Surface Topography: Metrology and Properties

PAPER

The influence of tool's surface topography on mechanical properties of injection moulded product

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Abstract

This publication deals with influence of tool topography (injection mould) on properties of a product. Surface of the mould was machined by various finishing technologies (milling, grinding, polishing and electrical discharge machining) which resulted in varying surface quality of the tool. The tested topography had an effect on the flow length of polymer and topographical and mechanical properties of the specimen. Examined properties (surface topography and mechanical properties) were measured in several places along the length of the product (starting at the gate and finishing at the end of the specimen). The results show that increase of the tool's surface roughness leads to longer flow length. These findings disprove the necessity for polishing of each and every shaping part of the mould when manufacturing non-visual products. Thus, from economical and manufacturing perspective the milled or grinded tool surfaces are sufficient. Furthermore, replication of the tool's topography is non-homogenous, which results in varying mechanical properties throughout the product. The discrepancy in mechanical properties along the length of the product is caused by differing cooling speeds in the mould. In practice, guided cooling can be used to achieve varying mechanical properties in desired places of the injected article. For example, highly stressed parts can be manufactured with the goal of having improved mechanical properties in specific places of the product. Future application of these findings poses a significant benefit for industrial practice, as it could lower the manufacturing cost of the injection mould in order of tens of percent.

1. Introduction

The topic of this work is the influence of flow length on selected properties. Literary research showed that no currently existing work is concerned with the problematic of flow length influence on mechanical properties in injected articles. In most cases, the mechanical properties, specifically hardness, were evaluated locally and this value was then ascribed to an entire sample. Overall, there were no research papers concerned with differing mechanical properties along the flow length. The papers listed below were concerned with research that partially encompasses the aforementioned problematic, specifically the influence of injection moulding process parameters on mechanical properties and the effect of tool's surface quality on flow length and surface replication ability.

The following paragraphs summarize studies concerned with the influence of process parameters on mechanical properties of injected article. Wang *et al* [1] evaluated the effect of process parameters (mainly injection speed) on mechanical properties of micro-injected PP specimen. It was found that hardness increases with increasing injection speed and that this effect is more pronounced in perpendicular direction to the flow than in flow direction. Sykutera *et al* [2] researched the influence of process parameters on polymer's viscosity, which was measured directly in the cavity. In general, rheological parameters are measured in rheometer, but the goal of this paper was to investigate real values found directly in the injection process.

Furthermore, research papers [3–6] investigated the influence of other process parameters, specifically pressure and temperature, on final flow length. The influence of process parameters was also investigated in publications [7–9]. And finally, following published papers [10–12] investigated various effects of process

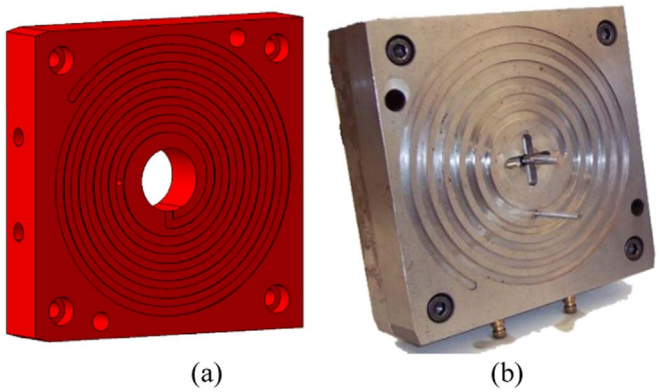

Figure 1. (a) Construction design of shaping plate, (b) shaping plate.

parameters, for example pressure and melt flow index, or the reason for the creation of flow marks.

Besides the process parameters and properties of injected material, the flow length is also affected by quality of the injection mould's surface. The ability of the melt to replicate the surface of the cavity onto the final product can be observed not only in macro-scale, but also in the micro-scale with micro injection moulding. Achieved flow length can lead to varying micro-mechanical properties along the flow direction. The influence of tool's surface quality in the realm of micro injection moulding was investigated by Surace *et al* [13]. This research showed that flow length increases with rising cavity surface roughness and growing contact angle. This problematic was researched by further studies [14–16], whose authors focused on different polymer materials. Otsuka *et al* [17] focused their research on the effect of various roughness values of the mould's surface on flow length and mobility of polymer in thin walled injected articles. Rebeggiani *et al* [18, 19] focused on evaluation of polished surface's quality in injection moulds and its influence on properties of polymer products.

Aside from physical injection moulding, published articles also focused on creation of credible simulation which could simulate the injection moulding process as close to the reality as possible. Publications [20–23] attempted to create a simulation in numerous softwares. There was also the work of Lucchetta *et al* [24], who focused on the influence of various coatings of the mould on melt flow in thin-walled products.

All of these studies are concerned with individual problems of polypropylene injection moulding and the effect of process parameters and flow length on micro-mechanical properties of final product. On the other hand, no current publication offers a comprehensive research on the topic of flow length and process parameters influence on micro-mechanical properties. The manner in which these properties can be affected is given by several mechanisms such as crystallization, or individual parameters that influence flow length. This topic can be of great importance to industrial practice, as mechanical properties of final product in a given position are significant for correct function of given product.

This publication deals with the problematic of tool's topography and its influence on specimen's final length. The length determines mechanical properties of the specimen, i.e. hardness, modulus. Gained experimental data is important for technical practice, due to economical manufacturing and quality of the final product.

2. Material and methods

Investigation of mould's topography on flow length of polymer, and surface topography and mechanical properties of specimen was done on spiral shaped specimen.

2.1. Material

PP was chosen as the tested material. It belongs to a group of semi-crystalline polymers, which are commonly utilized in technical practice to manufacture construction parts. Tested material designated BJ380MO was supplemented by Borealis (Linz, Austria). Melt flow index given by the material sheet is 80 g 10 min^{-1}

2.2. Injection mould

The injection mould in question is capable of producing one part per cycle. It was designed with simple manipulation in mind, thus the testing plates can be exchanged during injection moulding and some parameters can be modified, i.e. gate size.

The main parts contributing to preparation of the final specimen were the exchangeable plate, shaping plate and sprue puller. The specimen shaped into spiral (figure 1) can achieve length up to 2000 mm, while the cross section of the specimen was rectangular with dimensions 6 $\times$ 1 mm.

The test plate, which makes up the right side of the mould, was manufactured in four different versions. The dimensions were chosen to fit with the shaping

Table 1. Parameters of the surface of the injection mould.

