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NUMERICAL SIMULATIONS AND EXPERIMENTAL INVESTIGATIONS OF STRUCTURE AND THE DEGREE OF CRYSTALLINITY OF INJECTION MOLDED PARTS OF VARYING THICKNESS

Abstract

The aim of this work was to evaluate the effect of shear plastic into the mold cavity with a variable height on the structure and selected properties of molded parts. It was used as a special designed mold for producing test samples with varying thickness. It was shown, that the wall thickness of the molded part can significantly affect its properties, not only because of the greater volume of the amount of material, but also because of the process taking place within the the molded part during the solidification of the material. The degree of crystallinity can be different depending on the cooling time, which may contributes to the change in strength.

Key words

injection molding, HDPE, crystallization, structure

Introduction

During the flow of the liquid plastic in the mold cavity, occurs complex rheological and thermal phenomena, induced variable geometric shape inside the mold, i.e. the sprue channel, runners, gates, and the molding cavities. These phenomena should be taken into account in the process of constructing the molds, usually when determining the shape and size of runners and gates [1 ÷ 4]. These phenomena cause, inter alia, increasing the temperature and velocity of flow in the cavity, thus contributing to changes in the flowing plastic, for example. its viscosity. During the movement of the plasticized in the cavity of variable geometry, there is a further change in the rheological and thermal properties of the plastic in different areas of the mold cavity. As a result of these changes, the structure and properties of the molded parts are different in different areas thereof, for example. in the zones where the shear is more or less intense due to the change in the cavity height.
In the case of molded parts for which different mechanical properties in different locations of no great importance, (for example. simple everyday objects or toys), changes in the structure caused by not uniform polymer flow conditions are not relevant. However, in the case of technical moldings, which must meet specific requirements with regard to e. g. strength, such changes of mechanical properties in different places of molded part, are sometimes very important, often determining their suitability.

The flow of molten thermoplastic material in the runners and cavity injection is a complex phenomenon which depends on various factors, and therefore relatively difficult to model. In the description of the liquid polymer flow in feed channel is most commonly used model based on the occurrence of so-called. "Fountain effect" [3 ÷ 7]. Filling the cavity is largely determined by the shape and size of the gate. During the flow of thermoplastics in the mold runners are such phenomena as [4,6]:

- In the case of stenosis of runner: pressure drop, increasing the temperature, resulting from the increase of friction and flow rate of plastic
- For the extension runner reducing the pressure, temperature and flow rate.

Conditions of polymer flow in the mold determine the properties of the molded parts through their effect on [3,4,8 ÷ 10]:

- Orientation of the macromolecules that have a direct impact on mechanical strength of the molded parts,

- Stresses of molded parts, due to the solidification temperature differences in different areas of the cavity.

Furthermore, the properties of molded parts depend on their structure formed during the injection cycle. In the case of partially crystalline plastics content of the crystalline phase is determined largely by the cooling rate and material properties. The degree of orientation of the macromolecules is dependent on:

- Temperature of the plasticized plastic,
- The surface temperature of the injection mold cavities,
- The flow rate of the plasticized polymer.

In the phase of filling the cavity can be distinguished two basic ways simultaneously occurring formation of macromolecules orientation [8.11]:

- By shearing caused by the movement of the various layers of the plasticized polymer velocities. The layers adjacent to the surface of the cavity, material is cooled rapidly increases its viscosity and solidify plastic on the surface of the mold cavity. The macromolecules of the polymer are oriented along the direction of polymer flow. The longitudinal orientation (in the direction of flow) is greater than the transverse direction, because significantly higher tangential forces are present on the surface of the mold.
- Due to the elongation occurring mainly at the front of flow of liquid plastic, which is called. "Fountain effect". The macromolecules of the polymer are extended in a direction perpendicular to the direction of polymer flow. As a result of lowering the temperature of the polymer macromolecules orientation is maintained in the molded part. The consequence of the extension is the occurrence of a much higher degree of longitudinal orientation of the transverse direction.

The degree of orientation is also dependent on the size of the molded part. In large parts with thick walls, the orientation of the macromolecules of the polymer is less than in the thin-walled molded parts.

