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Warpage of injection moulded parts as the result of mould temperature difference

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ABSTRACT

Purpose: The purpose of the research was to explore what phenomena influence parts warpage after injection moulding by different mould temperature at the opposite walls.

Design/methodology/approach: The sample bars were injected into the injection mould and the warpage was observed. The deflection was measured and material structure was observed using optical microscope.

Findings: It was found that the different mould wall temperature values cause the asymmetrical polymer flow in the cross-section. It was discovered by short shots observation. As result the asymmetrical structure in the parts' cross-section occurs.

Research limitations/implications: In the future work the research of stress in the parts is recommended. This could be done by elastooptical investigation of transparent parts made from polymers like PS, ABS or PC.

Practical implications: It is required to assure homogeneous mould wall temperature across the entire cavity when injection moulding parts production is made.

Originality/value: This is an example of combined research that is not focused on one kind of tests only and helps to find reasons of the quality problem in polymer parts manufacturing.

Keywords: Engineering polymers; Injection moulding; Warpage

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MATERIALS

1. Introduction

Assuring the proper mould temperature for a specified polymer is a very important issue as well as keeping the temperature constant and equal across the cavity surface. Differences in mould temperature can lead to the problems with manufactured parts like warpage [1-7]. The reason of this are stresses in the parts. Since polymer with higher temperature exhibits more intensive shrinkage than in lower temperature, the temperature differences created during part cooling in the mould lead to part distortion. The deformation of such a simple injection moulded part is shown in Fig. 1. Because of difference in shrinkage a bending moment occurs in the part and causes deformation. Part becomes concave from the mould “hot” side and convex from the mould “cold” side [2].

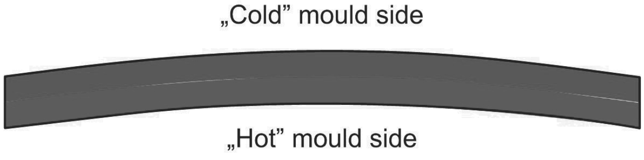

Fig. 1. Warpage of injection moulded part due to different mould wall temperature [2]

The non-uniform mould temperature in the mould plate can be also problematic in case of multicavity moulds. If the parts are formed in different temperature they can differ in structure and properties after manufacturing process [8-11]. The differences in properties are significant for semicrystalline polymers that crystallize during solidification process. The problem of different properties among the parts from one mould is especially important in case of moulding small parts in moulds with many cavities. Moreover, the different temperature can also affect polymer flow in runners of multicavity mould and this can lead to non-simultaneous filling of the mould cavities [12].

Computer simulation programs are very good tools for prediction of quality problems with injection moulded parts [13]. It is possible to predict polymer flow inside the cavity as well as other physical properties distribution of melt across the entire cavity like pressure, shear stress, shear rate, temperature etc. Weldlines and airtraps are also identified. Minimum warpage optimization can be done by CAE analysis by processing parameters optimization [14]. Gate location analysis also can be done to achieve this.

The warpage is also dependent on presence of filler in the plastic as well as on the kind of filler. Particularly it can be different across the part depending of the filler orientation [15].

The warpage is dependent also on processing conditions. Computer simulations are helpful with warpage optimization. In the work [16] with the use of simulation program it was found that the most influencing processing conditions in case of thin-shell parts are melt temperature and holding pressure. The holding pressure is especially important with minimizing the shrinkage of semicrystalline polymers, like POM [17]. The shrinkage can be also the reason of warpage.

To minimize warpage it is important to assure the uniformity of the temperature across the part. It will also result in preventing sink marks and different shrinkage in the parts [18][18].

A very important role in injection moulding process plays cooling of the parts. It is realized by cooling channels in the mould. These channels can be designed in many ways in the same mould but uniform mould temperature should be assured. When there is only one and long cooling channel the coolant heats up in the mould and is not efficient. One of good solutions is to use special manifolds and design many coolant inlets and also many outlets in the mould [19]. Some manufacturing techniques like for instance SLM - Selective Laser Melting, give the possibilities to manufacture mould inserts with conformal cooling channels. This is very effective solution because the channels are fitted to the shape of the cavity and can run always in the same distance from mould wall. The heat exchange between the mould and melt polymer is very good [20]. It is worth to use this solution if only the higher costs of injection mould manufacturing are acceptable, because rapid tooling techniques are relatively expensive.

