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Experimental investigation of polymer flow in injection mould

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ABSTRACT

Purpose: The examination of melt flow lines in injection moulded parts was the purpose of this research, as well as a new method of flow visualization was applied. This method can be helpful in predicting the weak areas in moulded parts, created during cavity filling

Design/methodology/approach: The method of visualization used here is not classified yet. It allows to observe how the cavity is filled by looking at a specially created flow lines pattern. These lines are surface defects and a production injection moulding process it is necessary to avoid them. The effect of flow lines on the part surface occurs by special moulding conditions. To obtain the flow lines for investigation the mould temperature was lowered, the holding stage was skipped (the holding pressure not applied), and injection time had to be short enough.

Findings: On the example of moulded plastic parts of simple shape it was found that the applied method of visualization allows to observe the filling process in mould cavity with good agreement to the theory and simulation results.

Research limitations/implications: The flow lines cannot be observed for all plastics grades, but only for these which are sensitive to special processing conditions, like POM or PE. The flow conditions are not the same as in a typical injection moulding process.

Practical implications: This method can be used in practice for melt flow examination in the case of more complicated cavities in injection moulds. The flow lines can be used to diagnose the problems during cavity filling, that are the reason of poor part quality, for example the undesired or unexpected weld lines location in parts.

Originality/value: Usually the visible flow lines on part's surface are treated as a defect. In this paper it was shown that it can be an easy method of flow visualization.

Keywords: Manufacturing and processing; Plastic forming; Flow visualization; Injection moulding

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

In the injection moulding process the injected polymer flows through the sprue, runners and gate to the cavity (or cavities). The polymer flow in mould channels is unsteady and non isothermal and depends on many factors, like the properties of polymer used, injection mould design (especially cavity shape and runners configuration), injection moulding machine and processing conditions [1-5]. The polymer and the machine are usually the factors determined by moulded parts' manufacturers and consumers. The melt flow in mould runners can be controlled by the design and manufacturing technology of the mould as well as by the processing conditions in order to obtain the moulded parts with expected morphology, properties, shape, dimensions and surface. The cavity in the injection mould should be filled totally during the injection phase and the way of filling should be laminar and with a wide flow front – the stream flow (jetting phenomenon) should be avoided. In the case of multicavity moulds simultaneous filling of all cavities is required in order to obtain the repeatable parts of a good quality, at low decrease in melt pressure and temperature [1, 3-5]. These requirements can be fulfilled when the proper melt flow in runners and gates is assured by the runners' and gates' design and proper processing conditions.

The way and sequence of filling of particular areas of mould cavity is the important issue. The decrease in melt temperature and pressure during the cavity filling should be as small as possible. The best situation would be if all border walls were reached by melt at the same time what is very difficult or even impossible to achieve in practice. The even cavity filling depends on the design of runner system (the number of injection points and their locations, the shape and dimensions of runners and gates), the accuracy of runner system manufacturing and the shape and dimensions of injection moulded parts (including the wall thickness and its distribution in the part). Sometimes it is necessary to control the melt flow in the cavity, for example in case of weld lines creation in the part. Weld lines should not be located in part's areas which are under load or, because of aesthetic reasons, in places which are visible during their using.

There are two kinds of melt flow fronts bond lines: weld lines (called also weld marks or knit lines), and meld lines. The formation of weld and meld lines behind the obstacle in the mould cavity was shown in Figure 1. The weld line is formed when the "meeting angle" θ of two flow fronts is smaller than 135°. For θ>135° the meld line is formed. Weld lines are created in the area of meeting of two melt fronts that flow from the opposite directions. Meld lines are created when two melt fronts flow parallel to each other [6]. Since the weld and meld lines are weak areas of injection moulded parts it is important to predict their location, what can be done by numerical simulation [7].

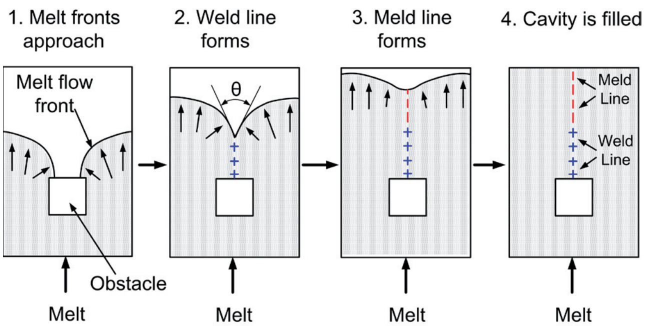

Fig. 1. Weld and meld lines formed behind the obstacle [6]