Test plates label	Type of machining	Surface quality
Plate 4.4	Electrical discharge	Ra = 4.4 μm
Plate 1.6	machining Milling	Ra = 1.6 μm
Plate 0.8	Grinding	Ra = 0.8 μm
Plate 0.1	Polishing	Ra = 0.1 μm

plate dimensions (200 × 200 × 12) mm. Surface of these plates was machined by four different methods (table 1), which are most often used in manufacturing of parts that come into direct contact with hot melt, i.e. mould cavity and channels. These four methods consisted of milling, grinding, polishing and electrical discharge machining.

2.3. Technological parameters of injection moulding

Specimens made out of PP were injected in injection moulding machine Allrounder 470E manufactured by Arburg (Losburg, Germany). The mould was tempered by oil tempering unit Regloplas 150 smart. Specimens were prepared with two variables - test plates with varying surface roughness and differing injection pressure. For each setting, 10 specimens were injected. These specimens were subsequently examined and measured (length, surface topography and mechanical properties). The measurements were then statistically evaluated.

Technological parameters settings can be seen in table 2.

Table 2. Technological parameters settings for individual materials.

Technological parameter	Unit	Value
Injection pressure	bar	800
Holding pressure	bar	640
Holding pressure duration	s	1
Shot size	mm	10
Switch-over position	mm	7
Cooling time	s	20
Decompression speed	mm s^{-1}	2
Decompression length	mm	3
Back pressure	bar	−1
Holding force	kN	1200
Screw rotation speed	mm s^{-1}	30
Mould temperature	°C	30
Melt temperature	°C	215
Settings of heat zone		
Zone n. 1	°C	215
Zone n. 2	°C	210
Zone n. 3	°C	205
Zone n. 4	°C	200
Zone n. 5	°C	200

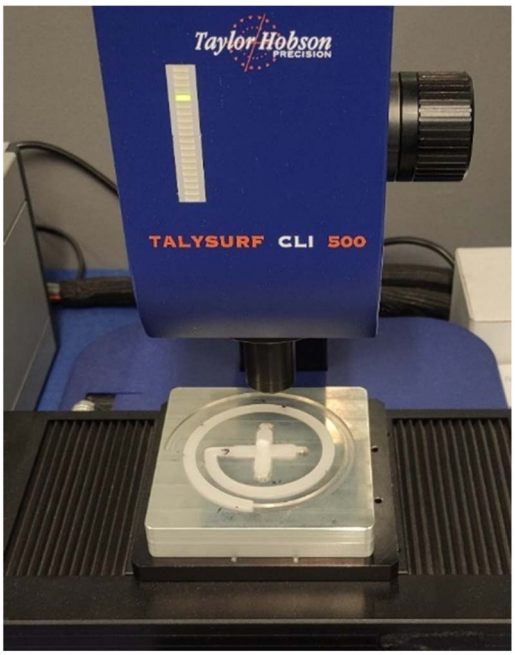

Figure 2. Scanning of the mould's surface.

2.4. Injection moulding simulation

Besides the real preparation of the specimens, a simulation of the injection moulding was performed. Technological parameters of the process that can be seen in table 2 were chosen in agreement with the simulation results. Individual parameters like shot size, cooling time and holding force were gained from simulation. The simulation was done with preset injection pressure (800 bar), melt temperature (215 °C), holding pressure switch-over (99%) and cooling medium temperature (30 °C). The simulated specimen was prepared in polished cavity, as the simulation software does not allow any changes to the roughness of the cavity and it only looks at specific used surface. It was done in MoldFlow Synergy software provided by Autodesk (San Rafael, CA, USA).

2.5. Surface topography

The surface quality measurements were performed by Talysurf CLI 500 (figure 2) with CLA sensor manufactured by Taylor Hobson (Leicester, UK). The manner of measurement was contactless and optical. Next, the results gained from the measurements were evaluated by Talymap software. The software evaluated 30 random points in scanned samples and calculated roughness parameters Rp, Rv, Rz, Rt, Ra and Rmr. The surface topography evaluation was done in accordance with ISO 21920–2:2021 and ČSN EN ISO 4288 standards. At first, 2D profile of the surface was scanned and numerical data (Ra and Rz) was evaluated. The scanning length of 2D profile was 2 mm and measurement speed was 100 μm s^{-1}. After that, 3D profile was scanned to provide graphical representation of the surface's texture.

The measurement area is 2*2 mm and there are a total of 800 points with 400 points in X & *Y* axis direction, which gives a lateral resolution (size of a point) of 0.005 mm (5 μm). Comparison of profiles was done by

rectangle method, while waviness and roughness was evaluated by Gauss filter (0.8 mm).

2.6. Mechanical properties

Mechanical properties were measured at 6 points spaced along the length of the specimen (0 mm, 79 mm, 158 mm, 195 mm, 225 mm and 266 mm). The measurement was done by DSI method (Depth Sensing Indentation) on MHT_3 device provided by Anton Paar (Graz, Austria). It was done in accordance with ČSN 14557 standard and the parameters were: indentation force 1N, load duration 90 s and loading de-loading speed 2N/s. Main results gained by this device were the indentation hardness and modulus.

Indentation hardness (H_{IT}) was calculated as the maximum load (F_{max}) on the projected area of the hardness impression (A_p) [25, 26].

$$H_{IT} = \frac{F_{max}}{A_p} \tag{1}$$

$$H_{IT} = \frac{F_{max}}{A_p} \tag{2}$$

The indentation modulus (E_{IT}) was calculated from the plane strain modulus (E^*) using an estimated Poisson's ratio (ν_s) of the sample (Polymer 0.3 to 0.4) [25, 27].

$$E_{IT} = E^* \cdot (1 - \nu_s^2) \tag{3}$$

$$E^* = \frac{1}{\frac{1}{E_r} - \frac{1 - \nu_i^2}{E_i}} \tag{4}$$

$$E_r = \frac{\sqrt{\pi}}{2 \cdot C\sqrt{A_p}} \tag{5}$$

where E_i is the elastic modulus of the indenter (diamond 1141 GPa), E_r is the reduced modulus of the indentation contact, and ν_i is the Poisson's ratio of the indenter (0.07).