Sometimes special injection moulding techniques are used to avoid quality problems with parts. For example to avoid sink marks in parts with thick walls polymer with foaming agent is used. It makes possible manufacturing thick-walled parts which is very difficult in conventional injection moulding because thick layer of polymer is cooled very slowly and exhibits very high shrinkage. This leads to sink marks occurring and to the warpage problems. Minimizing warpage is also possible when using compression injection moulding, which is especially recommended for thin-walled parts and parts with application for optics. The reason of minimal warpage after this manufacturing process are very low internal stresses in injection moulded parts [21].

The reason of warpage is usually unequal mould temperature or differences in part thickness. In addition, it is amplified by intensive shrinkage of fluid core inside the part. If the fluid core is placed not symmetrically in the middle of the part cross-section, one half of the part contracts more because of intensive shrinkage. A study on thermokinetical asymmetry of the melt polymer flow front inside mould cavity was presented in [22]. If melt polymer flows inside a mould channel (runner or gate) the flow front is formed in a fountain flow [1-7, 22]. The flow front is symmetrical to axis of symmetry, placed in the half-distance between mould walls, if only the conditions of flow are the same near both mould walls – equal temperature, surface roughness etc. However, if there is a temperature difference between opposite mould walls, the flow front is not asymmetrical, but shifted towards one of the walls – which is of higher temperature. This is caused by lower viscosity of melt which is in contact with higher temperature mould wall and therefore is heated up. Lower viscosity enables melt polymer to faster flow. Moreover, on this side of mould channel thinner skin layer is formed. The phenomenon described above is called thermokinetical flow asymmetry, because there are the differences in kinetics (flow velocity) across the channel cross-section that are caused by thermal asymmetry [22]. The scheme of melt behaviour in such situation is presented in Fig. 2.

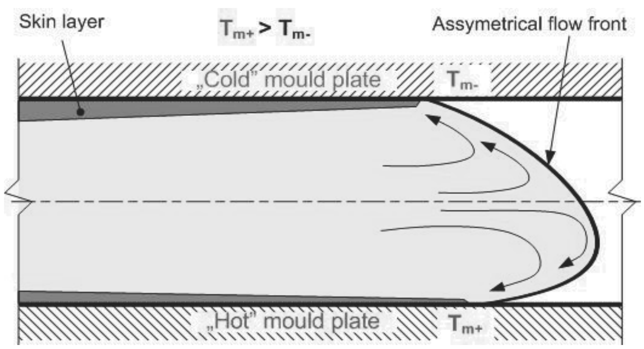

Fig. 2. Asymmetrical flow front due to different mould wall temperature [22]

The differences in mould temperature can be caused by different cooling of mould halves. The location of cooling channels is often determined by shape of moulded part – cavity in the mould. The unequal cooling and flow asymmetry causes further problems with moulded parts – first of all warpage. The moulded part is warped in the way like shown in Fig. 3. Due to stresses in the material caused by temperature the side of hotter wall is contracted. Therefore on this part wall the surface is concaved.

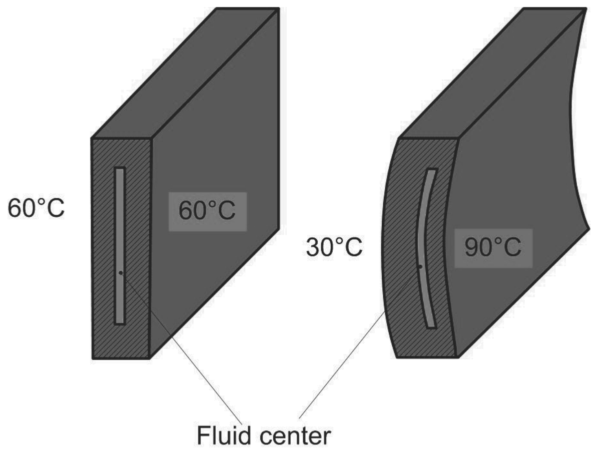

Fig. 3. The injection moulded part deformation due to mould wall temperature difference [23]

The theory presented in some publications explains the reasons of the warpage. It is required to do more research in this field to investigate for example how the polymer structure is formed across the moulded part cross-section. This could provide some information helpful in more detailed description of warpage phenomenon.

2. Experimental

The experiments were made with an injection mould for bar specimens sufficiently long that the warpage could be observed. After injecting the parts they were tested.