The rheological phenomena occurring during the melt flow in injection moulds must be known by the mould designers and controlled in the technological process. There are the economical reasons for this (decrease in material waste, the need of shortening the injection cycle time) as well as the quality requirements for moulded parts. The increasing requirements connected with injection moulding process quality and efficiency make monitoring and control of injection process stages a necessary issue [8]. It is therefore useful to make research, both computer simulation and experimental, of phenomena occurring during melt flow in injection moulds. Such research should make the evaluation of injection moulding efficiency easier and improved the physical and usage properties as well as the surface properties of injection moulded parts.

Numerical simulation of polymer processing is getting more and more popular in the industry because it helps to forecast the problems that may occur due to the wrong tool design or use not optimized processing conditions. As result, a lot of money and time can be saved. The simulation is done before the final tool design phase, when the changes in tool design are still possible. The simulation is usually done with special commercial programs, not only for injection moulding, but also for other processing technologies, like extrusion, blow extrusion [9, 10], calendering, thermoforming, etc. The target of numerous research conducted with the use of numerical simulation of the injection moulding process is usually to obtain the pressure, temperature and shear rate distribution in a closed mould and investigation of melt flow front (or fronts) movement in cavity [11-14] as well as determining the flow length in different injection moulding conditions. Mathematical models which allow to evaluate the orientation of short fibers used as filler in injection moulded parts were also worked out [15, 16]. It is possible to calculate the pressure required for total cavity filling, clamping force after cavity filling, evaluating the optimal processing conditions [5, 17-20]. The optimal processing conditions can be found during the filling, holding and cooling stage simulation. The criteria of optimization are the proper values of temperature, pressure, shear rate, etc., and even their distribution in the moulded part, what can guarantee the good properties of finally formed parts. The relationship between processing conditions and parts' properties (structure, shrinkage, crystallinity degree, mechanical properties etc.) is the topic of many research works [21-26].

The numerical simulation results not always are of good correlation with experiments. There are many simplifications in numerical algorithms used to solve the equations of fluid mechanics. There are some phenomena which cannot be simulated by the commonly used programs. It is for example jetting – the undesirable way of melt flow into the cavity [27]. The quality of numerical solution is also highly dependent on the used mathematical model, like viscosity models [12, 13] or modeling process, like for example mesh quality and process boundary conditions [14].

Much effort has been made to investigate the polymer flow inside the mould cavity. The experimental research, often combined with computer simulations, is of big importance. The following ways of experimental research of melt flow in injection mould can be distinguished:

- Moulds with transparent cavity walls

The transparent inserts are put into the injection mould and it makes possible looking at the moving melt inside the cavity [27-35]. This method often requires using some optical elements (prism, mirror) and of course a high speed camera to record the fast cavity filling.

- Short shots

It is an easy method used even in the industry to check, if the mould cavity is filled during the filling phase of injection moulding cycle [4, 5]. By special processing conditions – omitting the holding phase and adjusting injection time short enough – it is possible to obtain the not totally filled parts from the cavity. By changing the injection time the consecutive cavity filling steps can be observed [35-41].

- Gate magnetization method

The method of gate magnetization was presented by S. Owada and H. Yokoi [42]. The compound - polymer filled with strontium ferrite – is magnetized sequentially when flowing through the mould gate. Then the flow pattern is observed in the part cross-section after polishing the surface and using a magnetic detection liquid.

- Pigment as flow marker

Pigment addition to the polymer allows to observe the flow pattern in the part or in the polymer solidified in the runner [37-42]. It is also possible to observe the flow lines in polymer structure [39, 40]. The research of flow in co-injection moulding process [43] (two different materials injected into one cavity) and sandwich injection moulding [44] is also of big importance.

- Filler as flow marker

The research works are usually focused on the filler orientation in composite injection moulded parts and its impact of the part's properties. The other approach is to investigate the filler orientation and restore the flow history in the cavity. The research is made with the use of talc [41, 45-48] or fibres (for example glass fibre).

