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The analysis of injection molding defects caused by gate vestiges

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Abstract. Issues of product safety are the most serious problems of an injection molded product due to their risk to human health. Such a safety problem can be the needle-shaped vestige at the gate zone of injection molded products, called a gate vestige. Only observations of the formation of gate vestiges can be found in the literature, but the processing parameters influencing their dimensions, especially their height have not been studied yet. Our goal was to study the effect of various injection molding processing parameters and gate constructions on gate vestige formation.

Keywords: *processing technologies, injection molding defect, damage mechanism, gate vestiges, 3-plate mold*

1. Introduction

In the 21st century modern plastics have more and more roles and are so widespread that they are a part of our everyday lives. Their consumption has become a benchmark of how developed a country is. In the injection molding cycle defects can occur, such as burn marks [1], delamination [2], flash [3], jetting [4], sink marks [5], weld lines [6] or warpage [7] and these can cause injection molded parts to be rejected.

Typically, the most serious are problems that could damage the mold and/or affect product safety. Such a product safety problem can be a so-called gate vestige, which is a remnant of the gate, thus a separation phenomenon between the runner and the product. The size and shape of the vestige depend mostly on the shape of the gate (mold design) and the processing parameters.

The elimination or moderation of gate vestiges by using various valve gates in the case of a hot runner system are widely investigated [8]. Valve gates like reciprocating pinpoint gates have a mechanically activated pin that shuts off the gate as the pin moves forward, which provides mechanical sealing and a relatively clean vestige [9, 10]. These valve gates provide the most control over gate vestiges but they significantly increase the complexity of the mold and introduce wear problems. Vestiges can also be controlled by using a standard fixed hot tip torpedo in hot runner systems. Gate vestiges and freezing are controlled by the temperature and the location of the tip in the gate area [10].

Xie *et al*. [11] investigated the effect of gates on the cavity filling pattern and residual stress of the injection molded part. They concluded that if a larger gate is used, the cavity will be filled faster and the residual stress of the part will be smaller. They concluded that melt temperature and injection rate can significantly affect the above two aspects, which might have an effect on gate vestiges as well. Shen *et al.*

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[12] showed simulation methods for gate location analysis, in which they calculated the ideal location and size of gates. Zhai *et al*. [13] performed gate location optimization for injection molding. They concluded that if injection pressure at the end of fill is minimized, gate location can be optimized. In spite of the best location, possible injection molding defects were not mentioned by the authors.

Sánchez and Lladó [14, 15] investigated direct gates, which are similar to pinpoint gates but significantly larger, thus the conclusions cannot be used for those because of the significantly different shear effects. For cold runner systems like three-plate molds, gate vestige and other injection molding defects can be avoided or minimized if a suitable gate or nozzle design is used. The tapered region should be as short as possible to achieve lower pressure for filling and reduce the height of the vestige. Generally, its length ranges from 0.13 to 0.25 mm. A tapered region and sharp corners at the entry into the cavity are important to ensure that the plastic will break between the gate and the product but as near the product as possible, leaving no or only a little vestige. It is important to optimize gate size as it has a major influence on gate vestige, shear induced heat, holding time and other important parameters. The gates of a three-plate mold are inherently self-degating, since the gate breaks off as the product is ejected from the cavity [9].

Although the problem of gate vestiges seems to be solved in expensive and complicated hot runner molds, in three-plate molds gate vestiges can still occur. The height of gate vestiges is determined not only by the mechanical strength of the solidified thermoplastic, but as gate vestiges are formed as a result of a complex process, injection molding parameters probably also have a significant effect on it. No information was found in the literature on the effect of injection molding parameters on the formation of gate vestiges.

In this paper our goal was to investigate the effect of various injection molding processing parameters and examine various gate constructions influencing the formation of gate vestiges. A quick measuring method was also developed to determine the dimensions of gate vestiges without any need for time-consuming optical and/or scanning electron microscope measurements.