2.1. Injection mould

Double cavity injection mould for manufacturing test specimens (bars: 150x25x4 mm) was used for the investigation. The mould is used for investigation of polymers shrinkage (non standardized tests). The sketch of one of moulding plates in the mould showing the layout of cavities and runners is presented in Fig. 4.

The important aspect in injection moulding is cooling the part. In the case of experimental mould used here the cooling system is very simple – one circuit in each moulding plate. The details of cooling system in the mould are sketched in Fig. 5. The entire mould consists of several plates (mounting plates, ejector plates etc.) but cooling circuit is made only in two plates (moulding plates) that form the parts. One of these plates is flat – the plate on the right side, with sprue bushing mounted. In the second one the cavities are milled together with the runners and film gates, as it is shown in Fig. 5.

Since in the experiments different mould temperature values were applied in the moulding plates, it was important to measure the mould temperature. For this purpose temperature sensors were mounted in each moulding plate. The thermoresistive sensors Pt100 were used and placed near cavity surface, in the same distance from the part in each plate. Temperature value measured in the left moulding plate (cavity plate) was marked "T_{mL}" and in right moulding plate (flat plate): "T_{mR}". For identification the samples in the code first T_{mL} was given and then T_{mR}, for example: sample 20/90 – T_{mL}=20°C, T_{mR}=90°C.

The measurement and temperature control were assured by temperature controller for injection moulding - Wittmann Tempro-Plus-2:140. The mould was mounted on the injection moulding machine KraussMaffei KM/65/160/C4. The screw diameter in the plasticizing unit was 30 mm.

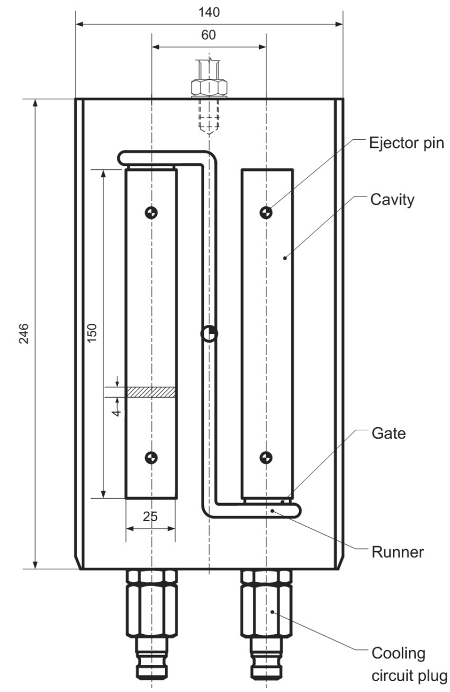

Fig. 4. Sketch of the injection mould used for the experiments

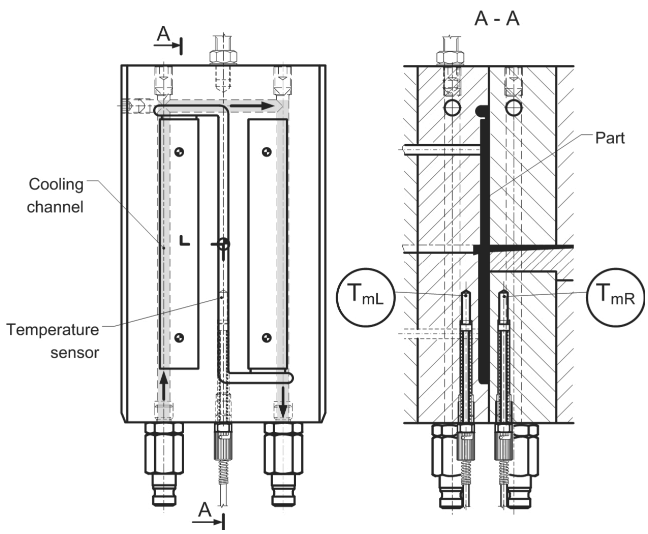

Fig. 5. Scheme of mould cooling and temperature measurement

2.2. Processing parameters

The polymer used for investigation was polypropylene MOPLEN HP501H (homopolymer) produced by LyondellBasell Industries. This material is used to manufacture such parts like caps, closures and furniture elements.