2.7. Differential scanning calorimetry (DSC)

Behaviour of the specimen during melting and solidification was observed by differential scanning calorimeter DSC Q20 (TA Instruments, USA). Weight of the sample was 6 mg, and it was sliced by microtome. Velocity of heating and cooling was set to 10 °C min^{-1}. The measurements were divided into two parts. First part consisted of heating from T_0 to T_1, which was followed by constant temperature hold for 1 min (isotherm) and cooling from T_1 to T_0 followed by another constant temperature hold for 1 min (isotherm). Second part consisted of same pattern. Observed properties were captured during the first part.

Crystallinity was calculated from heat flows according to following math equations:

$$X_c = \frac{\Delta H_m}{\Delta H_m^{100}} \times 100 \tag{6}$$

where X_c is crystallinity (%), ΔH_m is heat flow (J $g)^{-1}$ and $\Delta H_m 100$ is heat flow for 100% crystalline polypropylene (207 J g^{-1}), which was found in literature [28].

3. Results and discussion

The spiral shaped specimens could reach up to 2000 mm in length. These subjects were manufactured by injection moulding technology, after which their length was measured. During the injection moulding, technological parameters and test plates were varied. For each setting, 10 specimens were manufactured and subsequently their length, surface topography and mechanical properties (indentation hardness and modulus) were measured. This data was then statistically evaluated.

3.1. Injection moulding simulation

Simulation of the injection moulding process was done after the verification of the mould's functionality. The simulation put special attention to parameters that are important for the injection moulding process, such as cycle duration, shot size, cooling time, holding force and prediction of created skin-core structure.

Figure 3 displays the simulated results with the real specimen manufactured in polished cavity. As can be seen in figure 3(a), filling time 3.4 s led to 259 mm flow length, which was approximately the same as the real specimen (260 mm). Figure 3(b) demonstrates the course of injection pressure, which is important for the replication of mould's surface on the specimen. The simulation showed a decrease of pressure (50 MPa) at the end of the specimen and at the gate. On the other hand, pressure increased up to 120 MPa at the middle of the sample. Figure 3(c) shows the core orientation during filling, while figure 3(d) provides the skin orientation of the same process. This result demonstrates behaviour of polymer during flow and predicts incurred molecular orientation in both skin layer and core. This predicted skin-core structure is important to the creation of appropriate morphology that directly influences mechanical properties of the specimen.

3.2. Flow length

Surface of the mould was finished by 4 different technologies (electrical discharge machining Ra 4.4, milling Ra 1.6, grinding Ra 0.8 and polishing Ra 0.1) that are frequently used in practice in injection mould manufacturing.

Based on the findings characterizing the flow length on defined surfaces with specified material, it is possible to say that the quality of surfaces with which the melt comes into contact during the filling has a significant effect on the final properties of the specimen (figure 4). As the results indicate, the difference in flow length for all tested materials displayed similar

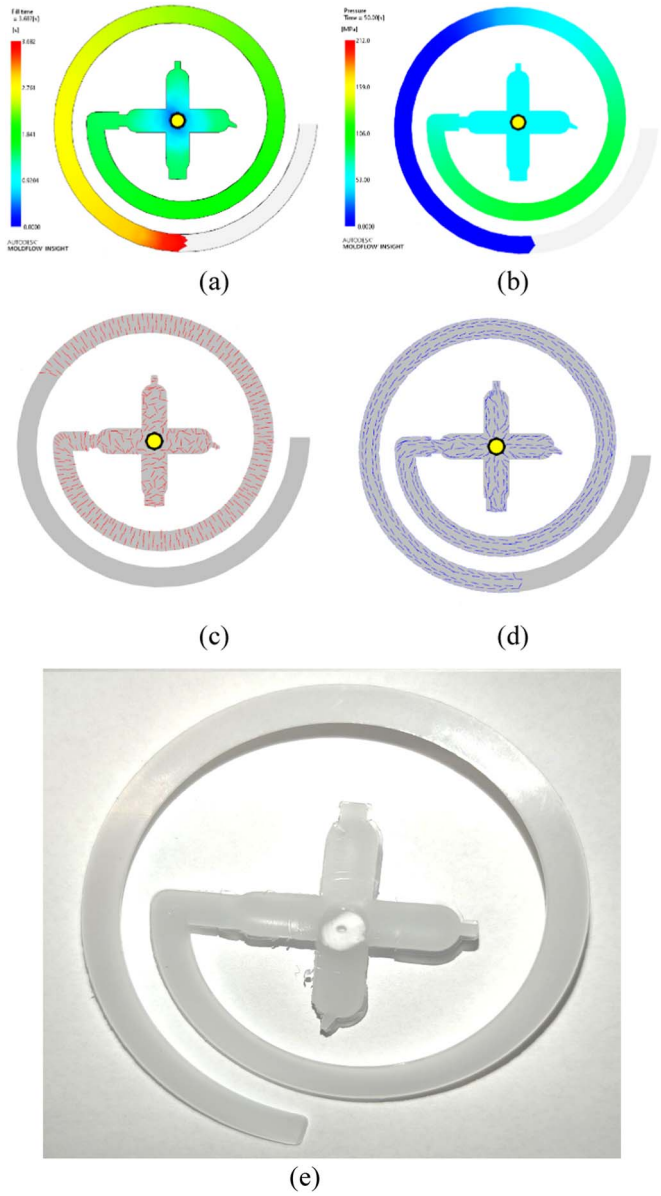

Figure 3. Injection moulding simulation: (a) filling time, (b) injection pressure, (c) orientation in the core, (d) orientation in the skin, (e) real specimen.

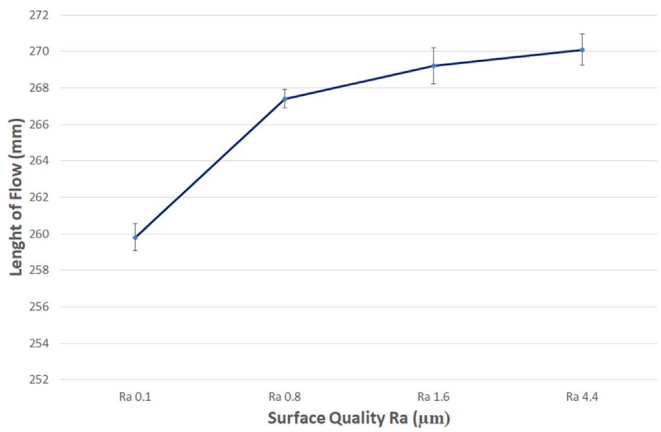

Figure 4. Tool surface quality influence on flow length.

