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ANALYSIS OF THE INFLUENCE OF THE MOULD TEMPERATURE IN THE WELD LINE AREAS ON STRENGTH OF THE INJECTION MOULDINGS

The weld lines that occur in injection mouldings are critical areas on which depends on the strength of the mouldings. The flow of the material in the injection mould takes place through the gate and then gradually in the mould cavity. Depending on the shape of the formed object, the weld line may or may not occur. In the case of spreading of plastic streams or bypassing obstacles in the form of cores in the mould, the joining lines run down. Most often, the strength of the moulded part is the lowest in these areas and the resulting lines can cause cracking. The aim of the research presented in the publication was to evaluate the properties of particular parts of mouldings obtained from an experimental injection mould equipped with 4 weld line areas. The tests were performed using the method of thermal analysis by Dynamic Mechanical Analysis DMA. Tensile tests were performed on the parts with weld areas and the maximum crack force was determined. The morphology of the obtained fractures was observed using an optical microscope.

Keywords: strength; injection moulding; mould temperature; Dynamic Mechanical Analysis

1. Introduction

Polymer injection moulding is one of the most popular industrial methods of processing thermoplastics. It is used to manufacture a wide range of products with very different shapes, which determines the occurrence of phenomena related to fountain flow and weld lines in injection moulds. These include the thermodynamic conditions of the streams flowing together, the rheological properties of the processed material, the shape of the mould cavity and the specific conditions that prevail in the weld line area [1-3].

The reason for the occurrence of weld lines are the specific constructional features of the injection moulded parts, which is reflected in the tool (mould) construction and the flow of the polymer in the cavity, which causes the separation of the streams and their re-flow [4].

Weld lines are most often formed in the following cases (Fig. 1):

– Injection into one cavity from two points,
– A frame-type moulded part where the polymer material surrounds the inner core,
– Single point injection moulding with different wall thickness,
– Floating around an obstacle located in the flow path of the polymer material.

The weld lines regions in injection moulding parts were described in many publications as a problematic [5-8]. In paper [9-11] authors indicate two types of weld lines: a.k.a. cold and

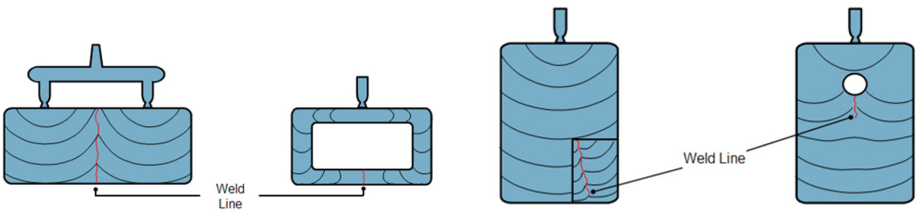

Fig. 1. Possible cases of occurrences of weld lines

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hot lines. Cold weld lines occur as a result of converging of the fronts of the polymer material in opposite directions. In turn, hot weld lines occur when two polymer material fronts appear parallel, forming a bond between them. Weld lines generally lead to a deterioration of the mechanical properties and aesthetic appearance of moulded parts.

Most often, the phenomena that accompany the flow of the material in the mould and the properties of the moulded parts are studied using standardised ISO-527-1/1B specimens, in which the material flows from two opposite ends during filling and flows exactly in the middle of the specimen. In this way, the strength of the weld lines and the influence of the processing parameters on the achieved maximum force are investigated. Appropriate mould design and process parameters contribute significantly to improving the mechanical properties and fibre orientation in the weld line area [12-13]. In turn, the use of chemical foaming agents contributes to improving the tensile properties and elongation at break as well as the structure in the weld line area (the degree of polymer bonding increases) and reducing the weight [14].