The processing parameters were as follow:

- injection temperature: 240°C
- mould temperature: 20 and 90°C (at opposite walls).
- injection velocity: 50 mm/s
- injection time: 1.2 s
- holding pressure: 40 MPa
- holding time: 20 s
- cooling time: 15 s

The mould temperature values were intentially very different at the opposite walls (20 and 90°C) to cause the stress in the parts and, as the result, deformation of the parts. The temperature values were changed: once left mould plate temperature was 20°C and for the second time it was 90°C. Some specimens were injected with the same mould temperature: 50°C to compare the warpage to highly deformed parts.

A run of short shots was made in order to observe the asymmetry of flow front in the mould. In this case injection time was relatively shorter.

2.3. Tests performed

The warped parts were first photographed after taking out of the mould. Then the surfaces of samples were scanned with the use of profile measurement gauge Taylor Hobson, type New Form Talysurf 2D/3D 120, to obtain the curves representing the deformation. Since the gauge has measurement length limit 120mm, only part of the sample was measured – total length of the sample is 150 mm.

Short shots parts were observed at stereoscopical microscope Nikon SMZ800. Microtome slices were taken out of the short shots and fully injected parts in order to investigate the structure of the parts. The microtome used for preparation the slices was Thermo Shandon Finesse Me+. The slices were put between two glasses and observed at Nikon Eclipse E200 microscope in polarized light.

3. Results and discussion

A very big difference in mould temperature values in the experiment resulted in significant part warpage which was observed after taking the parts out of the mould. The parts deformation was fixed and it was possible to measure the deflection.

3.1. Observation of parts deformation

The parts after processing with unequal mould temperature are deformed. The examples are shown in the Fig. 6, where the photographs of deformed part are presented. As it was described in section 1, the part face which was in contact with hotter mould plate (90°C) is contracted [23] and ends of this face are bended outside. The same tendency was observed in case of short shots.

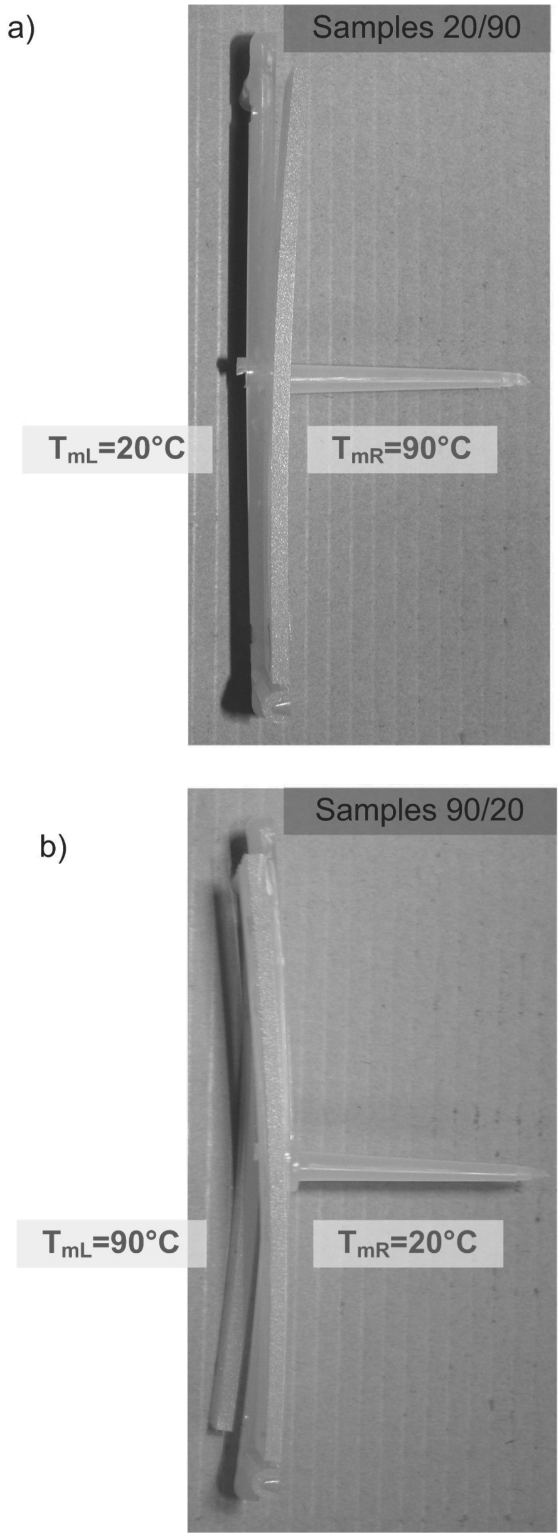

Fig. 6. Photography of deformed parts: a) samples 20/90, b) samples 90/20

The deformation measured with the use of the profile measurement gauge is presented in Fig. 7. The samples 20/90 and 90/20 were measured not on the same surface, because they were deformed in different directions. Measurement was done always on the convex surface – in case of 20/90 samples it was left side (T_{mL}=20°C) and in case of 90/20 samples it was right side (T_{mR}=20°C). The scan was performed on one line – in the middle width of part, as it is shown in Fig. 7.

