation of cavity pressure

In the injection molding process, cavity pressure is a good indicator for achieving high part quality and maintaining consistent tolerances and overall dimensions. Its trajectory during the filling phase of injection is highly dependent on other molding variables. Repeatable control of cavity pressure is therefore vital for producing parts with tight tolerances [18]. Shrinkage variations along the flowpath are usually directly related to the local cavity pressure [7], from which the importance of cavity pressure with regard to the final quality of parts readily becomes apparent. To achieve better product quality and control of the process, the measurement of cavity pressure during the injection phase requires sensitive measurement devices for an effective experimental study. In this study, a pressure sensor was placed in each cavity to measure the pressure therein. The fourth pressure sensor was placed at a different

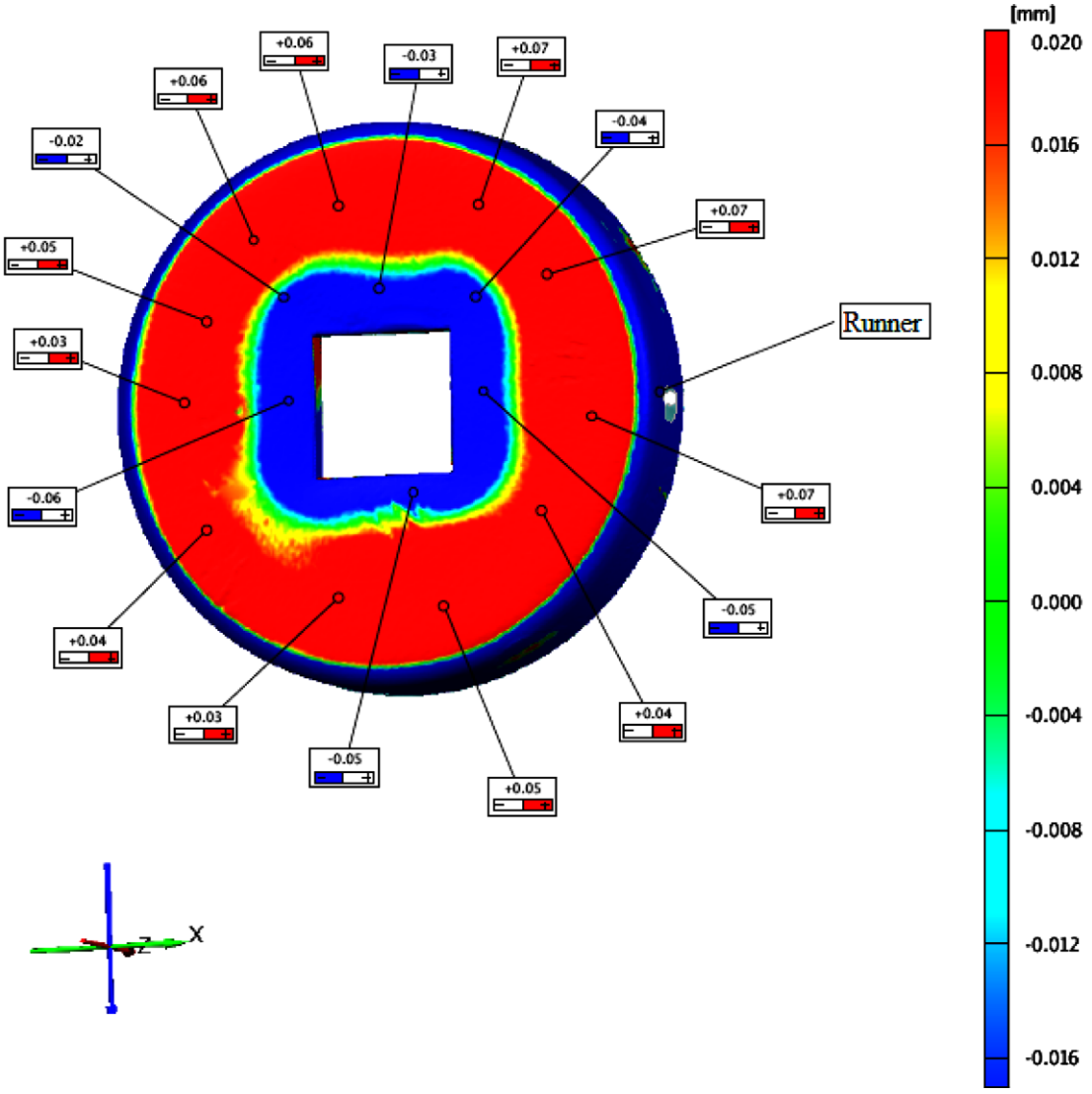


Fig. 6. Sample of GOM results.

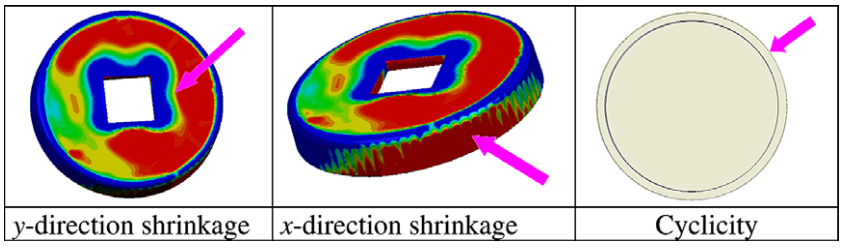


Fig. 7. Measurements of *x*- and *y*-direction shrinkages and cyclicity of parts.

distance from the flowpath compared to the other three cases. The aim of this different placement was to probe the effect of distance from the flowpath on the obtained cavity pressure.