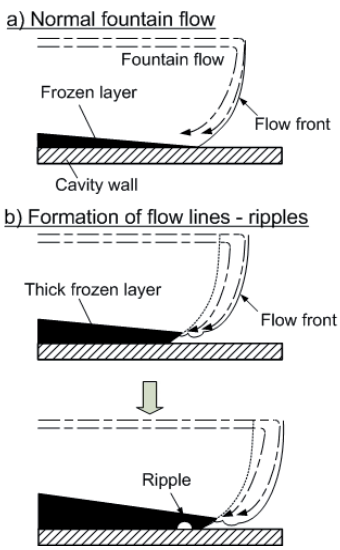

Fig. 2. Generation of flow lines with cold mould wall [6]

A new method of melt flow investigation was proposed in this study. In this method injection moulding is performed without the holding stage and with specific processing conditions. Flow line pattern can be observed on a part surface in a few forms. They are usually part defects. In this article one of the defect forms was named "flow lines", which is sometimes named "record grooves" [49] or "ripples" [6]. Such a defect appears by specific process conditions: too low mould temperature and injection speed, too low melt temperature, and at high melt cooling rate. In order to avoid this problem in moulded parts it is advised to change the process conditions.

Some experimental studies were made to explain the effect of "flow lines". The analysis made with the use of glass-inserted mould helped to understand the phenomenon of this defect formation. It was found that the reason of formation of flow lines known as ripples is repeated melt advance and cooling. The phenomenon of flow lines generation is shown in Figure 1. Melt freezes on a cavity wall, but the interior part of the melt stream moves forward. Due to the fountain flow melt is pushed towards the cavity wall. If the frozen layer is too thick (because of low mould temperature and flow velocity) the flow front has too much time to solidify and is deformed. As the result, the ripple on the wall is created [6].

2. Experimental

A multicavity injection mould with simple shaped cavities was used in order to record the process of cavity filling (Fig. 2). Injections were made by such processing parameters, that flow lines occurred on parts' surface.

2.1. Material

Polyoxymethylene (POM) SNIATAL M8 with MFR = 48 g/10 min. (2.16 kg, 230ºC) produced by Rhodia was used for investigation.

2.2. Machine

KRAUSS MAFFEI KM 65/160/C1 injection moulding machine was used for injection process. The maximum clamping force of the machine is 650 kN. The screw in plasticizing unit is of 30 mm diameter. Temperature controller Wittmann Tempro Plus 140 was used to keep the mould temperature at the requested value.

2.3. Injection mould

The injection moulded parts were manufactured in an experimental 16-cavity injection mould, described in earlier papers [36-41]. Four different kinds of part can be produced in this mould. The layout of parts taken out of the cavities with material from runners is shown in Figure 2. The parts are small plates of the shape and dimensions shown in Figure 3.

The thickness of parts A, B and C is 2.2 mm. Part D is stepped with two thickness values: 1.2 and 3.2 mm. Parts B and C have holes. The obstacles in cavities B and C form the holes and weld and meld lines inside the part. Each part is fed by the point gate of half-circular cross-section with radius of 1.5 mm. The runner cross-section is of 3.5 mm diameter with draft of 10º.

2.4. Processing conditions

The processing conditions were chosen so that the flow lines pattern on part surface was visible. The processing conditions were as follows:

- melt temperature T_{inj} = 180 ºC,
- mould temperature T_m = 30 ºC,
- injection velocity: v = 10 and 120 mm/s,
- holding pressure p_h = 0 MPa.

The mould temperature was too low for common injection processing of POM. It was also important to skip the holding stage of injection moulding cycle (holding pressure = 0).