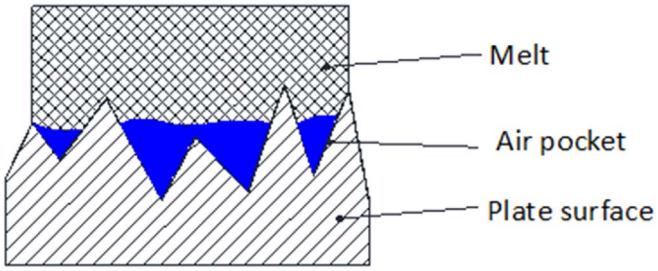

Figure 5. Air barrier created between the mould and the polymer.

tendencies when injected in cavities with varying surface roughness. In addition, plates with worse surface quality (Electrical discharge machining—Ra 4.4 μm) produced longer specimens than those with better surface quality (Polishing—Ra 0.1 μm). The difference in average flow length between these two plates was 4%. These findings can be considered quite important, as they can have a direct impact on industrial practice.

These results were confirmed by multiple other tested materials, as can be seen in previously published studies [29–32]. The measurements indicate that rougher surfaces left after electrical discharge machining (Ra 4.4), milling (Ra 1.6) and grinding (Ra 0.8) consist of irregular structures, which are not fully filled by the hot melt during injection moulding. This effect can be seen in figure 5. These depressions remain filled by air (isolant), which creates a heat barrier between the injection mould (mould temperature 30 °C) and polymer (melt temperature of injected polycarbonate 220 °C). This behaviour was also observed and studied in our previous study [29].

3.3. Surface topography

Surface topography was measured in six spots placed along the length of the specimen (gate—0 mm, 79 mm, 158 mm, 195 mm, 225 mm and at the end of the specimen—listed in table 3). The results show that flow length has a significant influence on the surface quality and replication of the tool's surface onto the specimen's surface.

Figure 6 shows the 3D scans of specimen's surface in individual spots. As can be seen in figure 7, the surface of the tool replicated to the surface of the specimen with worse quality. Surface roughness at the gate was Ra 0.17 μm; afterwards it rose to Ra 0.27 μm at the middle of the sample and subsequently fell to Ra 0.2 μm at the end of the specimen.

Figure 8 shows several 3D scans of mould's cavity surface that was finished by grinding (Ra 0.8). Furthermore, as can be seen in figure 9, the replication tendency of the grinded mould's surface was opposite of those found in polished test plate. The surface of the mould replicated with better quality than the surface quality of the mould. Roughness measured at the gate was Ra 0.51 μm; then it rose to 0.75 μm at the middle of the sample and past 158 mm from the gate declined down to 0.27 μm recorded at the end of the specimen. The difference between the worst and best surface quality was 178%.

Table 3. End of the specimen—flow length for individual test plates.

Test plates	Type of machining	End of the specimen
Ra = 4.4 μm	Electrical discharge	270 mm
Ra = 1.6 μm	machining Milling	269 mm
Ra = 0.8 μm	Grinding	267 mm
Ra = 0.1 μm	Polishing	260 mm

Figure 10 displays 3D scan of the product's surface, which was manufactured in milled mould cavity with surface roughness Ra 1.6. Structure of the milled surface that replicated to the product can be seen in this figure. Figure 11 demonstrates that milled plate had similar tendencies to grinded plate. Ra 0.52 μm was measured at the gate, Ra 1.42 μm was measured at 158 mm; following this point the roughness started to decline down to Ra 0.7 μm measured at 225 mm and 266 mm from the gate. The difference in surface quality between the highest (distance 158 mm) and the lowest value (distance 0 mm) was 170%.

Figure 12 displays 3D scan of the product's surface, which was manufactured in electrical discharge machined mould cavity with surface roughness Ra 4.4. Structure of the electrical discharge machining surface that replicated to the product can be seen in this figure.

Mould cavity finished by the electrical discharge machining (Ra 4.4) exhibited similar surface replication trend as plates with Ra 0.8 and Ra 1.6, although with smaller variance along the flow length (figure 13). Following surface roughnesses were measured: Ra 3.1 μm at the gate, Ra 3.4 μm at 158 mm and Ra 2.8 μm at the end of the sample. The difference between the highest and lowest values of roughness was 21%.

During the evaluation, a negative trend for surface replication, i.e. the replicated surface quality was worse for the specimen than for the cavity, was observed in mould with surface roughness Ra 0.1 μm. On the other hand, positive trend was found in moulds with surface roughness Ra 0.8 to 4.4 μm. Positive trend was most likely caused by cooling polymer, which was unable to fill greater irregularities in the surface before solidifying. Negative trend for mould

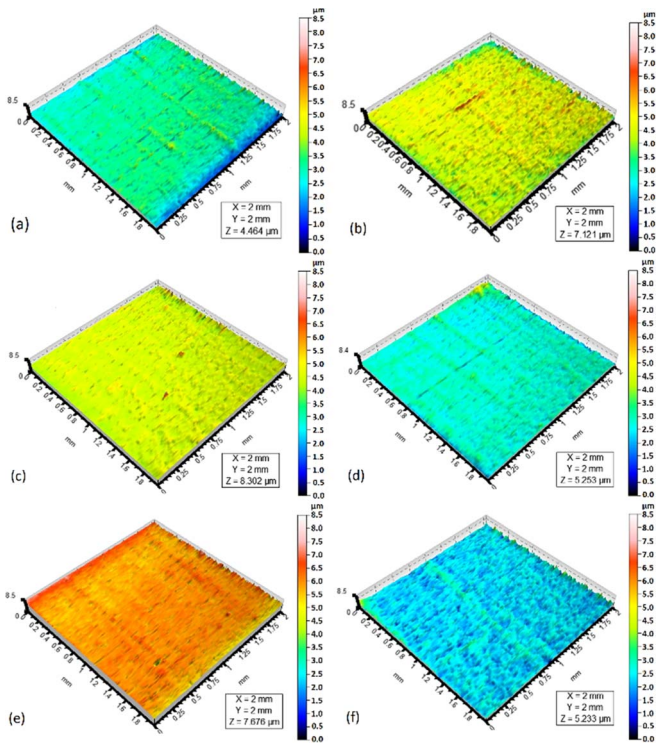

Figure 6. Surface quality of the specimen manufactured in polished mould (Ra 0.1): (a) distance 0 mm, (b) distance 79 mm, (c) distance 158 mm, (d) distance 195 mm, (e) distance 225 mm and (f) distance 266 mm.