Fig. 9 shows the measured pressure results from each cavity of the mold. One of the important results of this study, which is readily apparent from Fig. 9, is that the obtained pressure values from each cavity are different. Although the geometry of mold is theoretically symmetric, the reasons of these differences can be probably the unbalanced runner system and the gates. The absolutely uniform mold is necessary to encourage uniform filling and holding similar rate pressure within all cavities, otherwise, these differences can cause the production of varied quality parts.

Although different initial conditions were used, similar results are apparent from Fig. 10, corroborating those from Fig. 9. The effect of sensor position on the obtained results from the molding process can be shown Fig. 9 and 10. The cavity pressure increases with rising cavity number in each of our experiments. However, pressure values of the fourth cavity are lower than pressure values

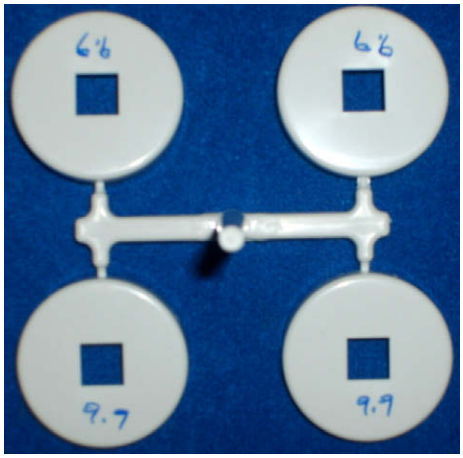


Fig. 8. A sample of the products.

of the third cavity. This is because of the distance of the measuring point from the flowpath. This is the second important result from this study. The relationship between the initial molding parameters and the cavity pressure can be observed by comparing Figs. 9 and 10. When the melt temperature was increased from 185 °C to 200 °C, the cavity pressure also increased. Our experimental results are supported by the study of Dubay et al. [19]. According to their research, melt temperature affects a velocity flow into the mold and cavity pressure.