Residual stresses of molded parts are the result of temperature differences in the various areas of cavity non-uniform cooling of liquid polymer in cross section of part (material solidifies faster in the layer in direct contact with the mold) and a residual pressure, which is the result of the application of pressure being too high hold pressure. The share of residual stress is relatively small and does not exceed 4% of all the stress induced in the in part, mainly by the orientation of the macromolecules of the polymer [8]. The balance of the residual stresses occurs only after removal of the part from the mold, whereby it may be spontaneous undesirable deformation.

The described phenomena occurring during the polymer flow in the mold depends on the shape and cross-section of the channel of mold. Cross-sectional dimensions of the flow channels, and particularly the cavity affects the conditions of a shear material. This impacts on the formation of a specific structure and properties of molded parts.

On the basis of investigations [12], it has been shown that in the case of the PP injection molded parts its cross section is observed classic layers: the skin at the wall of part, then - a layer of material having a high degree of orientation, and an outside layer of material in the core. It is also noted that the top layer spherulites are much smaller in size than in the core.

The size of skin and the core is dependent on the processing conditions, including the temperature of mold. In conditions of high mold temperature part is more cooled at a high temperature in the mold cavity, which promotes the growth of spherulites. Mold temperature dependence of the size of the skin and the size of the crystallites is shown in Fig. 1.

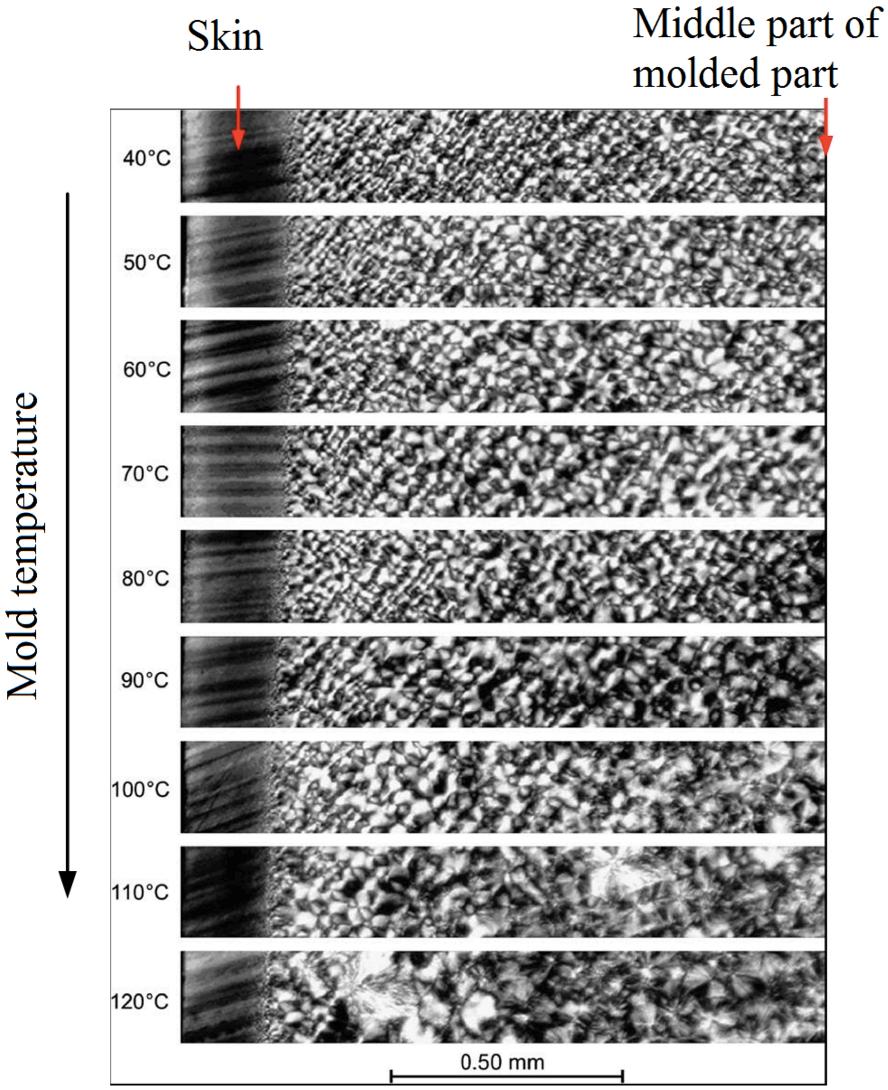

Fig. 1. The morphology seen in cross-section of molded parts of polypropylene (α-iPP) injected with various mold temperature

Source: [13]

Different structure of the different layers of molded parts affects their mechanical properties. An example would be static tensile test, in which different layers behave in a different way (Fig. 2).