2. Materials and equipments

BASF Terluran GP35 injection molding grade ABS terpolymer was chosen for the tests. This grade of ABS has a specific gravity of 1.04 g/cm^3, a melt volume rate of 34 cm^3/10 min (at 220°C and 10 kg of load) and a recommended melt and mold temperature of 220–270°C and 40–60°C respectively. The material was dried at 85°C for 4 hours prior to injection molding.

A three-plate mold with 16 cavities was chosen for the examinations. In the mold there were big differences between gate dimensions, therefore 15 cavities were blocked and the mold was used as a single-cavity mold. The effect of nozzle (gate) geometry on gate vestiges was also measured. Some geometrical parameters such as the diameter of the outlet, the nozzle end height and the internal angle near the outlet were varied in our experiments (Figure 1).

The other main geometrical parameters including the 2 mm inner diameter, the 15.6 mm length of the nozzle and the interior draft angle of 2° were the same. The varied geometrical parameters of the various nozzles can be seen in Table 1.

An Engel Victory 330/60 injection molding machine with a clamping force of 600 kN was used for producing parts for the investigation. The injection molding machine had a 35 mm diameter screw capable of a maximum injection rate of 151 cm^3/s and a maximum injection pressure of 1595 bars. The specimens were injection molded with the following parameters using pressure controlled filling (Table 2).

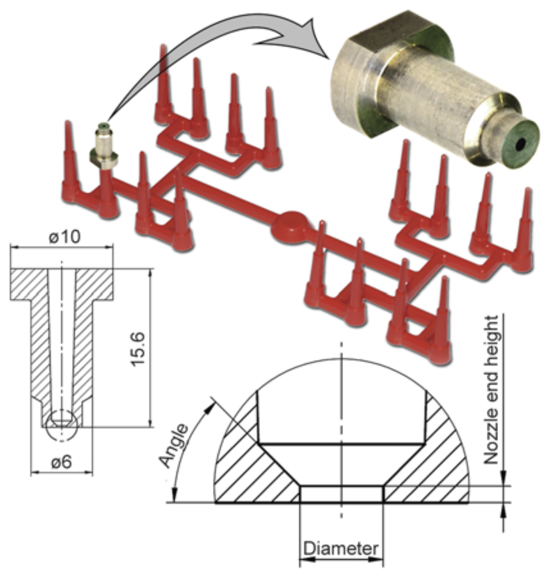

Figure 1. The varied geometrical parameters of the nozzles

Table 1. Geometrical parameters of various nozzle geometries

Nr.	Diameter [mm]	Nozzle end height [mm]	Angle [°]
1	0.8	0.08	45
2	0.8	0.2	45
3	0.8	0.8	45
4	1.0	0.08	45
5	1.0	0.2	45
6	1.0	0.8	45
7	1.2	0.08	45
8	1.2	0.2	45
9	1.2	0.8	45
10	1.0	0.2	30
11	1.0	0.2	60

Table 2. Injection molding set-up parameters

Injection molding parameter	Value
Total injection time (the sum of the filling and holding time) [s]	2.5
Pressure [bar]	600
Injection rate limit [cm^3/s]	110
Residual cooling time [s]	5
Screw rotational speed [m/min]	17.1
Back pressure [bar]	100
Temperature of the zones [°C]	238–200
Temperature of the stationary/movable mold half [°C]	35/16
Cycle time [s]	11.2

Injection molded specimens produced in the first 50 cycles were automatically rejected. Then, when steady-state production conditions were reached, injection molding was continued and every tenth specimen (cycle) was selected for measurement. A total number of twelve specimens were selected from continuous production to determine the average and the standard deviation of the measured values.

Mold temperature was set up based on preliminary studies and the inlet temperatures were chosen to maintain a uniform mold surface temperature. Some injection molding parameters (cooling time, mold opening speed, injection rate and total injection time) were varied to better understand gate vestige formation and to map their effect on the dimensions of the gate vestiges.