3.2. Evaluation of mold temperature

According to some researchers, such as Liu and Mamat, one of the most critical parameters determining the final quality of the products is the mold temperature [20,21]. Liu found that as the mold temperature was increased, the quality of the final part could deteriorate; however, Mamat reached a different conclusion. In order to delineate the actual influence of mold temperature on the quality of the final parts, specifically shrinkage and cyclicity, comprehensive measurements are required. Plots of mold temperature measurements with varying initial conditions are shown in Fig. 11. These plots illustrate the relationship between two important initial parameters (packing pressure and melt temperature) and mold temperature. It is evident from Fig. 11 that the effect of packing pressure on mold temperature is less than that of melt temperature. The collected data from the present experimental study show that when the melt temperature was increased from 185 °C to 225 °C, the mold temperature increased from 50.56 °C to 56.88 °C. When the packing pressure was increased from 850 bar to 900 bar at a temperature of 200 °C, the mold temperature increased by only 0.18 °C, which can be regarded as negligible. Hence, this influence on mold temperature can be neglected. The dominant factor responsible for increasing the mold temperature is clearly the melt temperature. A further significant result from this study is that the rise and fall of the mold temperature follows a similar pattern irrespective of the initial conditions. This regular behavior of the mold temperature may help to improve the reliability of the prediction software that is used to predict and control plastic injection molding processes.

3.3. Effects of the cavity pressure and mold temperature on the quality of the final parts

In order to evaluate the effects of cavity pressure and mold temperature on the quality of the final parts, the products obtained from the third cavity were considered because the maximum values of cavity pressure (P_{max}) and mold temperature (T_{max}) were recorded by the sensors in this cavity. Experimental results have

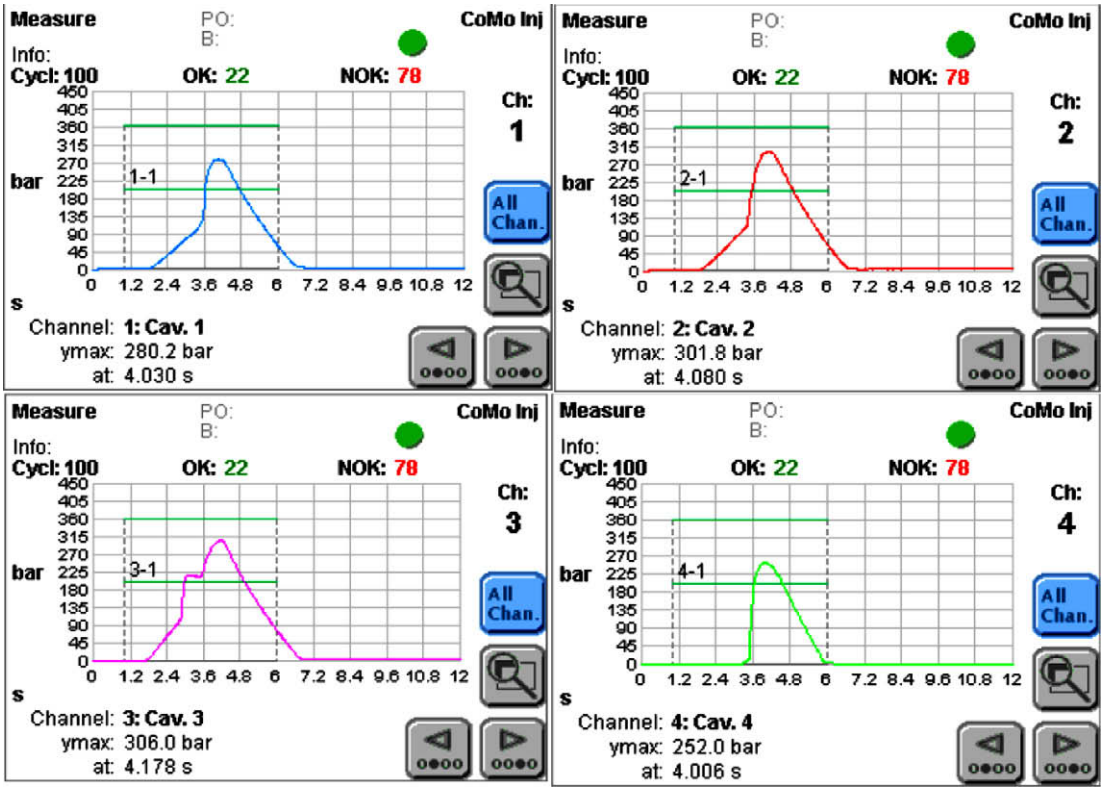


Fig. 9. Plots of cavity pressure vs. time (packing pressure 900 bar; melt temperature 185 °C).