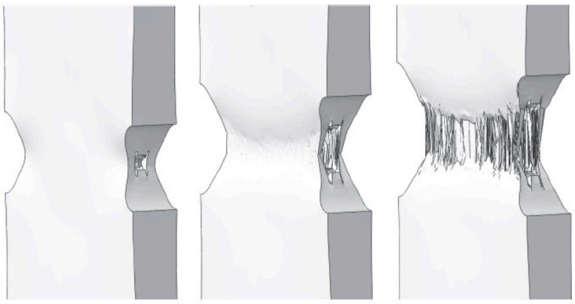

Fig. 2. Simulation of the tensile test of plastics using Abaqus program. First, the continuity is interrupted by a core part, and then to deform the plastic shear zones (skin)

Source: [14]

Experimental investigations

The aim of this work was to evaluate the effect of shear plastic into the mold cavity with a variable height on the structure and selected properties of molded parts.

It was used as test samples of molded parts with varying thickness of cavity, from 1 to 4 mm. The shape and dimensions of the part are shown in Fig. 3.

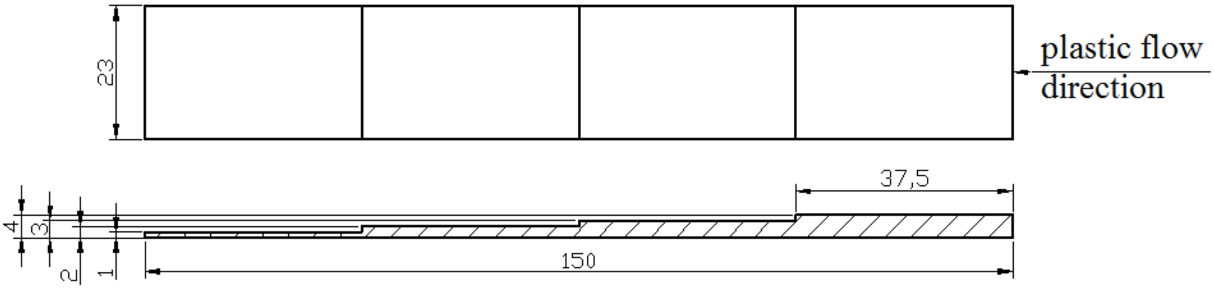

Fig. 3. Shape and dimensions of test sample

Samples were made using a dual-cavity mold with parallel circuit of runners (Fig. 4). The material is fed into the cavity through gate of height of 2 mm and a width of 15 mm, in the part with the largest thickness. The HD-PE Hostalen GC 7260 (Basell Polyolefins), with density 0,963 g/cm3 and MFR = 8 g / 10 min (190°C / 2,16 kg), and 23 g / 10 min (190°C / 5 kg) was used in investigations. Specimens were produced using two-cavity mold mounted on KraussMaffei KM65-160 C4 injection molding machine. Injection conditions were following:

▪ injection temperature	200 [°C]
▪ hold pressure	50 [MPa]
▪ injection velocity	65 [mm/s]
▪ holding time	3 [s]
▪ cooling time	10 [s]
▪ mold temperature	60 [°C]

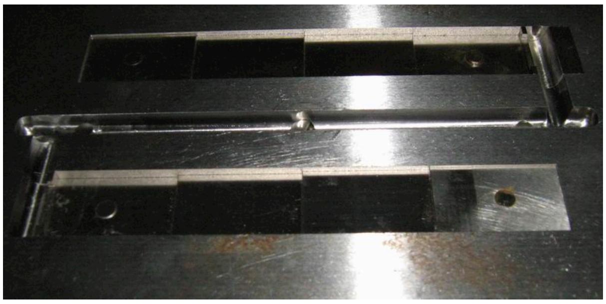

Fig. 4. Insert of two-cavity injection mould

Computer simulations injection was carried out using commercial software, Moldflow Plastics Insight 5.0. The program allows simulating the plastic injection molding. In a study modeled molded part consisting of 4354 finite elements. Numerical models have been developed using two-dimensional elements (triangles) in the case of the mold cavity and of runners, and the cooling channels 48 parts were modeled 1-dimensional (Fig. 5). In the simulations were used two available models: the Cross-WLF rheological model and thermodynamic Tait model.