Microscopic measurements were performed to observe gate vestiges by using an Olympus BX 51M type optical microscope and a Jeol JSM 6380LA type electron microscope. The optical microscope was used only to determine the geometry of the gate vestiges, while the scanning electron microscope (SEM) was used for deeper analysis to determine the causes of gate vestige formation. To speed up the measurement of dimensions and at the same time keep the accuracy of the optical microscope, a Universal Serial Bus (USB) microscope type Celestron Handheld Digital Microscope was used in a combination with and self-developed software to automatically identify gate vestige dimensions. The new system was previously tested and validated by the conventional optical microscopic measurements.

3. Measurement method

As the first step, the optical microscope was used to determine the dimensions of gate vestiges, namely their height, bottom (base) diameter, and top diameter. By using 50× magnification, the gate sections of the specimens were easily observable and the dimensions of the gate vestiges were measured (Figure 2). The standard deviation of measurement was found to be low when the same 12 specimens were measured by various operators (human factor) and also the repeatability of the measurements was found to be excellent. The maximum differences between the values measured by the three measuring persons were 48, 31 and 17 μm, (height, bottom and top diameter). The USB microscope was also tested; photos were taken, loaded into graphics software and the dimensions of the gate vestiges were determined by converting the dimensions in pixels into μm using the resolution of the image. There is no significant difference between the measured values obtained from the optical and the USB microscope. It can be stated that the USB microscope not only allows faster evaluation but is also at least as accurate as the optical microscope, which makes the USB microscope suitable for the measurements.

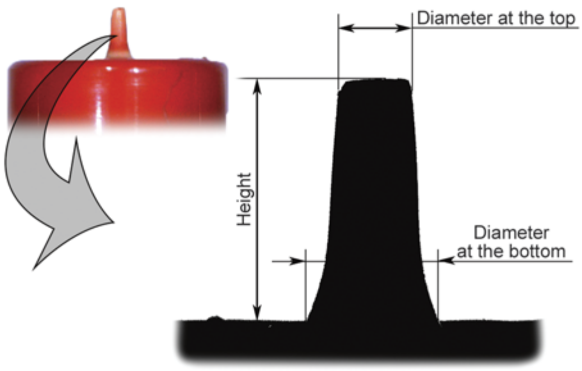

Figure 2. Analyzing the dimensions of gate vestige

4. Results and discussion

4.1. The effect of nozzle geometry on gate vestiges

Before analyzing the effect of various nozzle geometries, the reproducibility of the dimensions of gate vestiges was checked. Reproducibility was found to be very good. Injection molding was performed using different geometry nozzles. Figure 3 shows the most important dimension, the height of the gate vestiges according to the various nozzle geometries.

It can be seen that the height of gate vestiges can be significantly decreased by modifying the geometry of the nozzle. According to the height of the gate vestige, various types can be observed, such as low (nozzles number 1 and 2), medium (nozzles number 3, 6 and 7) and high (nozzles number 4, 5, 8, 10 and 11) and even no gate vestige in the case of nozzle number 9. Nozzles number 9, 1, 3, and 5 were chosen to represent no (zero), low, medium and high gate vestiges, respectively, for SEM observation and the images of the gate vestiges were also inserted into the drawings of the nozzles for visualization (Figure 4).

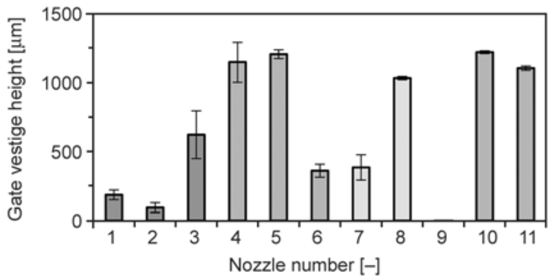

Figure 3. The height of the gate vestiges according to the various nozzles

It is obvious that nozzle number 9 was preferred as no gate vestige was produced and surprisingly, the highest gate vestige was not created with the nozzle with the largest nozzle end height dimension. It can also be seen that the diameter of the vestige is not equal to the diameter of the nozzle, thus the vestige does not form by the material simply detaching from the inner wall of the nozzle, but it is torn from its own material. This explains why a highly sheared region of material was found on the surface of the vestiges, which probably formed during degating due to the friction within the material or due to the high shear during the filling phase (Figure 5). This would mean that gate vestige takes place only as delamination at the interface of highly oriented layers. These