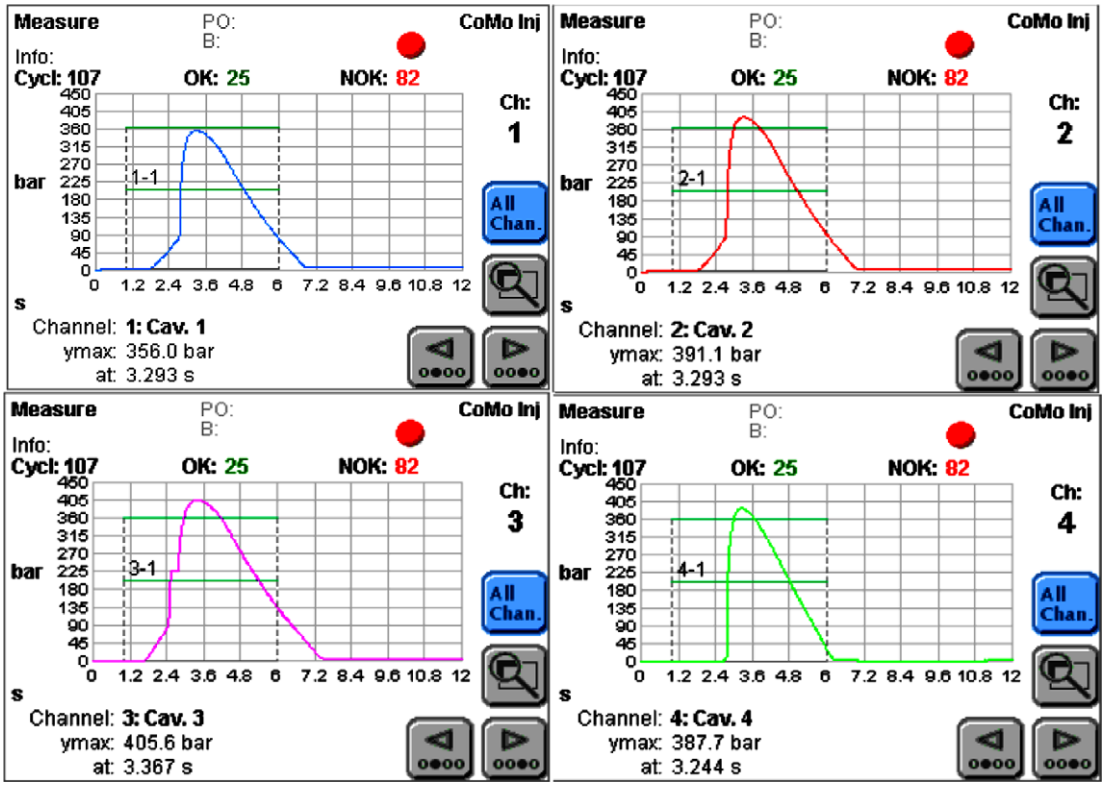


Fig. 10. Plots of cavity pressure vs. time (packing pressure 900 bar; melt temperature 200 °C).

