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ASSESSMENT OF THE IMPACT OF INJECTION MOULDING PROCESS PARAMETERS ON THE PROPERTIES OF MOULDINGS MADE OF LOW-DENSITY POLY(ETHYLENE) RECYCLATE LDPE

The parameters of the injection moulding process have a significant influence on the properties of the moulded parts. Selection of appropriate injection conditions (e. g. the injection temperature, mould temperature, injection and holding pressure, injection speed) contributes to the productivity and energy consumption of the injection moulding process as well as to the quality of the moulded parts. The aim of this study was to evaluate the influence of injection moulding parameters on properties of poly(ethylene) mouldings. Regranulate obtained from recycled film, which is a mixture of low-density poly(ethylene) and linear low-density poly(ethylene), was used for testing. Samples in the form of standardised tensile bars of type A1 were produced by injection moulding. A Krauss-Maffei KM65-160C4 injection moulding machine was used for this purpose. Variable parameters of the this process used in the study were: injection speed, mould temperature and holding pressure. The results of tensile strength tests of the obtained samples are presented. The weight and dimensions of mouldings from four different regranulates were also investigated. The effect of injection moulding conditions on the properties of poly(ethylene) mouldings was shown in the investigations. The mass of poly(ethylene) mouldings is dependent on the holding pressure.

Keywords: poly(ethylene); injection moulding; injection moulding process parameters

1. Introduction

Due to the diversity of properties, polymeric materials have been used in many fields, incl. as packagings, machine parts, components for medicine and car components in the automotive industry. One of the most popular processing methods for thermoplastic materials is injection moulding. This method is used for the production of details of complex shapes with a good repeatability, at a very small share of the final processing and waste. The production of injection mouldings is possible with very high efficiency at a relatively short cycle time, which is especially important in the mass production of plastic products [1-3].

The injection moulding process is a cyclic process, consisting of the injection, holding and cooling phases as well as the phase of removing the moulded part from the mould. The final quality of products is influenced by many factors, incl. the physicochemical and rheological properties of the processed material, design features of the injection mould as a tool, as well as process conditions [4-5]. The injection moulding conditions affect the physical condition and structure of the moulded part, which determines its thermal, functional and mechanical properties [6-11].

Obtaining mouldings with high gloss, desired surface microstructure features or shape mapping is possible thanks to the use of high mould temperature [12]. In turn, thanks to the use of a high holding pressure value, it is possible to reduce shrinkage differences in individual areas of the moulded part or reduce residual stresses [13-14]. Shrinkage plays one of the important roles in the production of plastic products. Its formation may depend on such process parameters as: injection pressure, cooling time, too high injection temperature or too low holding pressure, which significantly affect the shrinkage value [1, 15-16].

In the work [17] it has been shown that an increase in mould temperature may contribute to the deterioration of hardness and impact strength of polymeric parts. The injection parameters also significantly affect the process of chemical and physical foaming of mouldings [18]. Setting the optimal processing parameters considerably impacts the quality of the obtained products and the production costs [19-20]. Improper their settings can significantly contribute to the formation of numerous parts defects, such as: warpings [21], shrinkage, indentations or residual stresses,

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as well as surface defects of mouldings, which include burns, streaks, weld lines or the effect of a gramophone record [22-24]. In the works [25-26] it has been pointed out that the correct selection of injection moulding parameters significantly reduces warping and allows to avoid excessive processing shrinkage.

Summing up, a short review of already carried out research indicates that one of the important elements of the correct injection moulding process is the appropriate selection of processing parameters. This affects not only the strength properties or the geometry or mass of the obtained mouldings, but also allows to reduce numerous surface defects or even avoid their excessive shrinkage, which has a positive effect on the quality of the obtained products and production costs.

2. Research material and methods

The aim of the study was to assess the impact of injection moulding parameters on the properties of poly(ethylene) mouldings. Recycled film regranulate was used for the tests, which is a mixture of low-density poly(ethylene) (LDPE) and linear low-density poly(ethylene) (LLDPE). Poly(ethylene) is a thermoplastic material characterised by good strength properties and high chemical resistance. For this reason, it is very often used for the production of films for packaging and protecting products. The tested materials were given by recycling company but without permission of publication of the name and chemical composition. That is why estimation of MFR value and thermal properties by DSC method was the first stage of investigation. The DSC investigation were proved that tested materials were correct with description of recycling company. Four groups of materials with different values of the mass melt flow rate (MFR) determined at a temperature of 190°C and a load of 5 kg were used in the work:

- Material 1 – 1.432 g/10 min,
- Material 2 – 3.089 g/10 min,
- Material 3 – 7.860 g/10 min,
- Material 4 – 7.570 g/10 min.