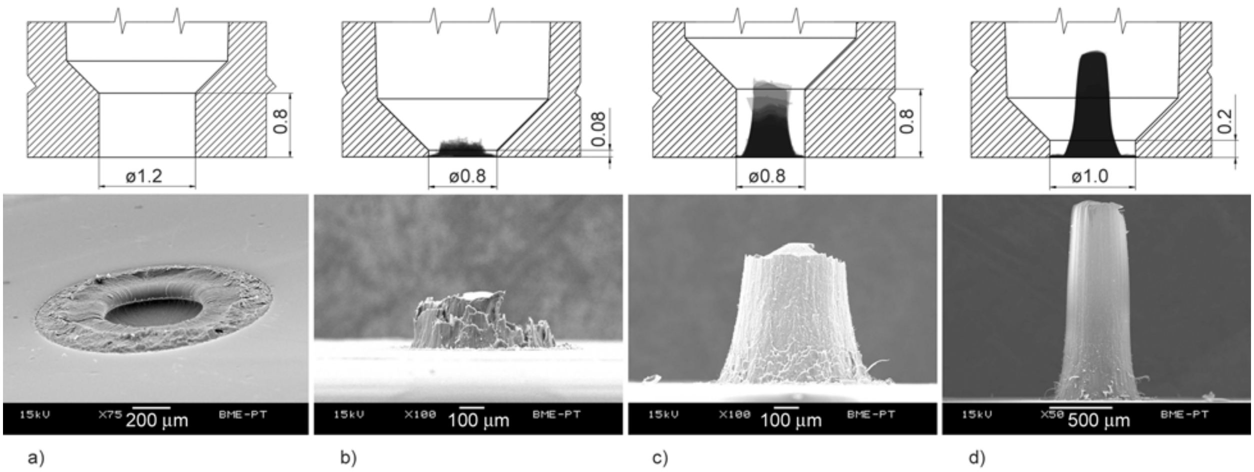

Figure 4. SEM micrographs and 10 superimposed microscopic pictures of the gate vestiges and the nozzle geometries for no (zero) gate vestige/nozzle number 9. (a), low (broken) gate vestige/nozzle number 1. (b), medium (broken) gate vestige/nozzle number 3. (c) and high (theoretically 'good') gate vestige/nozzle number 5. (d)