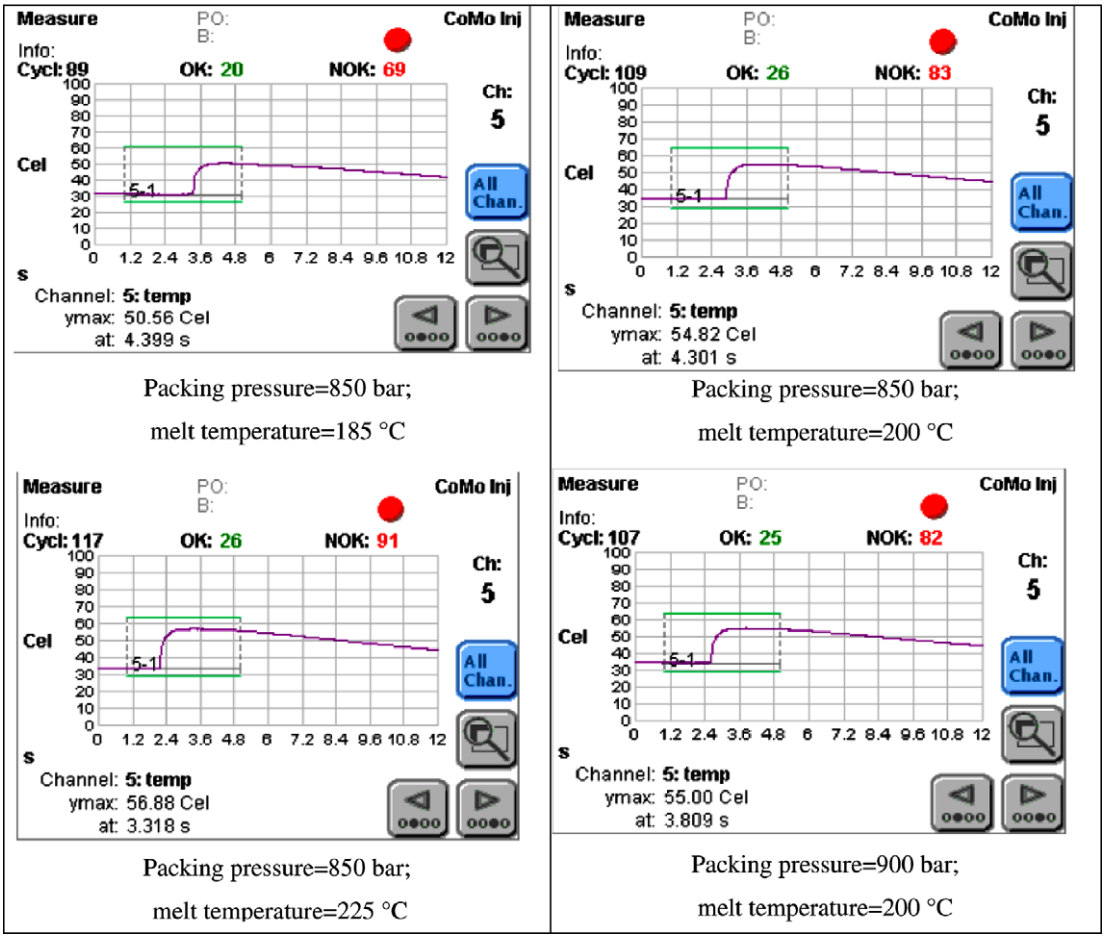


Fig. 11. Plot of mold temperature.

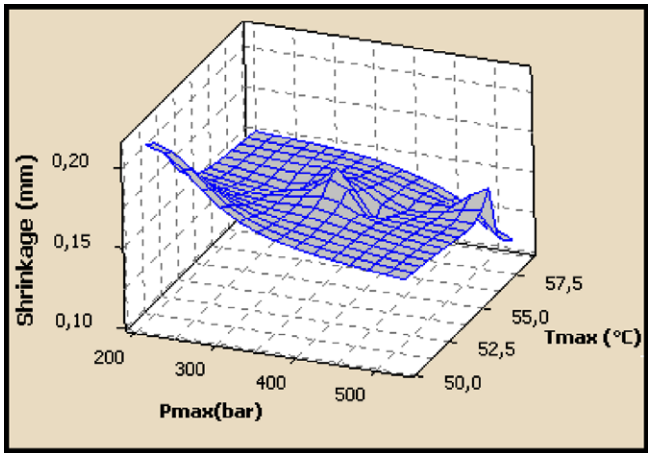


Fig. 12. Shrinkage in the *y*-direction vs. maximum mold temperature and maximum cavity pressure.