An important role in the prevention of occurrence of product defects is played by simulations of the injection process, which help to find the optimum gate location so that the length of the weld line is minimised as much as possible [15]. The formation of weld lines on external aesthetic car parts in the automotive industry is one of the problems encountered in the production of details made from polymeric materials. By means of flow analysis tools it is possible to comprehensively evaluate the filling of the mould cavity and to create an optimal design allowing to find the best solution to eliminate the formation of weld lines [16-19]. In work [20-21] authors investigated the influence of the injection and mould temperature on the mechanical and physical properties of mouldings with weld line areas. In turn, in paper [22] research related to the impact of processing parameters: injection speed, injection pressure and mould temperature on changes in strength and degree of crystallinity of samples with weld lines. With the optical microscope the thickness of the weld lines were also measured.

Studies generally show that higher values of applied mould temperatures result in better properties during static tests, with a clear effect only at temperatures approaching the processing temperature. The opposite tendency is characteristic for dynamic tests, where a higher temperature results in lower impact strength.

In the literature there are many attempts to describe the strength of weld lines areas. One of them is the model [23-24] of weld lines formation, which describes polymer-polymer interaction based on molecular interdiffusion.

The location of the weld line and the distance from the injection point are also important factors. These results were presented by Bociąga, Kaptacz, Duda and Rudawska in paper [25].

2. Research material and methods

The aim of the research was to evaluate the influence of various values of mould temperature and holding pressure on selected physical properties of the samples taken from the moulded part, in which weld areas of flowing streams were formed. To this end, injection moulding tests were carried out using a special two-cavity mould with different arrangement of obstacles. A view of the experimental mould and the obtained moulded parts, together with the cut-off lines for the test specimens, are shown in Fig. 2.

In one of the cavities 4 obstacles arranged transversely (P) to the polymer flow axis and in the other one – longitudinally (W) were used. Such an arrangement of obstacles makes it possible to produce mouldings with weld and melt lines in one injection process.

In this way, it is possible to analyse the different behaviour of the material in two characteristic cases that occur during injection moulding of polymeric materials.

Polypropylene with the trade name Moplen HP500 N and a melt flow rate of 10 g/10 min. (230°C/2.16 kg). In order to better analyse the weld line areas formed during injection moulding tests, a pearlescent pigment (Silver) from WEST was added to the processed material. These types of pigments are characterised by a lamellar structure which, like talc, emphasises the visibility of the flow areas of the plastic by means of the different arrangement of the flakes in space and the different reflection of light rays. A pigment dosage of 3% by weight was used.

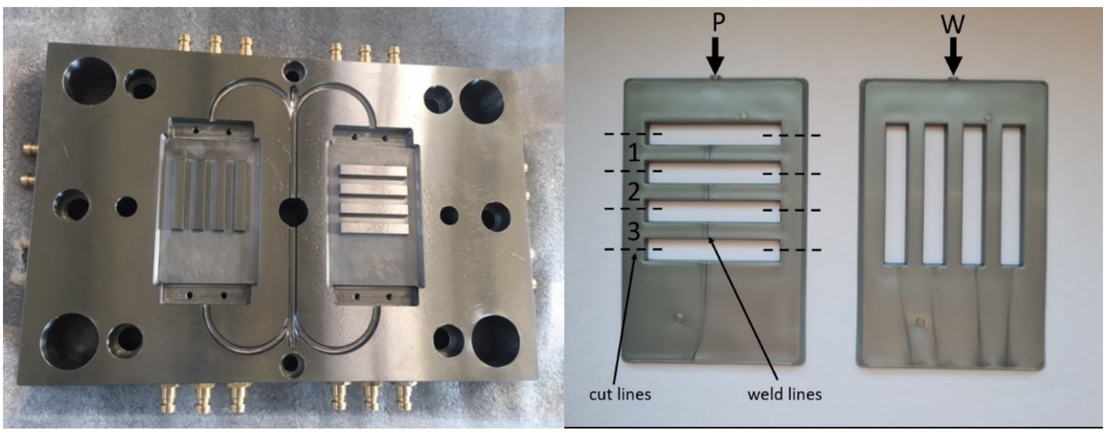


Fig. 2. Shape of the test mould and testing mouldings with cutting lines and weld line number

The tests were carried out using an Engel Victor 50 machine with a mounted test mould. The mould had a complex system of thermostatic channels located in parallel in both the punch and die sections. Two HB Therm Series 5 dual-circuit thermostats were used for thermostating.