The sample injected with mould temperature 50°C of both sides of the cavity is flat – the difference on the measurement length is 0.25 mm while the samples injected by different mould wall temperature are highly deformed. Moreover – the deformation is very similar in both cases, despite occurring in opposite directions – it was registered on opposite surfaces.

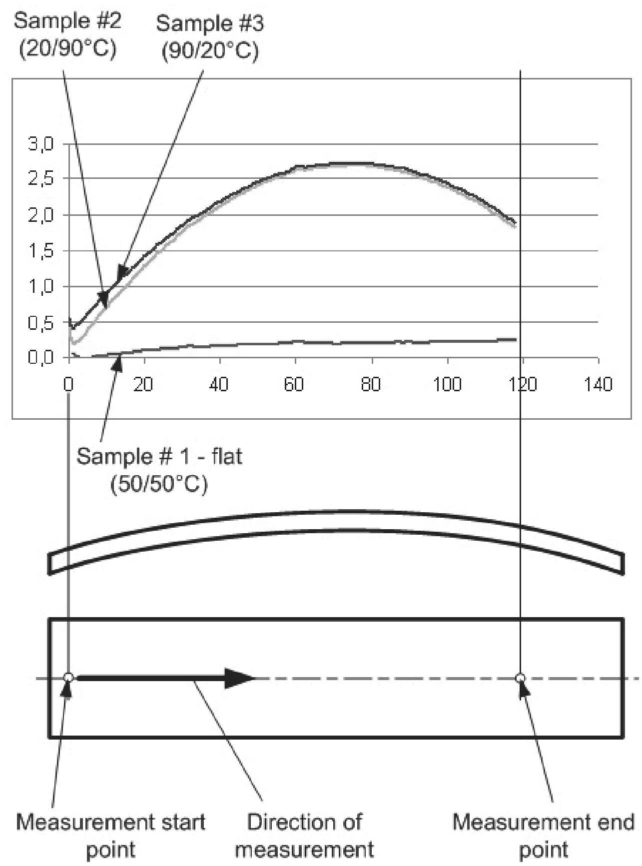

Fig. 7. Measured deformation [mm] in the parts length

3.2. Flow front asymmetry investigation

In order to confirm the thermokinetical asymmetry of flow front inside the mould the short shots were made. The short shots were obtained with special processing parameters – holding phase was skipped in the injection moulding cycle and injection time was shorter than in the normal cycle. An example of short shot in side view is shown in Fig. 8. It is remarkable that the flow front is pushed towards one cavity wall – the hotter with temperature of 90°. This is the same bend direction as the warpage of entire part.

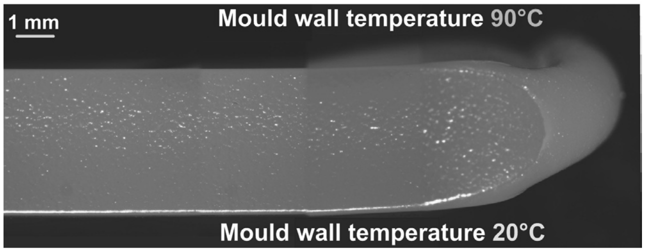

Fig. 8. Melt flow front deformation due to different mould wall temperature

3.3. Structure investigation

After observation and measurement of parts warpage the investigation of parts structure was made. Mould temperature strongly affects the formation of polymer structure because it determines conditions of crystallization and it was expected that the structure, directly influenced by different mould wall temperatures, would in turn influence parts warpage.

The short shot sample cut in the flow direction, in the middle of part width, is shown in Fig. 9. The deformation of short shot part end towards hotter mould plate (90°C) is visible. The part is finished by an expanded material (circle shape) which flown out of the contracting material and froze when the melt stopped flowing. The narrow area occurrence is caused by shrinking of the skin layers regions.