The samples for tests, in the shape of A1 tensile bars in accordance with the PN-EN ISO 527-2: 2012 standard, were made using a Krauss-Maffei KM65-160 C4 injection moulding machine with a mould holding force of 650 kN. The polymer material was not pre-dried. The samples were moulded in a thermostated two-cavity injection mould with a parallel system of runners with the following process parameters presented in TABLE 1.

Other parameters are the result of the selected setting parameters of the machine and were chosen in terms of obtaining correct test samples. In turn, TABLE 2 presents the test plan and the adopted labels of mouldings manufactured under various injection moulding conditions. Each of the used materials was a mixture of low-density and linear low-density poly(ethylene).

After the test samples were produced, they were conditioned in laboratory conditions for 48 hours. The manufactured mouldings were intended for mass and dimensions tests as well as tensile strength tests in accordance with PN-EN ISO 527-1: 2020-01 standard. The mass measurements were carried out using a Sartorius CP225 laboratory scales with an accuracy of ±0.1 mg with a closed measuring space. The thickness and width of the moulding were measured in its central part using a digital YATO micrometer with an accuracy of ±0.002 mm. In turn, the static uniaxial tensile test was performed with the use of the Inspekt Desk 20 universal testing machine by Hegewald & Peshke with an accuracy of 0.5% (maximum load 20 kN). The tensile speed was 50 mm/min. The values of maximum force (F_m), strain at break (ε_B), tensile strength (σ_M) and strain at maximum force (ε_M) were determined. 5 repetitions were used for each study plan.

TABLE 1

Constant and variable injection moulding parameters

Process parameter	Label and its unit	Value
Constant process parameters		
injection temperature	T_w, [°C]	180
injection pressure (maximal value)	p_w, [MPa]	100
injection time	t_w, [s]	0.91
cooling time	t_{chl}, [s]	20
Variable processing conditions		
mould temperature	T_f, [°C]	25
		80
injection speed	v_w, [mm/s]	20
		80
holding pressure	p_d, [MPa]	0
		15
		50

TABLE 2

The plan of experiment

Sample label	Mould temperature, T_f, °C	Injection speed v_w, mm/s	Holding pressure p_d, MPa
20a	25	20	0
20b	25	20	15
20c	25	20	50
20d	80	20	0
20e	80	20	15
20f	80	20	50
80a	25	80	0
80b	25	80	15
80c	25	80	50
80d	80	80	0
80e	80	80	15
80f	80	80	50

3. Results and discussion

3.1. Mouldings mass and dimensions

The conducted research shows that the lack of the holding phase resulted in the formation of numerous sinkholes on the

surfaces of the tested samples. In addition, in the case of materials with a lower melt flow rate (material 1 and 2), at a mould temperature of 80°C, it was impossible to obtain the full shape of the moulded parts without applying holding pressure. The weight and dimensions of the mouldings were determined in relation to the mouldings from one mould cavity, and the arithmetic mean was calculated from the obtained results. TABLE 3 presents the averaged results of the measurements of the weight, thickness and width of mouldings for materials 1 and 2. In turn, for materials 3 and 4, the results of these measurements are presented in TABLE 4.

TABLE 3

Averaged values of mass, width and thickness measurements for materials 1 and 2

Sample label	Material 1			Material 2		
	Mass, g	Width, mm	Thickness, mm	Mass, g	Width, mm	Thickness, mm
20a	6.541	9.58	3.91	6.724	9.66	3.89
20b	6.869	9.70	3.94	7.036	9.74	3.91
20c	7.124	9.87	3.96	7.182	9.83	3.92
20d	6.575	9.69	3.86	6.892	9.52	3.88
20e	6.787	9.71	3.89	6.924	9.66	3.90
20f	6.911	9.81	3.92	6.976	9.84	3.92
80a	6.461	9.38	3.87	6.647	9.47	3.91
80b	6.814	9.75	3.90	6.785	9.67	3.94
80c	7.081	9.80	3.95	7.149	9.81	3.94
80d	6.546	9.64	3.89	6.761	9.16	3.87
80e	6.746	9.68	3.92	6.894	9.71	3.88
80f	6.886	9.78	3.93	6.958	9.74	3.91