Samples were made at the following processing parameters:
Constant parameters:

– Injection temperature T_w – 185°C,
– Injection speed v_w – 23 mm/s, 18 mm/s, 12 mm/s.

Due to the different volume in the individual phases of filling the mould cavities and the need for good degassing during injection, a profiled injection velocity from the highest to the lowest was used.
Variable parameters:

– Mould thermostating profile: 20-90-20°C and 90-20-90°C,
– Holding pressure: 200 and 600 bar (20 and 60 MPa).

A view of the injection mould mounted on the machine is shown in Fig. 3.

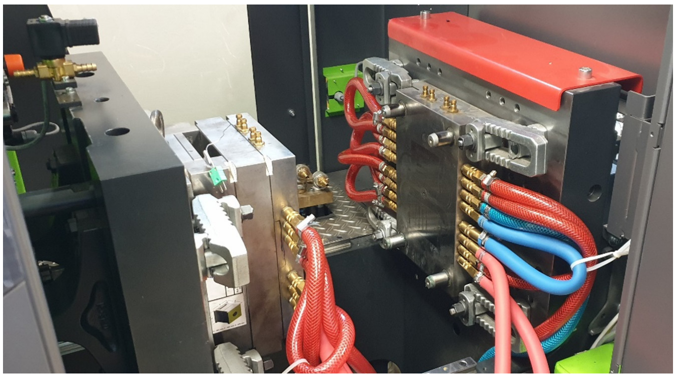


Fig. 3. View of the test mould in machine clamping unit

During preliminary tests it has been observed that at a constant mould temperature there is a deviation of the flowing polymer streams in the direction external to the mould cavity axis. This is most probably caused by heat accumulation in the central part of the mould at the flow system in the area of the material inlet to the mould. For this reason, the above mentioned parameters of mould thermostating were adopted for tests. Two variants of thermostating were applied, in which in one case the central part of the mould was thermostated to the temperature of 20°C and the outermost parts of the mould to the temperature of 90°C and in the second case the central part had the temperature of 90°C and the outermost parts – 20°C.

Only specimens taken from a cavity with obstacles placed transverse to the polymer flow direction (P) were used in the study. From these mouldings, specimens were prepared for the following tests: DMTA and determination of tensile strength of the weld line areas. The scheme of the mouldings, the gates locations and the cutting lines of the test specimens are marked with a dashed line in Fig. 2.

During the trials, the temperature distribution of the surface of the mould and moulded parts was analysed using thermal imaging method. Due to the unknown value of the emissivity coefficient of the mould surface and its high gloss, a special chalk-based substance produced by Standard Check Medium 3 for removing reflections during 3D scanning was used. This spray was applied manually on the surface of the entire parting plane of the injection mould and then thermal imaging measurements were performed using a Testo type 890 camera. The emissivity coefficient of the chalk coating was assumed to be 0.96, similar to that of the obtained moulded parts. Studies of the temperature distribution of moulded parts were carried out directly on the moulded specimens with an equal time interval between removal from the cavity and taking the thermal image.

The results of the mould temperature distribution adopted in the studies of the thermostating versions are shown in Fig. 4, while Fig. 5 presents a thermal image of an example moulded part.

3. Results and discussion

3.1. Thermal analysis using DMA method

The main objective of DMA (Dynamic Mechanical Analysis) tests was to evaluate changes in dynamic properties of samples taken from injection mouldings with transverse obstacles and weld lines in the middle of the part axis. Specimens were cut from the moulded part according to the scheme shown