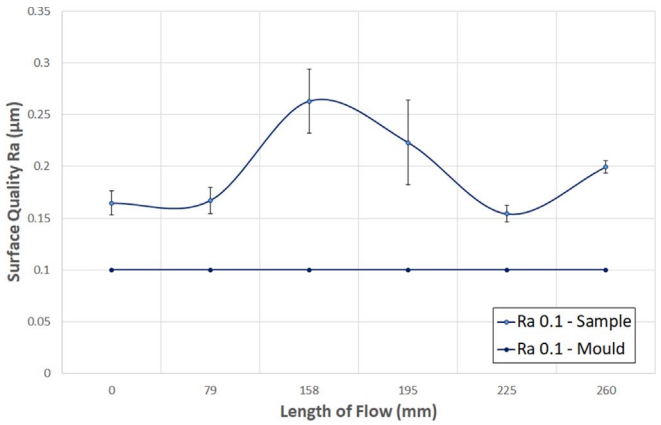

Figure 7. Influence of tool's surface quality (Ra 0.1) on the specimen's surface quality.

with surface roughness Ra 0.1 μm was probably caused by faster cooling of the specimen's surface. As can be seen in figure 5, the air gaps create sort of isolation barrier that hinders cooling of the specimen's surface. As a result it can be said that the influence of air gaps is negligible for moulds with surface roughness Ra 0.1 μm. The surface cools faster and causes irregularities in the surface of the specimen, which are caused by polymer flow and subsequently influence the roughness of the specimen.

Study of the effect that individual process parameters have on flow length on polymer material in previous chapters raised a question about the extent to which the injection pressure and its course influence the quality of the injected article.

Throughout the filling phase, the injection cycle gradually loses pressure (pressure drop) which drives the material into the cavity. The event can be seen in figure 14 that contains data from real mould fitted with 6 pressure sensors. As is obvious from the figure, pressure affecting the material was significantly higher at the gate area than at the more distanced parts of the mould. This effect can influence the surface quality of the specimen by forcing the melt to copy the mould's surface quality to a greater degree, due to higher pressure (the melt is forced into every irregularity of the surface). On the contrary, pressure further from the

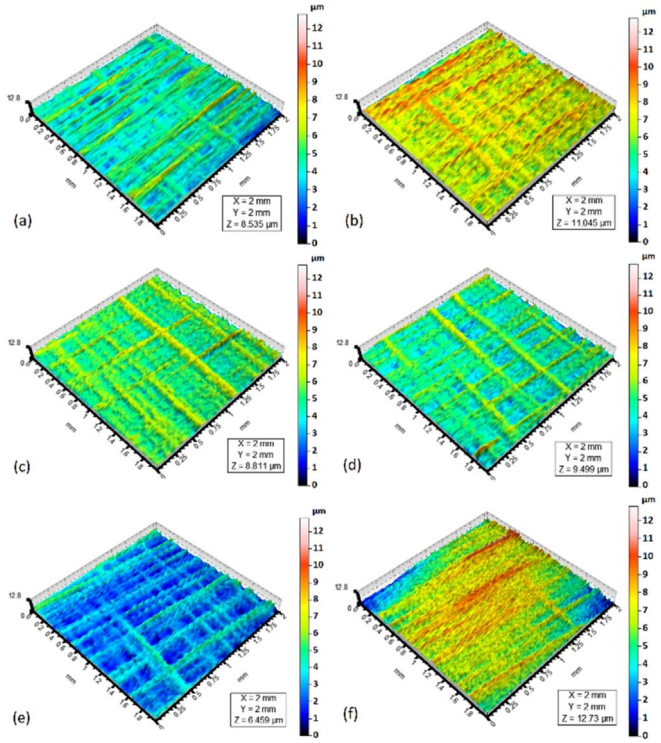

Figure 8. Surface quality of the specimen manufactured in grinded mould (Ra 0.8): (a) distance 0 mm, (b) distance 79 mm, (c) distance 158 mm, (d) distance 195 mm, (e) distance 225 mm and (f) distance 266 mm.

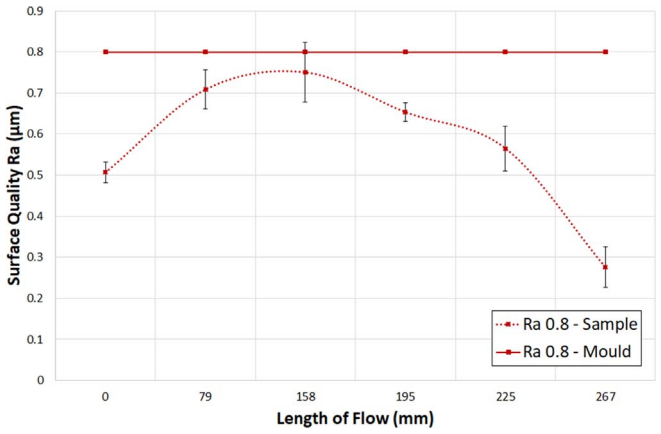

Figure 9. The influence of the tool's surface quality (Ra 0.8) on the product's surface quality.

gate is lower, thus the replication ability of the melt declines. In addition, this effect can be influenced by temperature changes, i.e. increasing viscosity equals worse filling of the surface's irregularities.

This claim is supported by results of injection simulation, specifically the simulation of injection pressure within the cavity which changes along the specimen length. The pressure was predicted to be highest at the middle of the specimen, after which it gradually decreased towards the end of the specimen. Due to this behaviour, the surface quality was higher at the middle of the specimen than it was at the end of the specimen. Higher pressure led to improved filling of mould surface irregularities.

3.4. Mechanical properties

Mechanical properties were measured at the same designated spots like surface quality (gate—0 mm, 158 mm, 195 mm, 225 mm and at the end of the specimen). Figure 15 shows indentation curves with photos for each indentation of the specimen manufactured in polished mould. Indentation curves represent the dependence of indentation force on depth of indentation. The curves can be used to calculate mechanical properties, such as indentation hardness and modulus. Furthermore, behaviour and properties of tested material can be determined from the slope and shape of the curves.