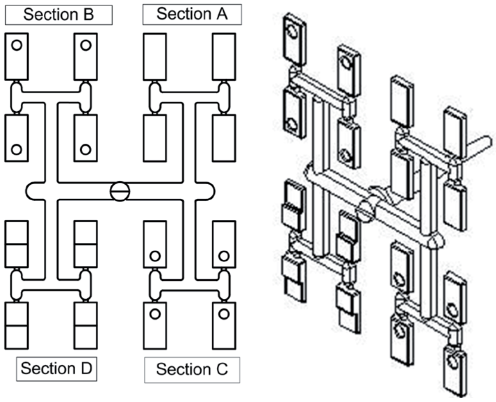

Fig. 3. Layout of parts in the experimental mould

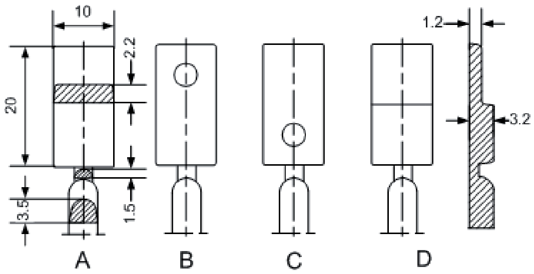

Fig. 4. Injection moulded parts with gates and runners

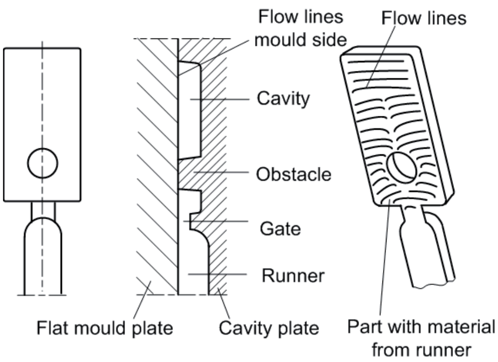

Fig. 5. Flow lines location on the part surface

2.5. Flow lines recording

Flow lines were created during injection moulding process. They are visible on one side of the parts. The part surface was observed in reflected light using the optical microscope and the pictures of surface were taken. The images presented in this article are negatives in black and white colours.

The results of experiments were compared with computer simulations of a filling stage made using the software Moldflow Plastics Insight, release 4.1. Usually the simulation is done before manufacturing the mould. The simulation results give much information about the process and they help to make some decisions concerning the mould design. It is important to check how the simulation results correspond with real melt behaviour. If the correlation between the simulation and experiment is not good, the simulation can lead to mistakes which cost money.

3. Results and discussion

3.1. Flow lines

The way of cavity filling was recorded as a flow lines pattern. The flow lines occurred more clearly on one surface of the part which is formed by the flat mould plate (Figure 4). This cavity mould wall is also of better surface quality, because it was grinded while the opposite side – the cavity side – was manufactured by spark machining.

The flow lines patterns were visible for low (10 mm/s) as well as for high (120 mm/s) injection velocity.

The comparison of cavity filling predicted by the computer simulation and shown by flow lines patterns obtained from experiments is presented in Figure 5. The examples of two parts were shown. In Figure 5a the lines correspond to melt flow front position, which was changing with the time during cavity filling. The flow pattern is similar in both cases except for the area just after the gate. The simulation result does not show the stream coming directly from the gate. The FEM method used for calculation does not consider such flow behaviour because of necessary simplifications in process modeling. Jetting, which is not an accepted phenomenon during cavity filling, can not be shown by the simulation software which was used for this study [27].

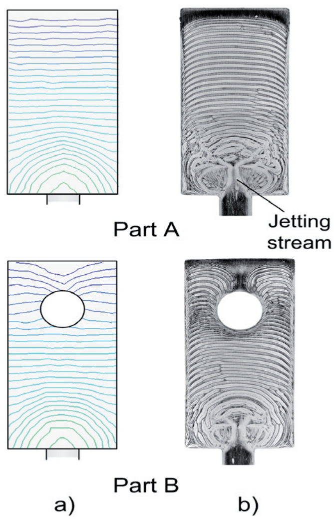

Fig. 6. Comparison of filling process simulated in Moldflow (a) and recorded as flow lines patterns in experiments (b)

Secondary flow in cavity corners - another phenomenon not predicted by the simulation - was possible to see in experiments. This kind of flow was described in [50]. for the opposite case – the inflow from wider to narrower channel. In the presented case melt flows out from the narrow gate into the wide cavity – Figure 6. When increasing the pressure with the injection time, the ripples disappear, but they are still visible in the part's corners, as it is shown in Figure 6c.

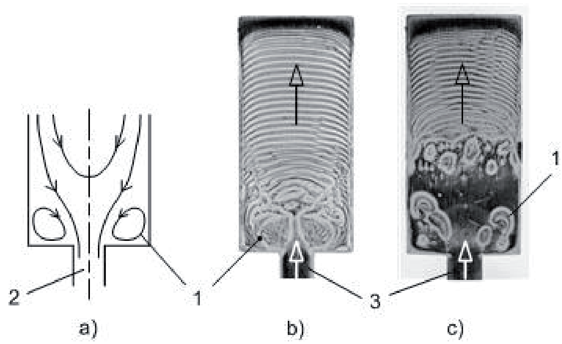

Fig. 7. Secondary flow: a) polymer inflow into a narrow channel [50], b, c) polymer inflow from the narrow gate into mould cavity at injection time t=0.15 s (b) and 0.25 s (c); 1 – secondary flow lines, 2 – narrow channel, 3 – gate

3.2. Weld- and meld lines

The weld and meld lines formation in parts was visualized by flow lines patterns in parts B and C (Fig. 3). For the cavity with simple shape and central located obstacles it is obvious, where weld line is created. However, sometimes weld and meld lines are not visible in part, but they weaken the parts in certain areas. Weld line (part B) and meld line (part C) is shown in Figure 7.