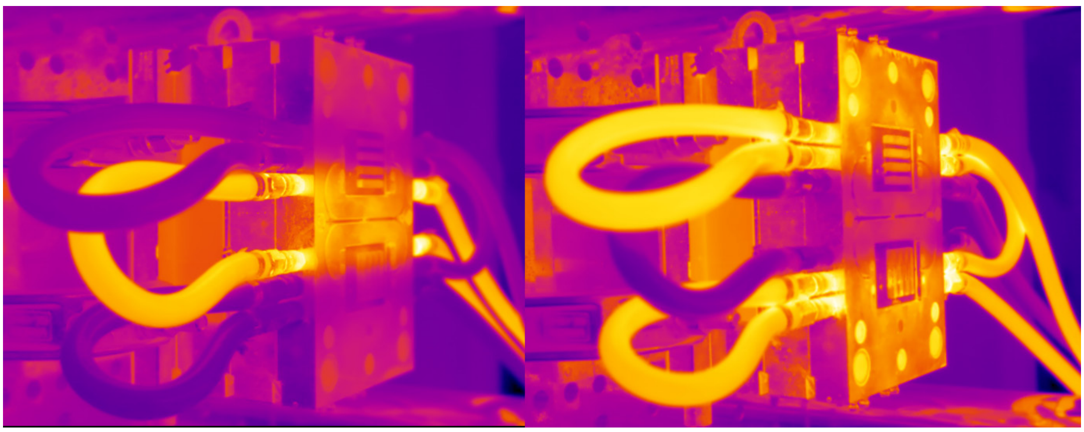


Fig. 4. Injection mould thermostated in temperature profile

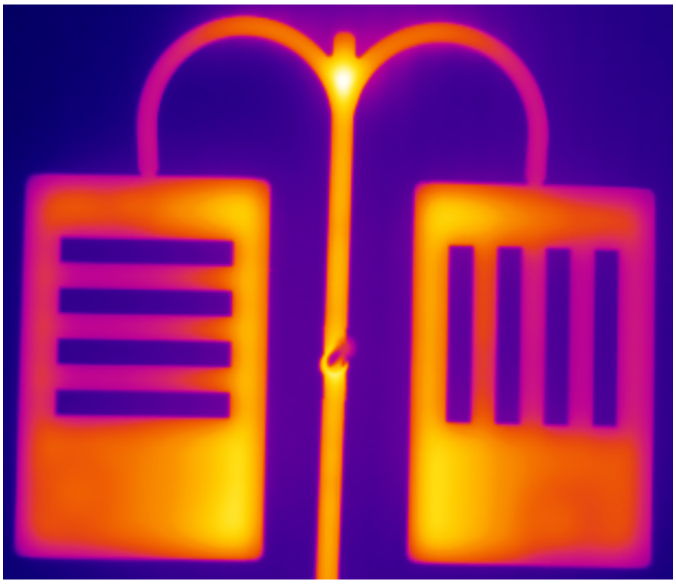


Fig. 5. Example moulded part obtained with the thermostatic profile 20-90-20 and a holding pressure of 20 MPa respectively

in Fig. 2. The tests were conducted for specimens produced at holding pressures of 20 and 60 MPa and two thermostatic profiles: 20-90-20 and 90-20-90. DMA tests were carried out using a Netzsch DMA 242C device in a three-point bending fixture with a support spacing of 50 mm. The following test parameters were used:

– Temperature range: –80 to 100°C,
– Function frequency: 10 Hz,
– Amplitude: 240 micrometres,
– Static force: 0.1 N,
– Dynamic force: 5 N.

The results of the DMA tests are shown in the thermograms (Figs. 6-9), where the red line (a) marks the specimens made at a pressure of 60 MPa and the green line (b) at pressure of 20 MPa.

The storage modulus E' and the values of loss factor tgδ are summarised in Table 1.

The greatest differences in storage modulus are observed with sample 1 (Fig. 6) located close behind the gate. This is most likely a result of the short flow path and greater pressure

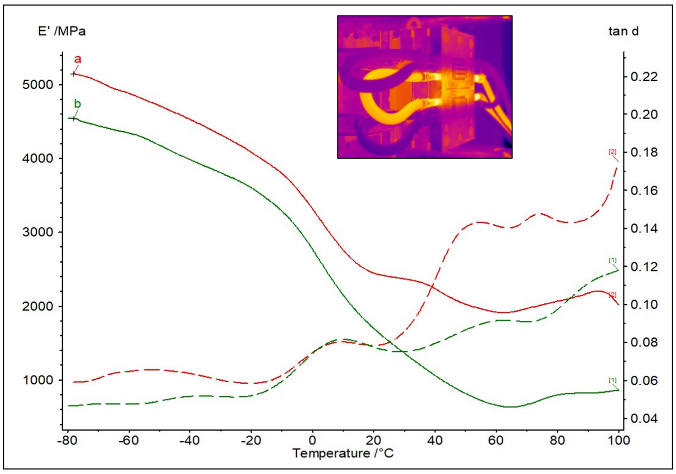


Fig. 6. DMTA thermogram for thermostating variant 20-90-20 for two holding pressure values a – 60 MPa and b – 20 MPa for a sample taken behind obstacle 1