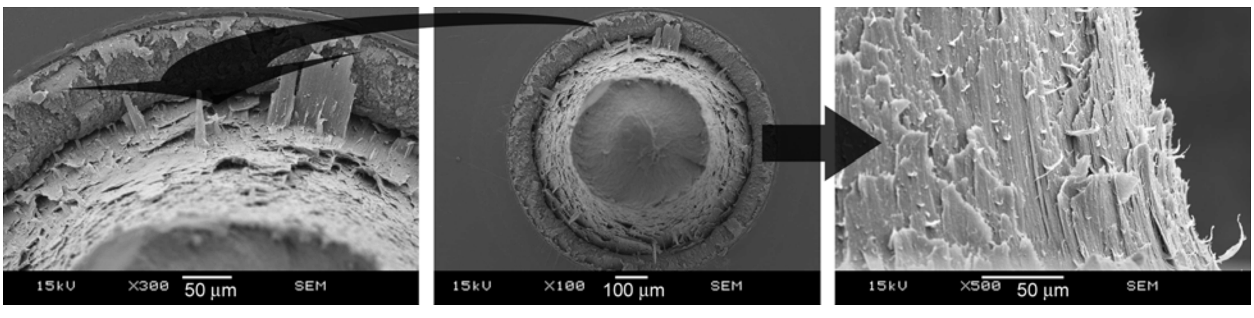

Figure 5. The highly sheared region of the gate vestige

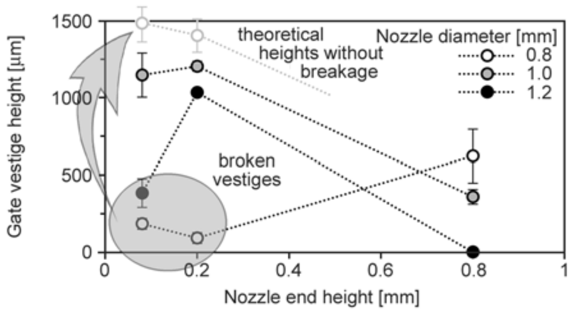

Figure 6. Gate vestige height produced with various nozzles as a function of nozzle end height

kind of delamination was observable on all gate vestige surfaces.

It is assumed that the height of gate vestiges is limited because if the gate vestige forming during filling the cavity was too high, it would break during degating due to the long grip length and this would result in a shorter and broken gate vestige. The height of the gate vestige can be seen as a function of nozzle end height and nozzle diameter in Figure 6.

The results seem to be stochastic at first sight, but if it is taken into account that some of them are broken, and some of them are undamaged, just pulled out from the inner core, a clearer tendency can be observed. No significant difference was found in the bottom diameter of gate vestiges as nozzle end height was increased, but there is a positive correlation between gate vestige bottom diameter and nozzle outlet diameter. As expected, when the outlet diameter of the nozzle was increased, the bottom diameter of gate vestiges increased (Figure 7). In the case of nozzle number 9 (1.2 mm nozzle diameter and 0.8 mm nozzle end height) no gate vestige exists thus only the outer diameter of the remaining 'ring' (Figure 4a) could be measured by SEM. Changing the internal angle near the outlet of the nozzles did not have a significant effect on the dimensions of gate vestiges.

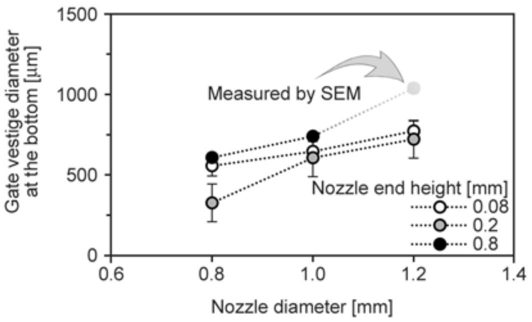

Figure 7. Gate vestige diameter at the bottom as a function of nozzle diameter, produced with various nozzles

4.2. The effect of injection molding parameters

In this chapter the effect of injection molding parameters, such as cooling time, mold opening speed, injection rate and total injection time on the dimension of gate vestiges were investigated. For further experiments, nozzle number 9 was used.

4.2.1. Analysis of cooling time

Gate vestiges may be caused by the breaking of the still hot and thus rubber-like runner system. In order to analyze this possibility, specimens were injection molded with an extremely long cooling time of 10 minutes. It was found that the height of the gate vestige did not change significantly; only a negligible decrease was found. It means that gate vestiges do not form because of the breaking of a still warm runner system, but form previously in the filling and holding phases.

4.2.2. Analysis of mold opening speed

Since the mechanical properties of polymers depend on the rate of deformation, the effect of mold opening speed was investigated to find whether it is possible to tear the specimens from the runner system leaving no gate vestige by using extremely high or low mold opening speeds. The original value of mold opening speed of 150 mm/s was used as a reference, while 10 and 450 mm/s of mold opening speeds were investigated as the smallest and highest possible speeds. The results showed that mold opening speed has only a minor effect on the height of gate vestiges. A possible explanation of the results is that it was not possible to vary deformation rate by mold opening speed at the desired level, where it could have had a significant effect on the gate vestige; only the top of the vestige was broken.