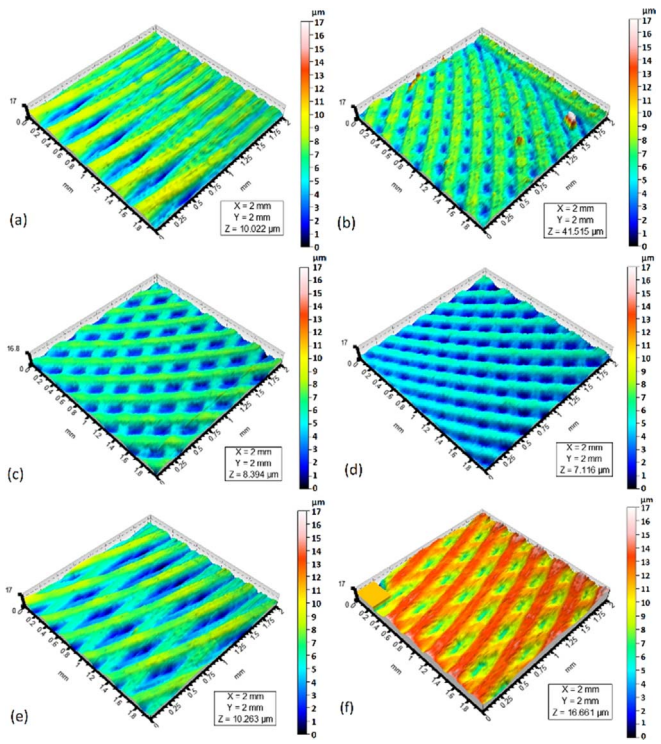

Figure 10. Surface quality of the specimen manufactured in milled mould (Ra 1.6): (a) distance 0 mm, (b) distance 79 mm, (c) distance 158 mm, (d) distance 195 mm, (e) distance 225 mm and (f) distance 266 mm.

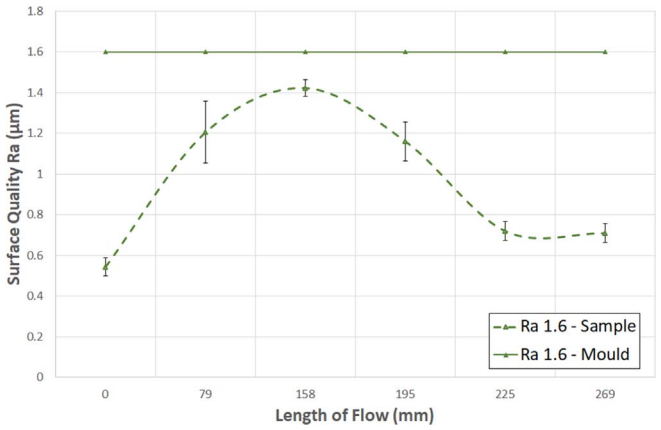

Figure 11. Influence of the tool's surface quality (Ra 1.6) on the specimen's surface quality.

Besides the mechanical properties, character of tested material, e.g. elastic-plastic behaviour, variance of individual measurements, can be inferred from the indentation curves.

Indentation hardness is an important property, which describes the influence of polymer flow length on final properties of the specimen. As can be seen in figure 16, indentation hardness significantly varies along the length of the specimen and with differing surface quality. The indentation hardness for specimen manufactured in a polished mould (Ra 0.1) was 82 MPa. The indentation hardness was declining with increasing surface roughness. For comparison, specimens made in milled and grinded moulds displayed higher indentation hardness (100 MPa). On the other hand, specimens prepared in mould finished with electric discharge machining displayed lower hardness (66 MPa) than specimen prepared in polished cavity. The difference between specimens made with polished and grinded or milled mould was 22%. These differences were caused by wall slip and varying speed of surface layer solidification. Temperature gradient along the flow length also played a significant role, as it resulted in varying degree of crystallization and thus differing hardness. As can be seen in figure 5, surface with bigger irregularities was filled with air, which creates a thermal barrier between the mould and melt. This led to slower cooling and crystallinity changes,

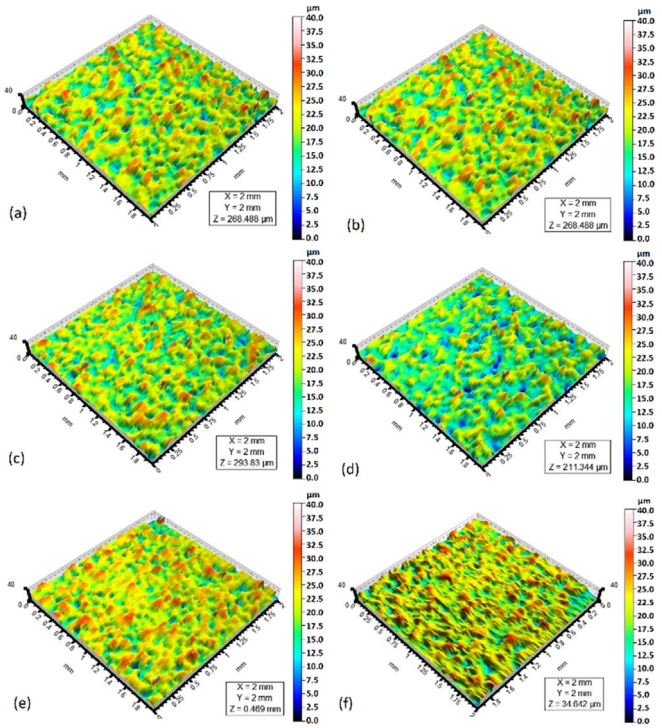

Figure 12. Surface quality of the specimen manufactured in electrical discharge machined mould (Ra 4.4): (a) distance 0 mm, (b) distance 79 mm, (c) distance 158 mm, (d) distance 195 mm, (e) distance 225 mm and (f) distance 270 mm.

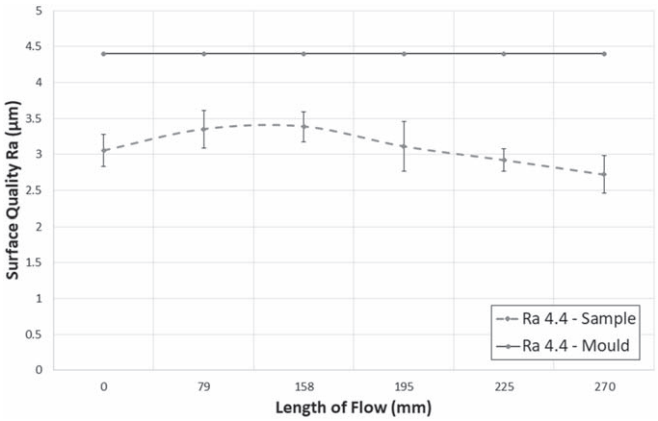

Figure 13. Influence of tool's surface quality (Ra 4.4) on the specimen's surface quality.