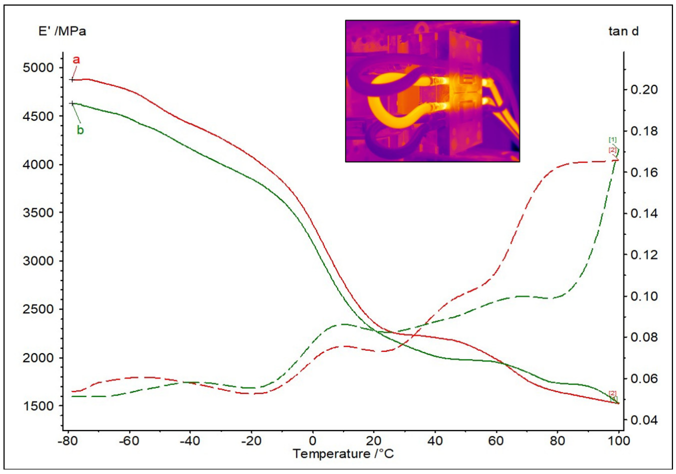


Fig. 7. DMTA thermogram for thermostating variant 20-90-20 for two holding pressure values a – 60 MPa and b – 20 MPa for a sample taken behind obstacle 3

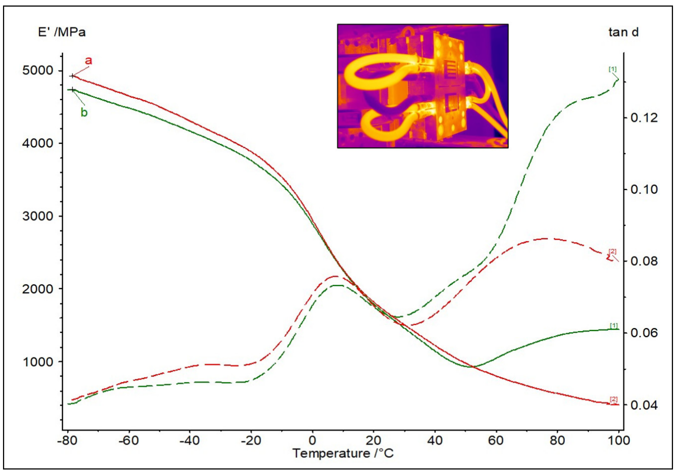


Fig. 8. DMTA thermogram for thermostating variant 90-20-90 for two holding pressure values a – 60 MPa and b – 20 MPa for a sample taken behind obstacle 1

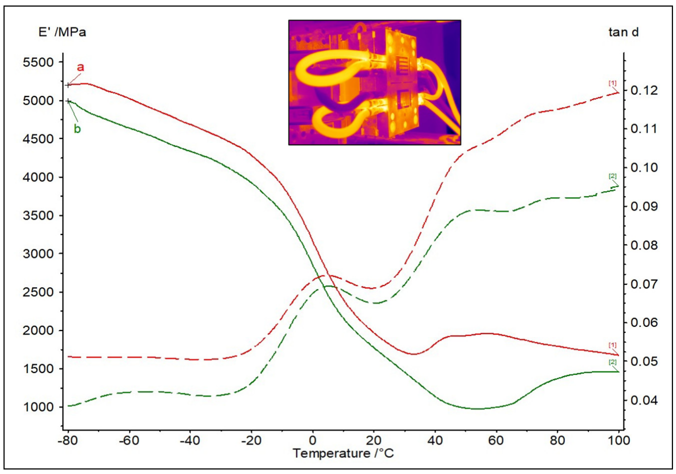


Fig. 9. DMTA thermogram for thermostating variant 90-20-90 for two holding pressure values a – 60 MPa and b – 20 MPa for a sample taken behind obstacle 3