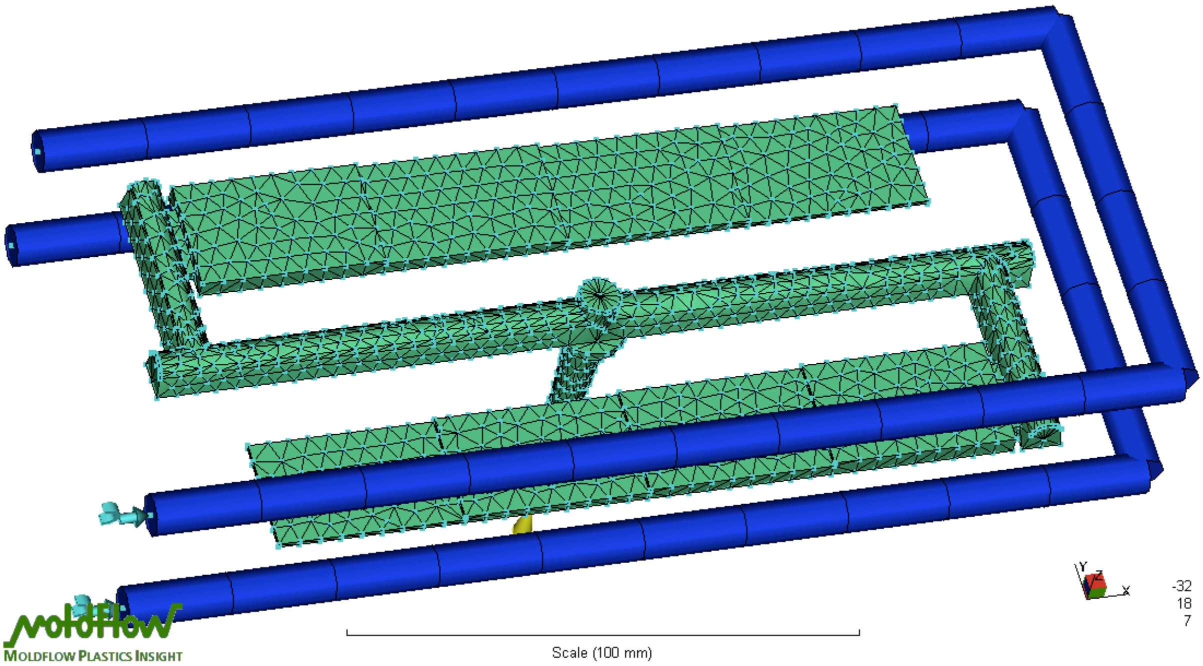

Fig. 5. The model of injection molded parts with two-dimensional elements (the cavity and runners), one-dimensional (cooling channels) with a finite element mesh

In structural studies of molded parts were used optical microscope Nikon ECLIPSE E200. Observations were carried out in polarized transmitted light. The image was recorded with a digital camera and analyzed using computer software NIS. Preparations for microscopic observation was prepared using a rotary microtome Thermo ShandonFinesse ME +, which cut shreds with a thickness of 12 microns. The cut was taken from the centre of each zone, in a plane perpendicular to the direction of polymer flow in the mold.

Result and discussion

Numerical simulations

From analysis of the simulation showing the average relative crystallinity of plastic can be seen, that during the 5.81 seconds of the start of injection, the complete crystallization is obtained in molded part area with a thickness of 1 mm. In the areas when polymer is cooled slowly (because of the greater thickness), can be seen smaller proportion of crystalline phase (Fig. 6).