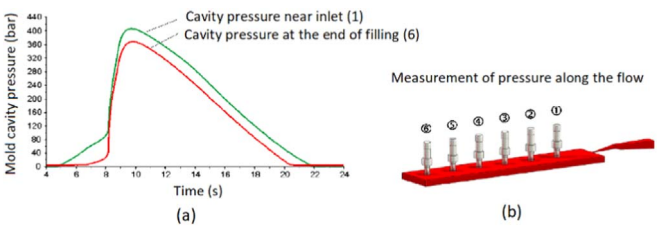

Figure 14. Pressure measurements within the mould's cavity: (a) pressure profile, (b) pressure sensors placement.

which caused differing hardness. This claim is supported by crystallinity measurements done on DSC, as can be seen in chapter 3.5.

Hardness was measured to have a declining trend (from gate to middle of the sample) in all specimens injected into every test cavity with varying surface roughness. Past middle of the sample, the hardness

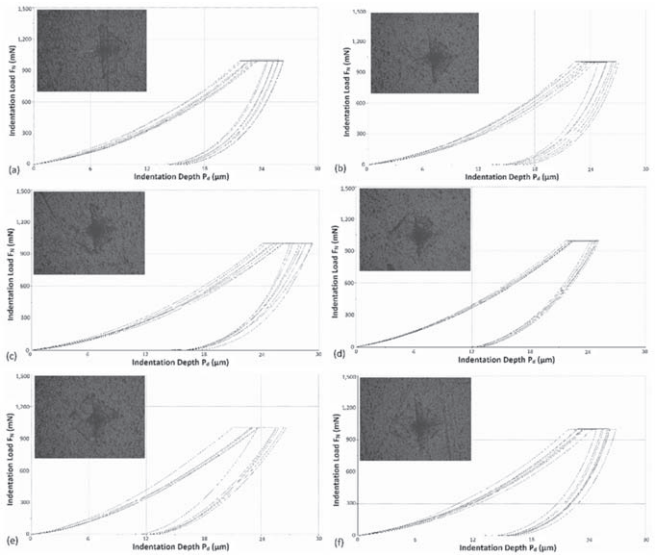

Figure 15. Indentation curve load—depth for polished mould: (a) 0 mm, (b) 79 mm, (c) 158 mm, (d) 195 mm, (e) 225 mm, (f) 260 mm.

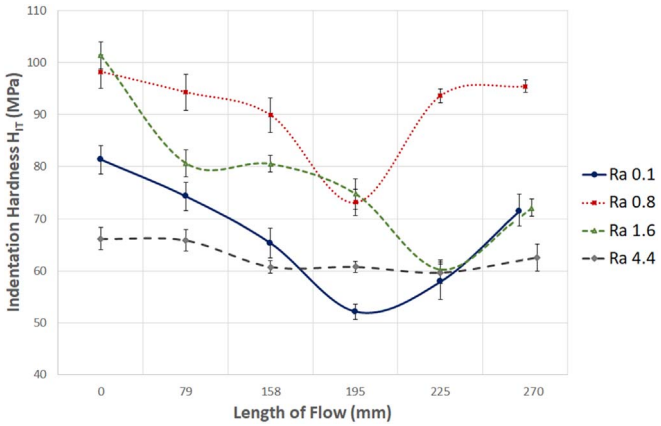

Figure 16. Dependence of indentation hardness on length of specimens that were manufactured in moulds with varying surface quality.

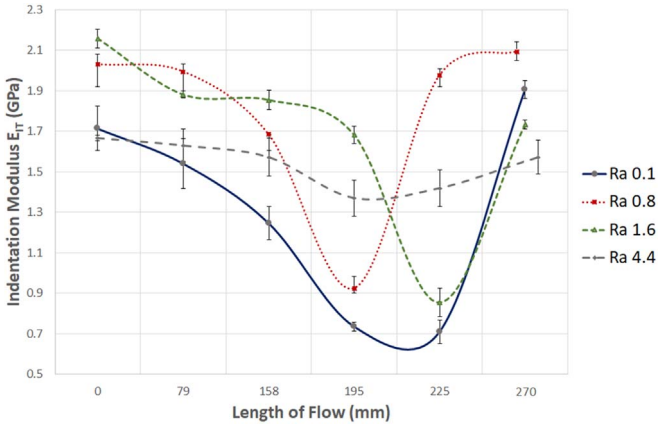

Figure 17. Dependence of indentation modulus on length of the specimen for moulds with varying surface quality.

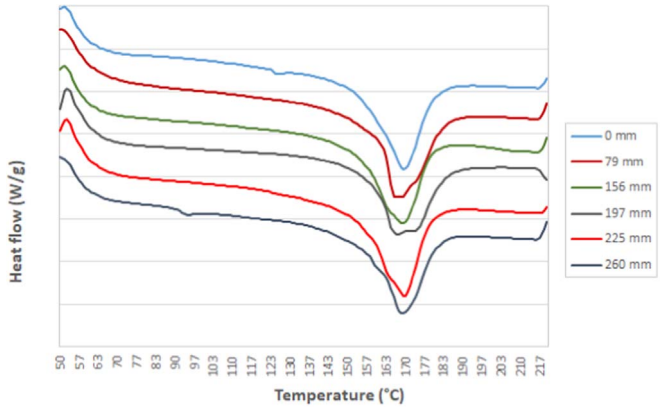

Figure 18. DSC process—Ra 0.1 μm.