TABLE 1

The storage modulus E' and the values of loss factor tgδ

Temperature		–80°C	5°C	100°C	–80°C	5°C	100°C
Parameters		E', MPa	E', MPa	E', MPa	tgδ	tgδ	tgδ
Mould thermostating profile_weld line no.	**Holding pressure, MPa**						
20-90-20_1	20	4538	2444	864	0.047	0.080	0.118
	60	5148	3024	2015	0.059	0.079	0.175
20-90-20_3	20	4629	2886	1530	0.051	0.084	0.171
	60	4878	3076	1527	0.054	0.074	0.166
90-20-90_1	20	4734	2557	1444	0.040	0.073	0.131
	60	4926	2582	405	0.041	0.075	0.080
90-20-90_3	20	4992	2460	1455	0.038	0.069	0.095
	60	5204	2745	1678	0.051	0.072	0.119

effects on the weld area, as well as the higher packing of material in these regions of the mouldings. Large differences in the loss factor tgδ are revealed in the temperature range 30-80°C.

For samples injected at the 90-20-90 thermostating variant (for which the cavity temperature has a higher temperature value) smaller differences can be observed between the storage modulus E' for individual holding pressure values. For example, for the sample located closest to the injection point, marked as (1), the difference is about 20 MPa and decreases with increasing temperature during the test, reaching the same values around 0°C. Therefore, it can be concluded that for higher mould temperature values, the value of holding pressure loses its importance.

3.2. Mechanical properties investigations

In order to evaluate the strength of individual weld areas and the effect of applied injection moulding conditions (mould temperature and holding pressure), the values of maximum fracture force were determined for uniaxially elongated samples taken from the cavity (P). The tests were performed on a test-bench equipped with an AXIS FM series digital force sensor mounted on a tripod stand allowing its axial displacement with a holder.

The force sensor was connected to the force course recording software during measurement. Just as with the universal testing machine, the lower part of the specimen was gripped and the upper part was displaced together with the measurement head. 5 repetitions for each series of parameters were performed and the results in the form of averages are presented in Table 2.

The carried out tests showed that higher values of the maximum force during tensile test were achieved for the specimens produced with a holding pressure of 60 MPa. This effect was observed for both variants of mould thermostating. However, for lower values of the mould cavity temperature (thermostating variant 20-90-90) the differences between the applied holding pressures are much greater. For a holding pressure of 20 MPa, an average tensile force value of 509.7 N, 506.0 N and 503.2 N was achieved, respectively, for successive samples away from the injection point. A higher value of holding pressure resulted in higher values of maximum force 540.8 N, 526.6 N, 511.9 N for the same thermostatic variant. For higher holding pressure values, a greater influence of the distance from the injection point on the value of the maximum force can be seen, which is most probably the effect of a decrease in holding pressure in particular areas of the mould distant from the injection point.

For the 90-20-90 thermostatic variant, higher average maximum force values and smaller differences between specimens 1-3 were obtained, which can be explained as the influence of the impact of a higher holding pressure in the flow areas caused by a higher mould temperature and a better transfer of pressure in the holding phase from the injection point to the individual weld areas in specimens 1-3.

This means that the holding pressure parameter has a decisive influence on the interaction of the interlocking flow polymer material fronts.

3.3. Microscopic research

The specimens obtained from the weld line tensile tests were subjected to microscopic observations at 150× magnification on a Keyence VHX-7000 digital microscope. The software

TABLE 2

Tensile test results for specimens with weld lines taken from the moulded part (P)

Parameter		Maximum value of force, N		
Mould thermostating profile, °C	**Holding pressure, MPa**	**1st weld line**	**2nd weld line**	**3rd weld line**
20-90-20	20	509.7	506.0	503.2
20-90-20	60	540.8	526.6	511.9
90-20-90	20	552.1	545.8	544.3
90-20-90	60	556.2	546.0	534.9