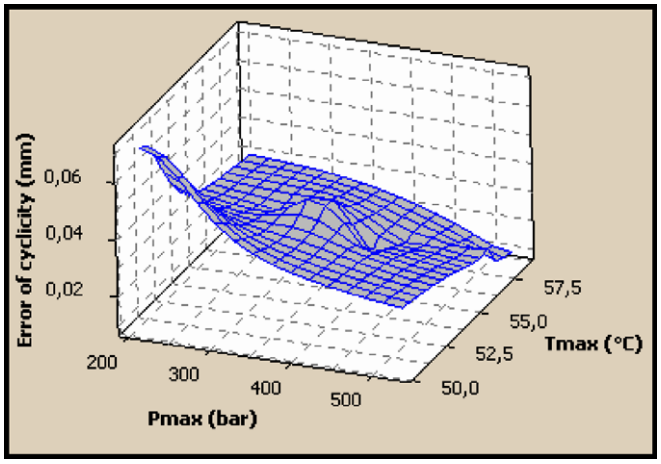


Fig. 14. Error of cyclicity vs. maximum mold temperature and maximum cavity pressure.

shown that the final dimensional quality of a part, such as the shrinkages in the *y*- and *x*-directions and cyclicity, is affected by the cavity pressure and mold temperature during the filling stage of the molding process. Figs. 12 and 13 show shrinkages in the *y*- and *x*-directions vs. the maximum mold temperature and maximum cavity pressure. The plots illustrate that the shrinkages of the part in the *y*- and *x*-directions are affected to different extents by cavity pressure and mold temperature. Both of these control parameters have strong effects on shrinkage of the product in the *y*- and *x*-directions; specifically, the higher the cavity pressure and mold temperature, the smaller the shrinkage of the product in the *y*- and *x*-directions. However, these relationships are not completely linear, as is evident from the figures. According to the experimental study and the measurements results, the definition of these unexpected rising which can be shown in the middle of the charts in Figs. 12 and 13, may not be exactly explainable. The reasons of this situation can be sharply changing of the cavity pressure and mold temperature in the mold. However, controlling each point of cavity is not possible during molding process. Yet, the general inclination of shrinkage rates with cavity pressure and mold temperature can produce acceptable opinion about process.

Fig. 14 shows the error of cyclicity vs. maximum mold temperature and maximum cavity pressure. As in the case of shrinkage in the *y*- and *x*-directions, the effects of the control parameters on the cyclicity of the product are significant. The error of cyclicity is higher at low cavity pressure and low mold temperature, and decreases as the cavity pressure is increased. Furthermore, the influence of the mold temperature on the accuracy of cyclicity becomes more pronounced as the cavity pressure is increased.

To produce better quality products, the shrinkage values must be decreased. As is evident from the figures, use of the optimal cavity pressure and mold temperature led to a 50% decrease in the shrinkage. While this is a notable improvement, by using the relationship between the initial parameters of cavity pressure and mold temperature, it may be possible to develop models and to determine optimal molding conditions by statistical techniques.

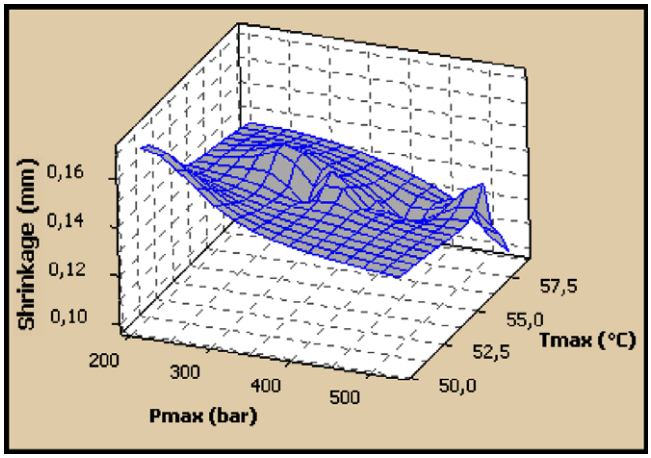


Fig. 13. Shrinkage in the *x*-direction vs. maximum mold temperature and maximum cavity pressure.