The differences in the polymer structure near the skin are observed. At the side of "hot" mould plate the skin layer is thin and big spherulites are formed just behind the skin – Fig. 9a. At the side of "cold" mould the skin layer is thicker and big gradient of spherulites size is observed. The spherulites are very small near the skin and become bigger towards the part centre – Fig. 9b. This is caused by mould temperature. Skin layer is formed during mould filling immediately, during the contact of hot melt polymer with colder mould and due to very intensive cooling the material with no spherulites is created. Contact of the melt polymer with hot mould affects the slow cooling and creates good conditions for crystallization and for forming large spherulites. Moreover, the size of the spherulites is more homogeneous that is convenient from the point of view on the parts quality.

The observation of the cross-section of the sample injected in normal injection moulding cycle (with holding phase) shows asymmetry in skin/core morphology – Fig. 10. In this case the cavity was filled totally and holding pressure of 40MPa was used. Strong asymmetry of the structure in the cross-section is remarkable. The non-oriented core layer is shifted towards hotter mould plate while oriented core layer is much thinner in this half of the part cross-section. The polymer structure just behind the skin is similar like in case of short shots parts.

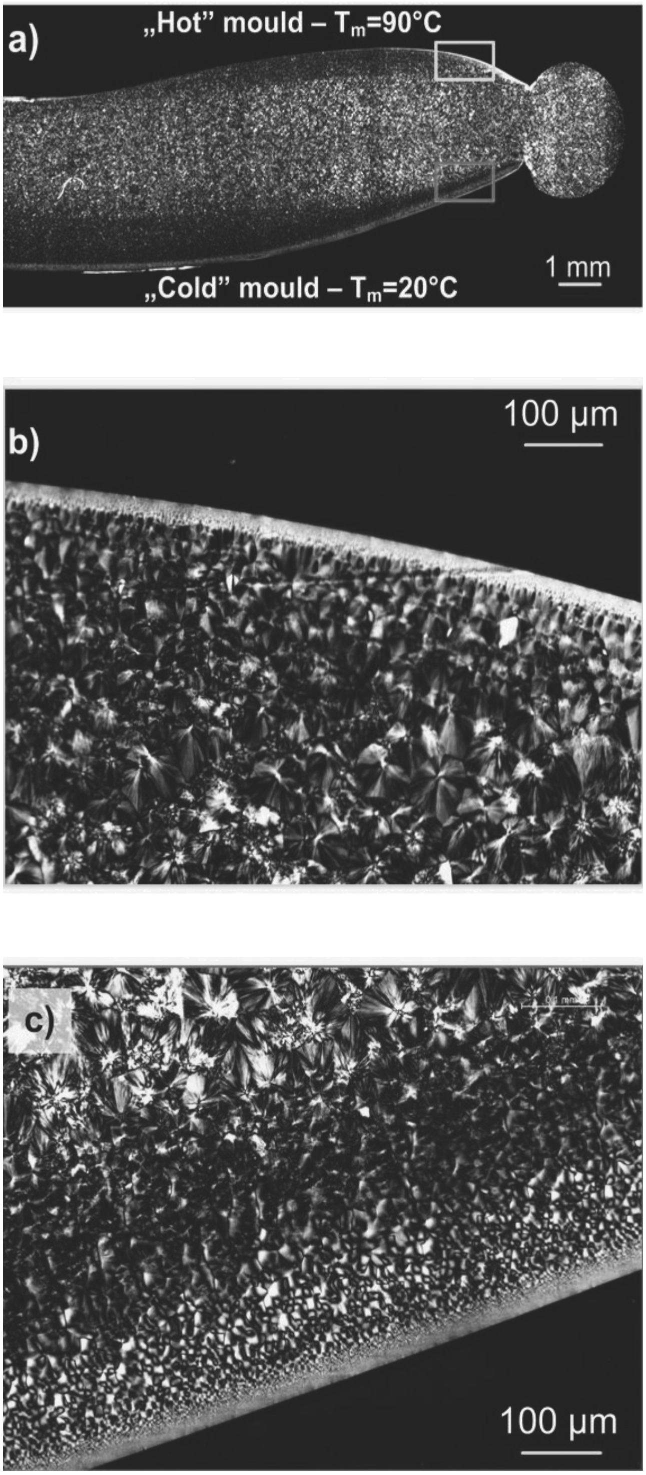

Fig. 9. Structure of short shot part in the cross-section parallel to the flow direction (in the middle of sample width)