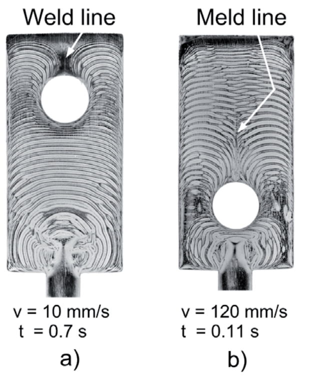

Fig. 8. Moulded parts with weld lines (a) and meld lines (b)

3.3. Cavity filling under increasing pressure

Mould cavity is filled in the injection stage of a technological process. When melt flow front reaches all border walls (the cavity is filled up) the melt pressure increases rapidly. If the process is conducted properly the holding pressure is applied at this moment, when cavity is being filled up.

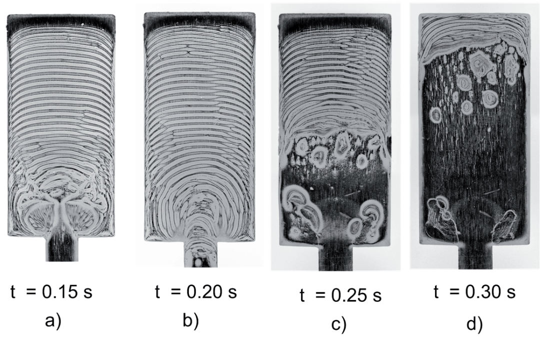

Fig. 9. Flow lines patterns in parts obtained at different injection time

In the experiments the holding stage was omitted and the parts were moulded with different injection time (t). The melt flow in the filled cavity was observed. If the injection time was sufficiently long, the flow lines disappeared. Figure 8 presents the change of the flow lines with increasing injection time. With the increasing injection time also the melt pressure increased and the flow lines disappeared. What is noticeable – the disappearing of flow lines starts from the gate, where the melt pressure is higher than at the end of cavity.

3.4. The influence of cavity thickness

The cavities of D shape have two stepped thickness. It was found that the flow lines have different patterns in both sections. In the first section, which is thicker (3.2 mm) than for parts A, B and C, longer jetting stream occurs. In the second section, which is thinner than other cavities (1.2 mm) the flow lines are closer together (Figure 9). This phenomenon can be explained by the higher cooling rate of polymer in thinner cavity area which causes higher frequency of flow lines creation.

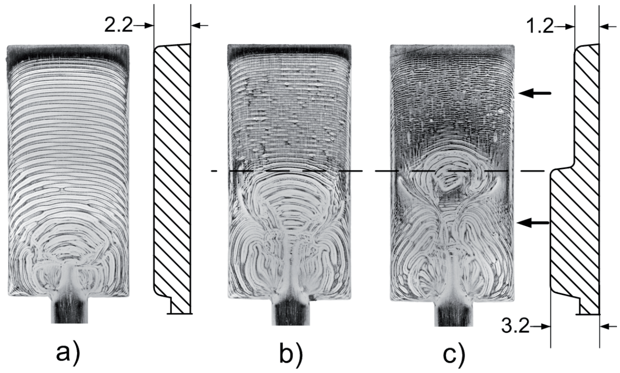

Fig. 10. Flow lines patterns in parts of different thickness: a) part A – injection velocity v=10 mm/s injection time t=0.8 s, b) part D – v=10 mm/s, t=0.7 s c) part D – v=120 mm/s, t=0.11 s

4. Conclusions

The possibility of flow lines observation is important for injection mould filling investigation. It helps to understand and solve some problems with mould cavities' filling and to obtain parts of high quality. One of the possible solutions can be the gate correction or, if it is possible, adding a new injection point.

The experiment results lead to the following conclusions:

- Flow lines patterns can be used to check how the cavity is filled
- Computer simulation does not allow to predict all phenomena of the melt behaviour, e.g. jetting and secondary flow
- Weld and meld lines location can be checked with this method
- Flow lines occur only by some special processing conditions (low mould temperature, low melt pressure in cavity)

The flow lines were obtained not only by low injection velocity, but also for high velocity values. In the studied case the low mould temperature played the most important role in flow lines formation. The applied mould temperature was 30 °C while recommended values for POM are 70 – 120 °C.

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Additional information

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