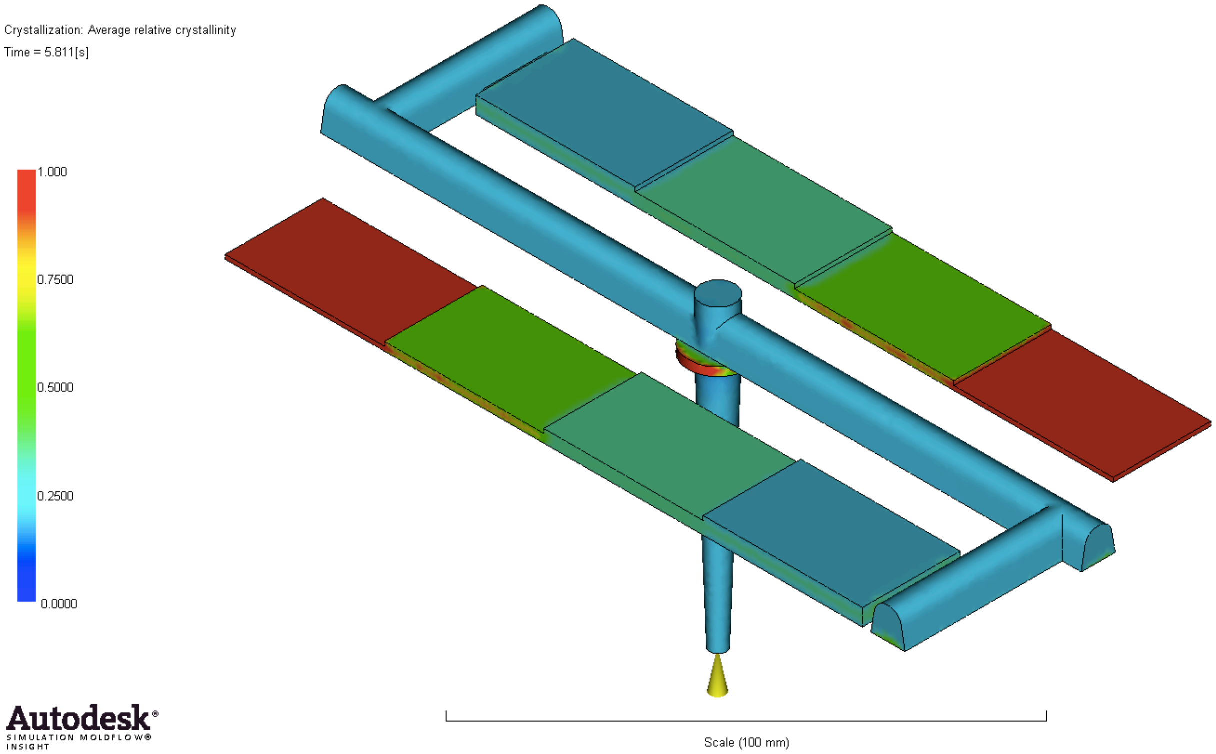

Fig. 6. Avarage relative crystallinity of molded part with various thicknesses from HDPE

The phenomenon of varying the rate of crystallization in different parts of the molded part is caused by differences solidification time of the plastic in different parts thereof, and thus different amounts of time transferring heat to the mold. This can be seen for example as a result of the imaging temperature of molded parts during injection cycle. The figure 7 shows the temperature distribution during the 21 s since the start of the injection cycle.