4. Conclusions

In this study, the dimensional accuracy of molded parts has been accurately delineated and analyzed by using effective experimental measurement techniques, highlighting the relationships between cavity pressure and mold temperature and the dimensional quality of the final parts. The following conclusions can be drawn:

- Continuous sensitive measurement and data collection from a multi-cavity mold have been successfully performed by using piezoelectric pressure transducers and a pressure–temperature combined transducer.
- The distance of the measuring point from the flowpath affects the obtained data values.
- The pressure values obtained from each cavity are different. Because of the unbalanced runner system and the gates.
- The rise and fall of the mold temperature follows a similar pattern, irrespective of the initial conditions.
- The cavity pressure and mold temperature strongly affect the shrinkage of the product in the *y*- and *x*-directions and its cyclicity. Specifically, the higher the cavity pressure and mold temperature, the smaller the shrinkage in the *y*- and *x*-directions and the lower the error of cyclicity of product.

References

[1] Fu MW, Fuh JYH, Nee AYC. Undercut feature recognition in an injection mould design system. Comput Aided Des 1999;31:777–90.
[2] Zhai M, Lam YC, Au CK, Liu DS. Automated selection of gate location for plastic injection molding processing. Polym Plast Technol Eng 2005;44:229–42.
[3] Shi F, Lou ZL, Lu JG, Zhang YQ. Optimisation of plastic injection moulding process with soft computing. Int J Adv Manuf Technol 2003;21:656–61.

[4] Huang MC, Tai CC. The effective factors in the warpage problem of an injection-molded part with a thin shell feature. J Mater Process Technol 2001;110:1–9.
[5] Yang Y, Gao F. Adaptive control of the filling velocity of thermoplastics injection molding. Control Eng Practice 2000;8:1285–96.
[6] Postawa P, Koszkul J. Change in injection moulded parts shrinkage and weight as a function of processing conditions. J Mater Process Technol 2005;162–163:109–15.
[7] Jansen KMB, Dijk DJV, Husselman MN. Effect of processing conditions on shrinkage in injection molding. Polym Eng Sci 1998;38:838–46.
[8] Kazmer D, Barkan P. Multi-cavity pressure control in the filling and packing stages of the injection molding process. Polym Eng Sci 1997;37:1865–79.
[9] Bushko WC, Stokes VK. Solidification of thermoviscoelastic melts. 3. Effects of mold surface-temperature differences on warpage and residual stresses. Polym Eng Sci 1996;36:322–35.
[10] Zhang L, Theurer CB, Gao RX, Kazmer DO. Design of a wireless sensor for injection molding cavity pressure measurement. Department of Mechanical and Industrial Engineering. University of Massachusetts, Amherst, MA 01003; 2001.
[11] Titomanlio G, Jansen KMB. In-mold shrinkage and stress prediction in injection molding. Polym Eng Sci 1996;36:2041–9.
[12] Angstadt DC, Coulter JP. Cavity pressure and part quality in the injection molding process. Intell Mater Manuf Lab, Pennsylvania, USA: Lehigh University.
[13] Tang SH, Kong YM, Sapuan SM, Samin R, Sulaiman S. Design and thermal analysis of plastic injection mould. J Mater Process Technol 2006;171:259–67.
[14] Garcia N, Gonzalez E, Baselga J, Bravo J. Critical thickness estimation in ISO-MC cards injection using CAE tools. J Mater Process Technol 2003;143–144:491–4.
[15] Turng LS, Peic M. Computer-aided process and design optimization for injection moulding. IMechE 2002;216:1523–32.
[16] Ozcelik B, Sonat I. Warpage and structural analysis of thin shell plastic in the plastic injection molding. Mater Des 2009;30:367–75.
[17] <http://www.kistler.com/>.
[18] Dubay R. Predictive control of cavity pressure during injection filling. ANTEC 2001:3351–4.
[19] Diduch C, Dubay R, Li WG. Temperature control of injection molding. Part I: modeling and identification. Polym Eng Sci 2004;44:2308–17.
[20] Liu C, Manzione LT. Process studies in precision injection molding. I: Process parameters and precision. Polym Eng Sci 1996;36:1–9.
[21] Mamat A, Trochu TF, Sanschagrin B. Analysis of shrinkage by dual kriging for filled and unfilled polypropylene molded parts. Polym Eng Sci 1995;35:1511–20.