4.2.3. Analysis of injection rate

The effect of injection rate, or screw (ram) speed on gate vestiges was also analyzed. For this test 15, 20, 30, 40 and 50 cm^3/s were set for injection rates. It was found that by decreasing the injection rate, the height of the gate vestige also decreased (Figure 8).

By increasing the injection rate, the bottom diameter of gate vestiges remains constant, while their height increases and their top diameter decreases, which means that they get more and more tapered. A possible explanation of the decreasing height of

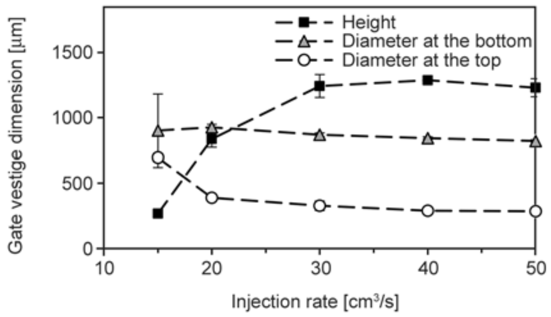

Figure 8. Dimensions of the gate vestige as a function of injection rate

gate vestiges is the lower melt rate during the filling of the cavity, which results in less shearing.

4.2.4. Analysis of total injection time (filling + holding)

The effect of total injection time on the formation of gate vestiges was also investigated. The original value of total injection time (2.5 s) was varied between 2 and 5 s, while cooling time was also changed to keep the same cycle time. Since total injection time can be divided into filling time and holding time, if total injection time is changed, the parameter that is actually changed is holding time. As total injection time was increased, the height of the gate vestige gradually decreased (Figure 9).

There is a noticeable tendency that if the total injection time is increased, the height of the gate vestige decreases. However, a special phenomenon can also be observed: when the total injection time is around 2.5 s, no gate vestige, while at a total injection time of 2 or 3 s, a gate vestige with a certain height appeared. This most preferred 'no gate vestige' interval was only stable when total injection time was between 2.3 and 2.8 s. This special phenomenon is to be further investigated so that this kind of gate vestige can be reproduced on other products. The fact that the size of gate vestiges decreased as the total injection time was increased can be explained by the longer holding phase within the total injection time.

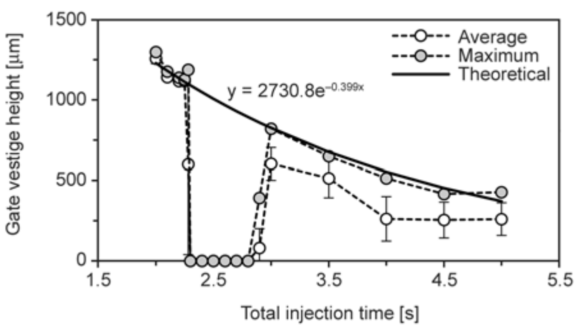

Figure 9. The height of gate vestiges as a function of total injection time. (For every single point 10 measurements were made where 'Maximum' is the highest measured value and 'Average' is the average of the ten samples.)

5. Conclusions

In our work, the product safety problem of injection molded parts called gate vestige was investigated with a three-plate multi-cavity mold. Since the unbalanced runner system strongly influences the results, 15 cavities were blocked. As the first step, we developed a quick measuring method suitable for accurately determining the dimensions of gate vestiges with the help of a USB microscope. 11 different nozzles were produced to examine the effect of nozzle geometry. The reproducibility of the technology with the single-cavity mold was checked and found to be excellent. It was demonstrated that by increasing nozzle end height and/or the outlet diameter of the nozzle, the height of the gate vestige could be decreased.