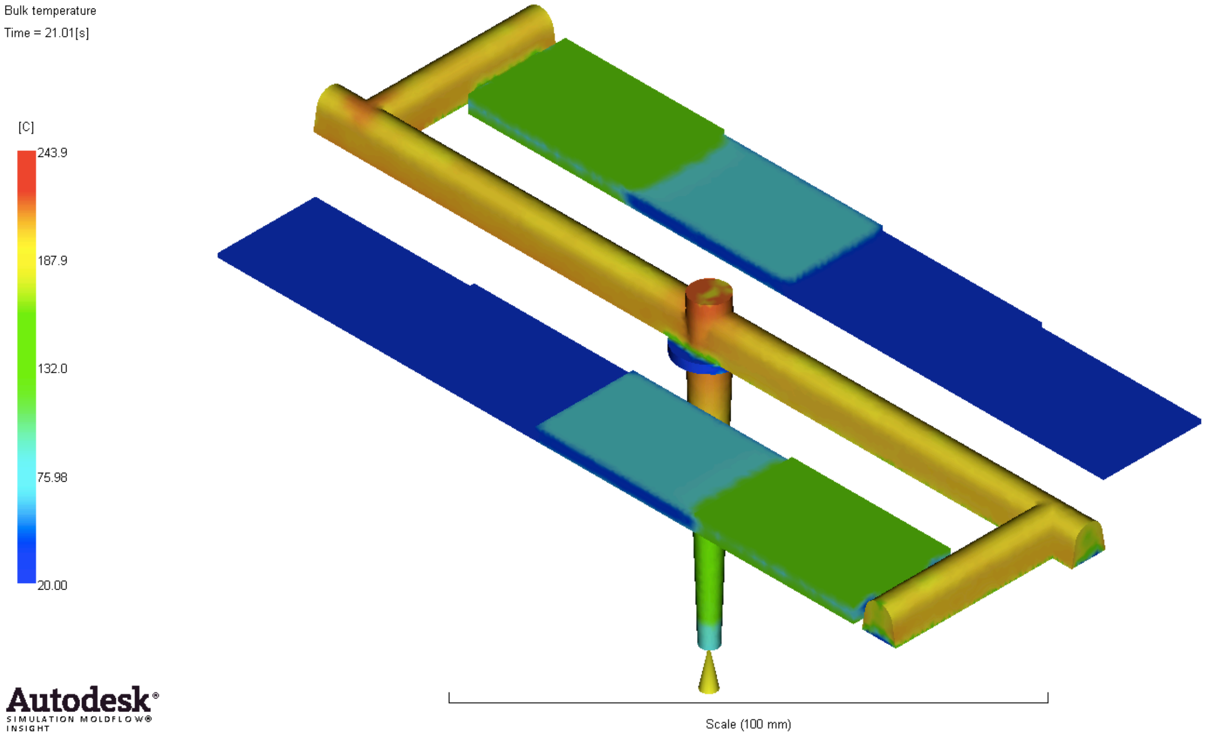

Fig. 7. Bulk temperature of molded part with various thicknesses from HDPE

Figure 8 shows the time needed to complete the growth of crystallites for various parts of the molded part. Can be seen, that the growth of crystallites in area of part with a 1 mm thick, ends after about 4 sec., respectively, for the molded part area with a thickness of 2 mm this time is 12 s, for a part having a thickness of 3 mm is 20 s, and for the part with the greatest thickness (4 mm) over 30 s.