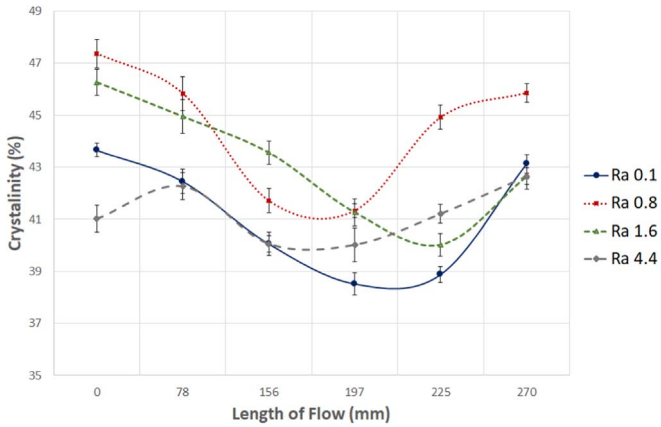

Figure 19. Dependence of crystallinity on length of the specimen for moulds with varying surface quality.

had an increasing trend. For the specimens prepared in polished mould (Ra 0.1), the hardness measurements were as follows: 82 MPa at the gate falling down to 52 MPa at 195 mm and then rising up to 73 MPa at 260 mm. The difference in hardness between the 0 mm and 195 mm points was 58%. Further, the hardness at the gate for specimens injected in grinded mould (Ra 0.8) was 98 MPa, and then it declined to 74 MPa at 195 mm, which was a 32% difference. At the end of the specimen, the hardness was measured at similar levels to the gate. Next, the milled mould (Ra 1.6) produced samples with indentation hardness of 101 MPa at 0 mm. Hardness of this specimen subsequently declined down to 60 MPa, which was measured at 225 mm from the gate. The difference in between the highest and lowest measured value was 68%. Finally, the specimen manufactured in electric discharge machined mould had 67 MPa at the gate, which gradually decreased to 60 MPa at 225 mm. The overall difference between these values was 12%. These significant changes were most likely caused by varying cooling speed along the flow length, which resulted in differing crystalline content.

Another important parameter which describes mechanical behaviour of the specimen is the indentation modulus (an equivalent for Young's modulus). Tendencies found in indentation modulus (figure 17) were similar to those in hardness. The lowest values were found in specimens prepared in polished (Ra 0.1) and electric discharge machined (Ra 4.4) mould. An increase of indentation modulus was recorded in specimens manufactured in grinded (Ra 0.8) and milled (Ra 1.6) mould cavity. The difference between the polished (1.7 GPa) and milled (2.12 GPa) variant at the gate was 25%. The indentation modulus was decreasing with increasing distance from the gate up to 195/225 mm. On the other hand, the indentation modulus measured at the end of the specimen was similar to the gate.

The parameters gained from the injection moulding simulation correspond with measurements of flow length, topography and mechanical properties. The results were affected by the mould's surface temperature, which led to varying crystallinity.

In conclusion, the results indicate that higher values of surface roughness of distribution channels and cavity lead to improved flow length. Thus, non-visual or non-functional products can be injected in moulds manufactured with common technologies, without the need for expensive finishing operations. In

industrial practice, the prevalent opinion is that better surface quality leads to improved flow length and mechanical properties. The experiments that are described in this publication prove the opposite tendency. The explanation of these findings can be found in the way the melt flows along the individual surfaces.

The measurement results indicate that chosen indentation method is sufficiently sensitive in order to evaluate mechanical properties (indentation hardness and modulus) and allows a detailed description of polypropylene's complex behaviour. Due to the relatively low values of indentation force and maximum achieved depth of indentation (in orders of μm) it is possible to spot the changes in crystalline morphology of the polymer and correlate them with gained mechanical properties. Alterations in crystalline morphology lead to changes in hardness and elastic modulus of final specimen.

3.5. Differential scanning calorimetry (DSC)

The variation of crystallinity caused by different distance from the gate was observed by DSC method. Course of DSC curves in dependence on flow length for specimen injection in mould with Ra 0.1 μm can be seen in figure 18. The results related to skin layer (figure 19) indicate that highest content of crystalline phase can be found at the gate and at the end of the specimen. On the other hand, decrease of crystallinity was observed closer to the middle of the sample. The highest values of crystallinity were found in specimen injected into grinded (Ra 0.8 μm) and milled (Ra 1.6 μm) mould. The highest content of crystalline phase (47%) was found in specimen injected in grinded cavity (Ra 0.8). Highest crystallinity of specimen injected into polished cavity (Ra 0.1 μm) was 43.5%, which was observed at the gate. However the crystallinity once again decreased at the middle of the specimen all the way down to 38.5%. Observed crystallinity trend was very similar to the trend of mechanical properties, therefore it can be said that changes in mechanical properties could be caused by changes in crystallinity incurred by the flow and cooling of polypropylene in the mould.

Aforementioned findings closely relate to polymer behaviour in the mould. Fountain flow causes the polymer to flow from the centre to the cold walls of the mould, where the melt rapidly cools and creates a solid layer. This rapid cooling means that surface or skin layers have a great deal of elongation orientation while molecules in other layers have more time to relax. Combined effect of solidifying and relaxing creates several regions with varying degree of orientation (skin zone, shear zone and core). Skin zone solidifies after a very short period of time with no or little relaxation, and so contains highly oriented molecules caused by the fountain flow. Furthermore, shear zone solidifies before the shear orientation can relax. And finally, velocity of the melt is quite slow at the core, therefore the polymer has a lot of time to relax and thus the molecules have little or none residual orientation. Consequently, great variance of the crystalline morphology can be found in semi-crystalline polymers. Degree of orientation, especially the difference in crystalline morphology in individual layers of the specimen has a big influence on mechanical properties of the specimen. These claims were based on previously published works of various authors [33, 34].

4. Conclusion

This work studies the influence of injection mould's surface topography on the polymer flow and subsequent mechanical properties. The current literature says that in order to gain superb injection moulded articles, the mould itself needs to posses high surface quality, which is mostly done by polishing. This study demonstrates completely opposite findings.

The main contribution of this publication for industrial practice is that in case of selected types of polymer, changes in processing conditions lead to differing flow length. Specifically, injection of these materials into the mould's cavity proved that in many cases worse surface quality had not negatively impacted flow length. On the contrary, in numerous cases the flow length was better.

Flow of the polymer and its length had an effect on replication ability of tool's topography on the final specimen. Surface quality of the specimen was not the same along its entire length, but it was increasing from the gate to the middle and then decreasing from the middle to the end, approximately to gate values. Furthermore, flow length influenced mechanical properties as well. The mechanical properties demonstrated a decreasing trend up to middle of the specimen, which was caused by air filling in the surface irregularities and varying crystallization along the flow path. The former created a thermal barrier between the mould and the melt, while the latter was induced by differing temperature.

The aforementioned findings could have a positive impact specifically on the cost of injection mould manufacturing, where finishing methods represent a non-trivial amount. In addition, finishing operations can be very time heavy as they are mostly hand operations which required skilled workers. Thus, these findings can also lead to time saving which indicate higher capacity for production. And finally, these findings can help with understanding of the final mechanical properties and how to modify them with temperature changes during the course of production.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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