The analysis of the obtained results shows that the holding pressure has the greatest impact on the changes in the mass of the material and the dimensions of the mouldings. TABLES 2 and 3 show that with constant mould temperature and constant injection speed for all tested materials, an increase in the holding pressure caused an increase in the weight and slight increase in the dimensions of the mouldings. Samples produced without the use of holding phase were lighter in weight than those produced with the holding. In turn, other variable processing parameters, i.e. injection speed and mould temperature have more smaller, even slight influence on the weight and dimensions of samples. However, setting the higher temperature of the mould (80°C) reduced the differences in the weight of the mouldings made of all four types of materials. In the case of mouldings produced without holding, a large dispersion of mass and dimensions was observed, which proves that the injection process is less repeatable. The largest dimensions and mass of mouldings were observed for samples produced with an injection speed of 20 mm/s and 80 mm/s at a mould temperature of 25°C and a holding pressure of 50 MPa. They are also characterised by the greatest dimensional stability. Probably, based on this observation, it can be concluded that lower value of mould temperature caused smaller shrinkage of samples and thus their higher dimensions. Moreover, the lowest average mass was observed

TABLE 4

Averaged values of mass, width and thickness measurements for materials 3 and 4

Sample label	Material 3			Material 4		
	Mass, g	Width, mm	Thickness, mm	Mass, g	Width, mm	Thickness, mm
20a	6.815	9.76	3.87	6.807	9.54	3.86
20b	7.024	9.81	3.89	6.996	9.71	3.88
20c	7.145	9.86	3.93	7.107	9.88	3.92
20d	6.789	9.67	3.86	6.862	9.54	3.88
20e	6.956	9.69	3.87	6.933	9.69	3.88
20f	6.982	9.73	3.89	6.938	9.72	3.89
80a	6.812	9.61	3.86	6.761	9.54	3.85
80b	6.984	9.69	3.88	6.966	9.64	3.88
80c	7.211	9.85	3.93	7.071	9.81	3.92
80d	6.835	9.60	3.57	6.843	9.58	3.84
80e	6.942	9.62	3.87	6.922	9.61	3.86
80f	6.946	9.64	3.89	6.933	9.71	3.90

for the samples made of the material with the mass melt flow rate equal to 1.432 g/10 min, while the highest for the samples with MFR of 7.86 g/10 min. The reason for this is the use of different PE varieties in tests, which are dedicated to different applications and processing methods, which – in turn- forces the use of different flowabilities due to the action of forming tools (slit cylinder heads, calenders).

3.2. Tensile strength studies

By analysing the results obtained during the uniaxial tensile test (Fig. 1-2), it can be concluded that the use of a higher mould temperature, higher injection speed and higher holding pressure resulted in an increase in the maximum force. The highest value of the force for all materials is characteristic for the mouldings produced with variable injection parameters: T_f = 80°C, v_w = 80 mm/s, p_d = 50 MPa. On the other hand, samples produced at zero holding pressure and a mould temperature of 25°C show a reverse tendency. The smallest values of the maximum force are characteristic for mouldings made of material 2, with a mass melt flow rate of 3.089 g/10 min, and the highest values – for samples of material 3 (MFR = 7.860 g/10 min). As the mould temperature and the holding pressure increase, the maximum force increases. The injection speed also contributed to this increase. It is probably caused by an increase in the degree of crystallinity due to the longer residence time of the material in the injection mould.

As the melt flow rate increases, an increase in the value of strain at maximum force can be observed (Fig. 3 and Fig. 4). For the mouldings manufactured with the highest injection parameters, i.e. T_f = 80°C, v_w= 80 mm/s, p_d = 50 MPa, the strain at the maximum force ε_M reaches the highest values. For all materials, the strain value at the maximum force increases with the increase of the holding pressure. Increasing the mould temperature and injection speed also increases the strains. This may