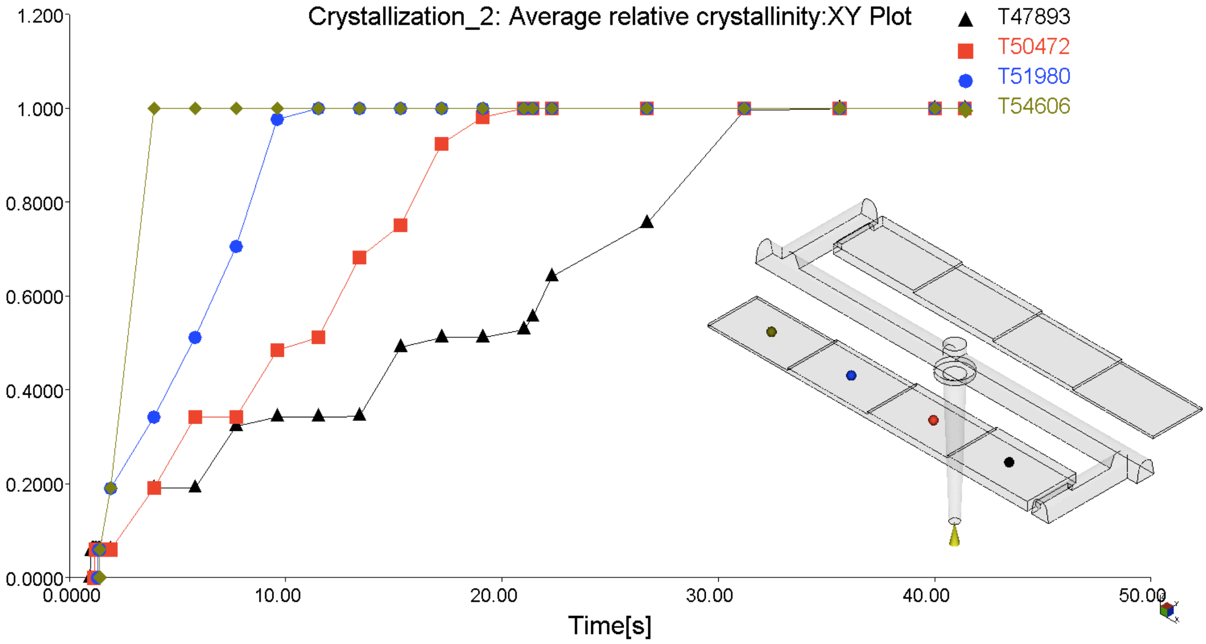

Fig. 8. Average relative crystallinity dependence of time of molded part with various thicknesses

It is worth mentioning that a large wall thickness of the molded part is disadvantageous not only due to the long cooling, and thus long cycle time, but also because of the possibility of sink marks.

Structural investigations

Figure 9 shows the morphology of the of molded parts of varying wall thickness from HDPE.

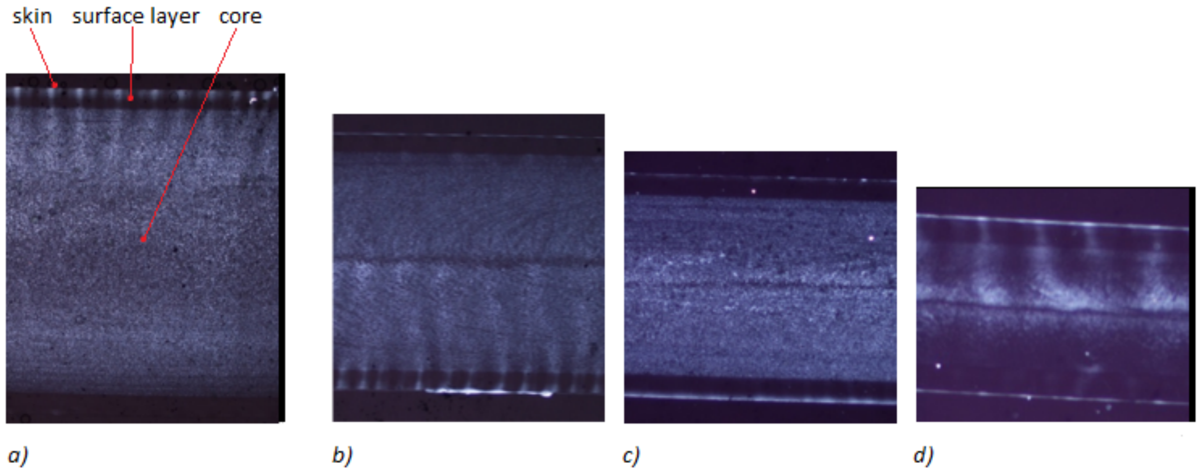

Fig. 9. The morphology of injection molded parts from polypropylene at different wall thicknesses: a) 1 mm, b) 2 mm, c) 3 mm, d) 4 mm

From Figure 9 it can be observed classic layers: the skin at the wall of the molded part, then - a layer of material having a high degree of orientation of the resulting high shear material in this area during the flow in mold cavity, and an outside layer of material in the core. It can also be noted that in the outer layer crystallites have a much smaller size than in the core. This is due to the rapid cooling of the liquid plastic layer in contact with the cold wall of the mold, which is not conducive to the growth of the crystallites. A transition layer decreases with increasing thickness of the wall of molded part. Is a layer wherein the different structural features due to the conditions of plastic flow in the mold. The higher temperature of the material in high shear zone between the layer of solidified material at the wall of the mold and the liquid material in the core in combination with high shear in this region promotes the formation of fine crystalline structure. Can also be observed that if the molded part has a greater thickness, the core of the molded part is also larger.

Summary and conclusions

Investigations have shown that the wall thickness of the molded part can significantly affect its properties, not only because of the greater volume of the amount of material, but also because of the process taking place within the molded part during the solidification of the material. The degree of crystallinity can be different depending on the cooling time, which contributes to the change in strength. Furthermore, different thicknesses of the wall of molded part contribute to the occurrence of different sizes of skin and the core. The limitation may be the fact that it is not easy to investigate the strength properties of molded parts with varying wall thickness. In future studies other crystalline polymers should be investigated.

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