The effect of some of the process parameters like total injection time, cooling time, injection rate and mold opening speed were also tested. It was proved that by increasing total injection time or decreasing the injection rate, it is possible to decrease the height of gate vestiges, while cooling time and mold opening speed had only a minor effect on their height.

The main causes of gate vestiges were found to be shear and orientation conditions during molding. It is assumed that the formation of the gate vestige structure itself is already completed during filling and can be found within the nozzle in the solidified polymer, however, degating can still modify this structure by breaking it at a certain cross-section.

Finally, the low standard deviation of the height of gate vestiges proved that the whole process of gate vestige formation is not stochastic or random. This proves that if all the parameters and conditions of the injection molding process are known, the height of gate vestiges can be calculated, although probably in a very complex way.

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References

[1] Garcia J. L., Koelling K. W., Xu G., Summers J. W.: PVC degradation during injection molding: Experimental evaluation. Journal of Vinyl and Additive Technology, **10**, 17–40 (2004). DOI: 10.1002/vnl.20004

[2] Karger-Kocsis J., Csikai I.: Skin-core morphology and failure of injection-molded specimens of impact-modified polypropylene blends. Polymer Engineering and Science, **27**, 241–253 (1987). DOI: 10.1002/pen.760270403

[3] Zhu J., Chen J. C.: Fuzzy neural network-based in-process mixed material-caused flash prediction (FNN-IPMFP) in injection molding operations. The International Journal of Advanced Manufacturing Technology, **29**, 308–316 (2006). DOI: 10.1007/s00170-005-2528-x

[4] Oda K., White J. L., Clark E. S.: Jetting phenomena in injection mold filling. Polymer Engineering and Science, **16**, 585–592 (1976). DOI: 10.1002/pen.760160811

[5] Mathivanan D., Parthasarathy N. S.: Prediction of sink depths using nonlinear modeling of injection molding variables. The International Journal of Advanced Manufacturing Technology, **43**, 654–663 (2009). DOI: 10.1007/s00170-008-1749-1

[6] Kovács J. G., Sikló B.: Experimental validation of simulated weld line formation in injection moulded parts. Polymer Testing, **29**, 910–914 (2010). DOI: 10.1016/j.polymertesting.2010.06.003

[7] Kovács J. G., Sikló B.: Investigation of cooling effect at corners in injection molding. International Communications in Heat and Mass Transfer, **38**, 1330–1334 (2011). DOI: 10.1016/j.icheatmasstransfer.2011.08.007

[8] Beaumont J. P.: Runner and gating design handbook. Hanser, Munich (2004).

[9] Rees H.: Mold engineering. Hanser, Munich (2002).

[10] Campo E. A.: The complete part design handbook. Hanser, Munich (2006).

[11] Xie P., Guo F., Jiao Z., Ding Y., Yang W.: Effect of gate size on the melt filling behavior and residual stress of injection molded parts. Materials and Design, **53**, 366–372 (2014). DOI: 10.1016/j.matdes.2013.06.071

[12] Shen Y-K., Wu C-W., Yu Y-F., Chung H-W.: Analysis for optimal gate design of thin-walled injection molding. International Communications in Heat and Mass Transfer, **35**, 728–734 (2008). DOI: 10.1016/j.icheatmasstransfer.2008.01.014

[13] Zhai M., Lam Y. C., Au C. K., Liu D. S.: Automated selection of gate location for plastic injection molding processing. Polymer-Plastics Technology and Engineering, **44**, 229–242 (2005). DOI: 10.1081/PTE-200048523

[14] Sánchez B., Lladó J.: Surface quality of PVC fittings based on the design of the sprue. Journal of Materials Processing Technology, **207**, 13–20 (2008). DOI: 10.1016/j.jmatprotec.2008.04.041

[15] Lladó J., Sánchez B.: Influence of injection parameters on the formation of blush in injection moulding of PVC. Journal of Materials Processing Technology, **204**, 1–7 (2008). DOI: 10.1016/j.jmatprotec.2007.12.063