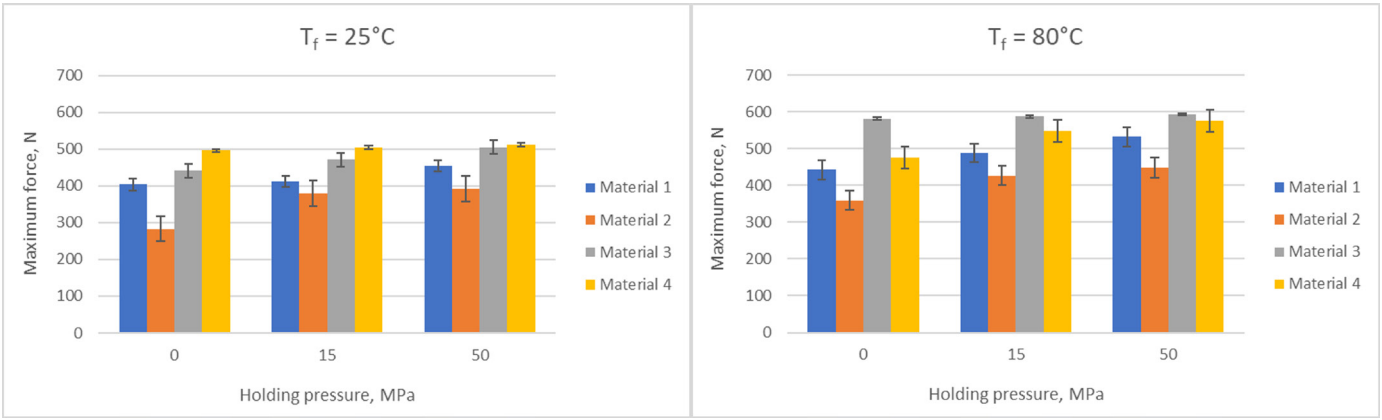

Fig. 1. Averaged values of maximal force for injection speed 20 mm/s

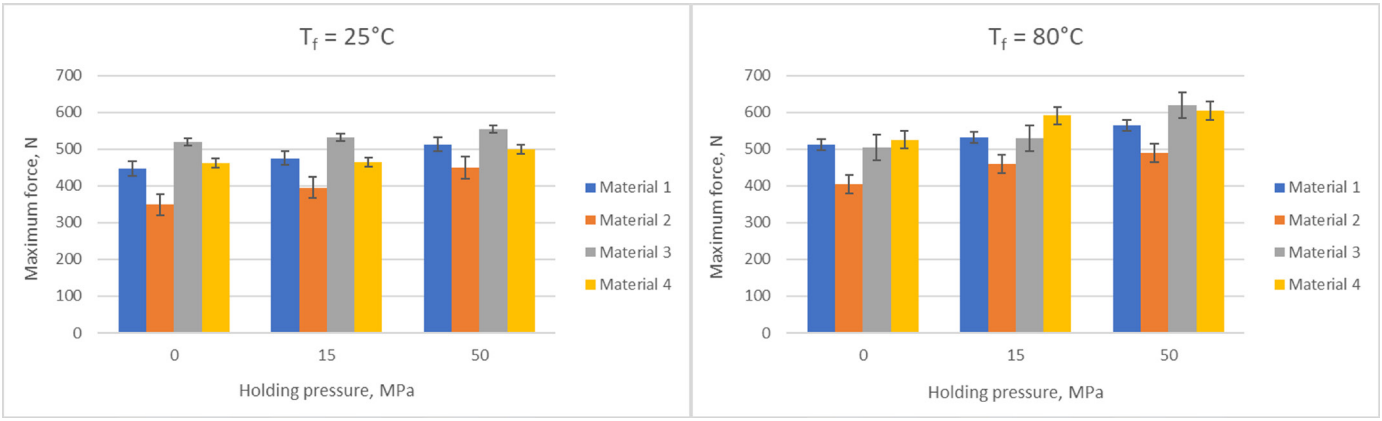

Fig. 2. Averaged values of maximal force for injection speed 80 mm/s

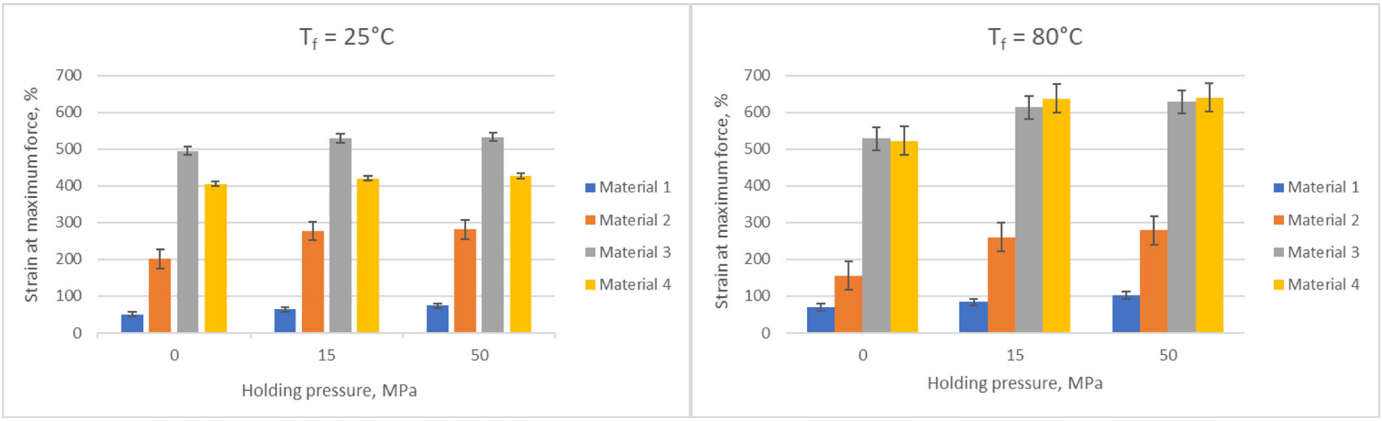

Fig. 3. Averaged values of strain at maximal force for injection speed 20 mm/s

indicate obtaining a greater macromolecular orientation during the flow in the mould, which in turn contributes to obtaining better strength properties.

Figs 5 and 6 show the averaged values of strain at break for all tests. When analysing the obtained results, it can be seen that the mouldings from material 3 and 4 are characterised by the highest strain at break, when the mould temperature was $T_f = 80$°C and the holding pressure was $p_d = 50$ MPa. When using a higher mould temperature, the