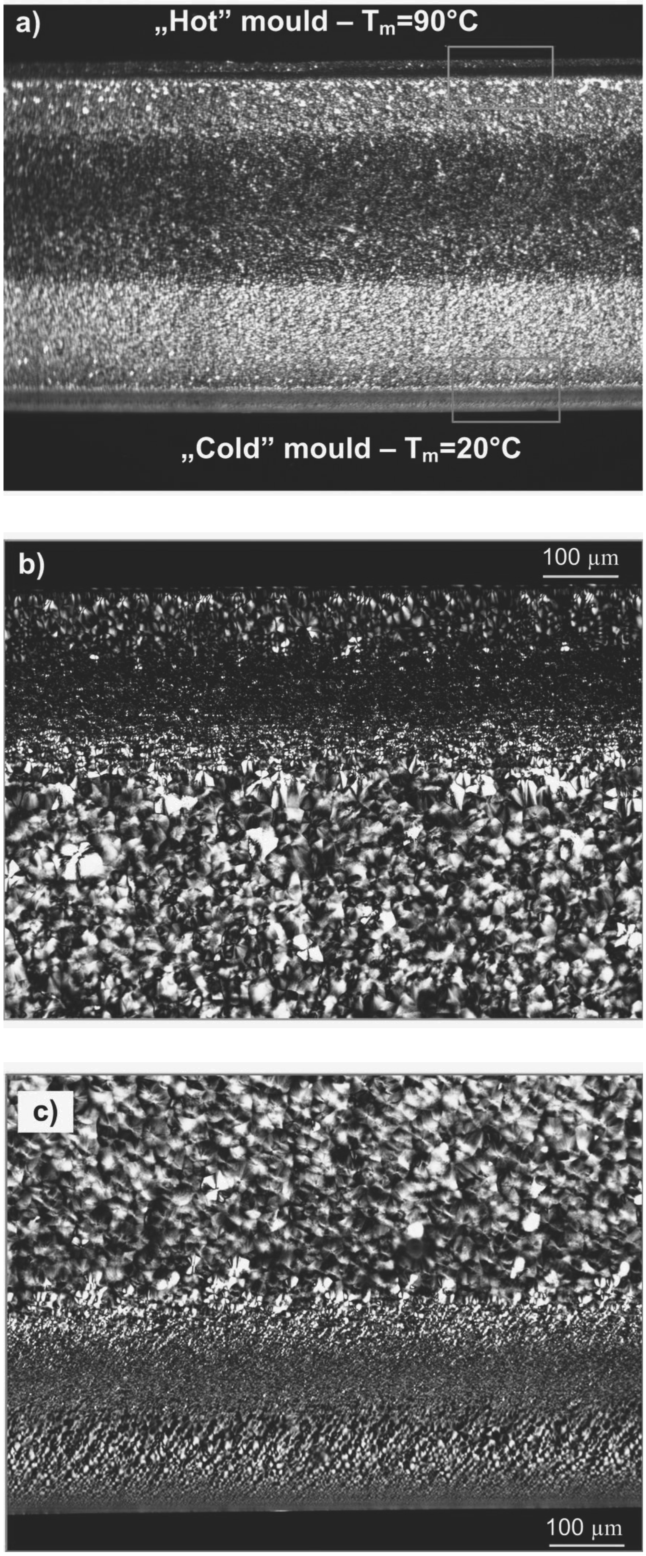

Fig. 10. Structure of short shot part in the cross-section parallel to the flow direction (in the middle of sample width)

4. Conclusions

The results of the experiments showed consecutive phenomena leading from the mould temperature difference to injection moulded part warpage. If the mould temperature is not equal on two mould walls this leads to thermokinetical asymmetry of melt flow. This, in turn, causes the asymmetrical structure development in the part cross-section. As the result, different stress in part's cross-section occurs, which results in part warpage.

It is very important to assure uniform cooling of moulded part in the injection mould by proper cooling system design. It can be done with the help of CAE simulation software. Such software usually performs an analysis of the mould temperature on two sides of the moulded parts or even shows the differences between these two temperature values and it helps to identify the regions in parts that tend to warpage.

In this study the investigation was focused on stresses caused by unequal mould temperature. However, in practice, there are also other factors influencing the stresses in injection moulded parts, like polymer flow, different wall thickness in the part, shape of the part, ejection forces etc. The mould temperature differences can in some cases compensate inner stresses that are caused by other factors.

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