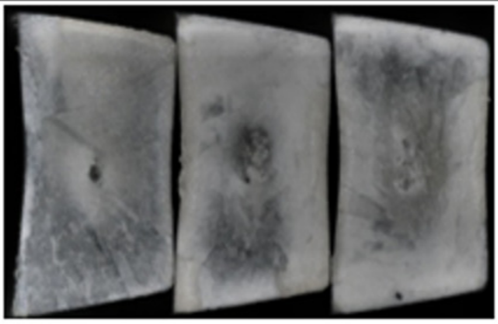
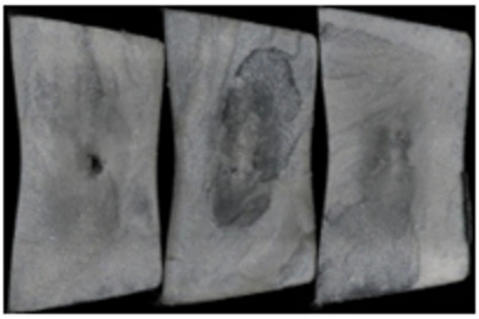
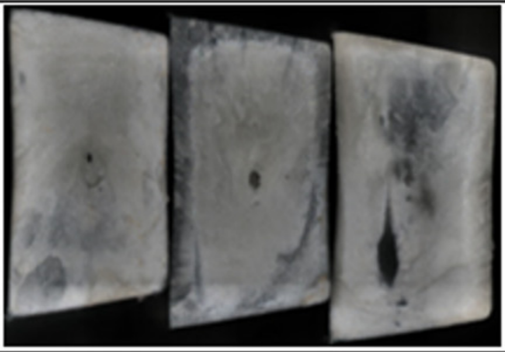
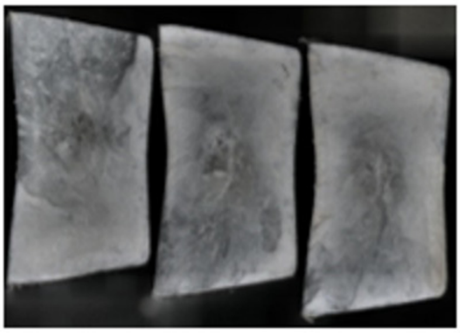
Clamping pressure MPa	Weld line cross-section 1 2 3 Mould temperature setup: 20-90-20	Weld line cross-section 1 2 3 Mould temperature setup: 90-20-90
20		
60		

Fig. 10. Results of microscopic observations of the tested fractures of the specimens obtained after tensile tests

function for sequential image assembly was used. The results of microscopic observations of the tested fractures of the specimens obtained after tensile tests are shown in Fig. 10.

In the images of the fractures obtained during the tensile test, it can be seen that for the 20-90-20 thermostating variant, in which the area of the moulded part has a lower temperature, there is an effect of faster cooling of the surface layers. Furthermore, bubbles and shrinkage cavities are visible in the fracture structure. For samples obtained at a tool forming part temperature of 90°C, the fractures are smoother and more uniform, which may indicate smaller anomalies of flow and formation of flow areas.

4. Conclusion

The method of thermostating injection moulds is a very important technological aspect connected with polymer processing. It does not only influence the rheological properties of the plastic and facilitates the flow of the plastic in the mould, but also contributes to obtaining better properties of the polymer-polymer joining area. in the progress of the injection moulding trials and performed tests the following conclusions can be presented:

– From the viewpoint of the quality of joining of the polymer streams, the mould temperature is an important factor.
– A higher mould cavity temperature contributes to higher values of breaking force of polymer streams.
– The effect of holding pressure and its influence on the strength of the weld area is most visible at lower mould cavity temperatures and becomes smaller at higher values.
– At low mould cavity temperatures anomalies can occur in the weld area which make it difficult to achieve the correct structure in this area. Air bubbles and shrinkage cavities are more frequent. Furthermore, the weld area has a different structure in the mould contact zone and a different structure in the inner zone.

In conclusion, there is a need for further exploration of this topic due to the fact that the formation of weld lines is an effect that occurs in 95% of industrial moulds and is often a serious problem in the subsequent exploitation of moulded parts.

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