holding pressure has a smaller impact on the values of the strain at break – the differences between individual tests are smaller. The smallest values of strains at break were characteristic for samples from all materials at the mould temperature of 25°C and zero holding pressure within the range of 73.8÷514.1% for the injection speed of 20 mm/s and 116.4÷509.2% for the injection speed of 80 mm/s. Materials 3 and 4 are characterised by significantly higher values of strain at break compared to samples from material 1 and 2.

In turn, from results of tensile strength for samples of all materials it can be concluded that the highest values of this parameter are characteristic for mouldings injected in the highest

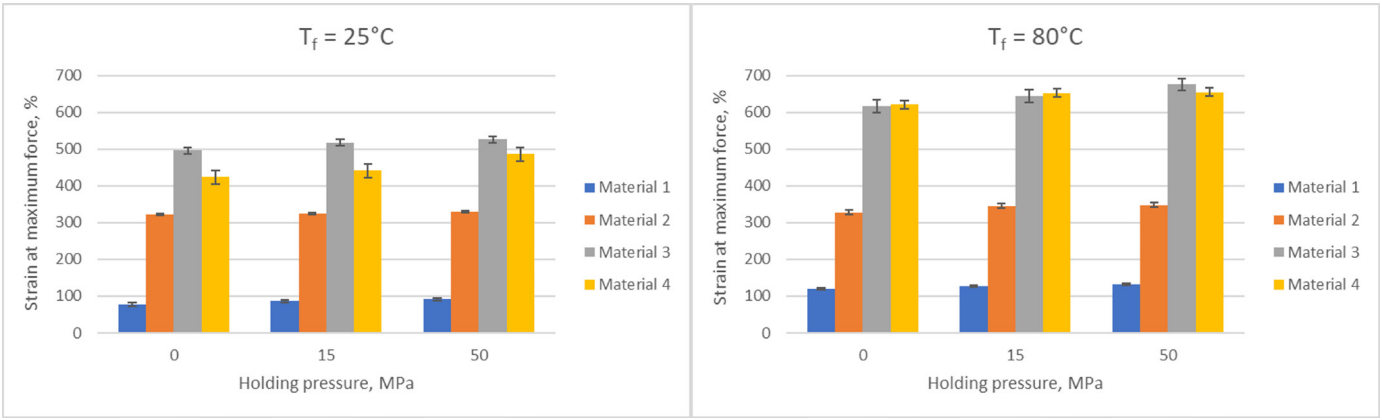

Fig. 4. Averaged values of strain at maximal force for injection speed 80 mm/s

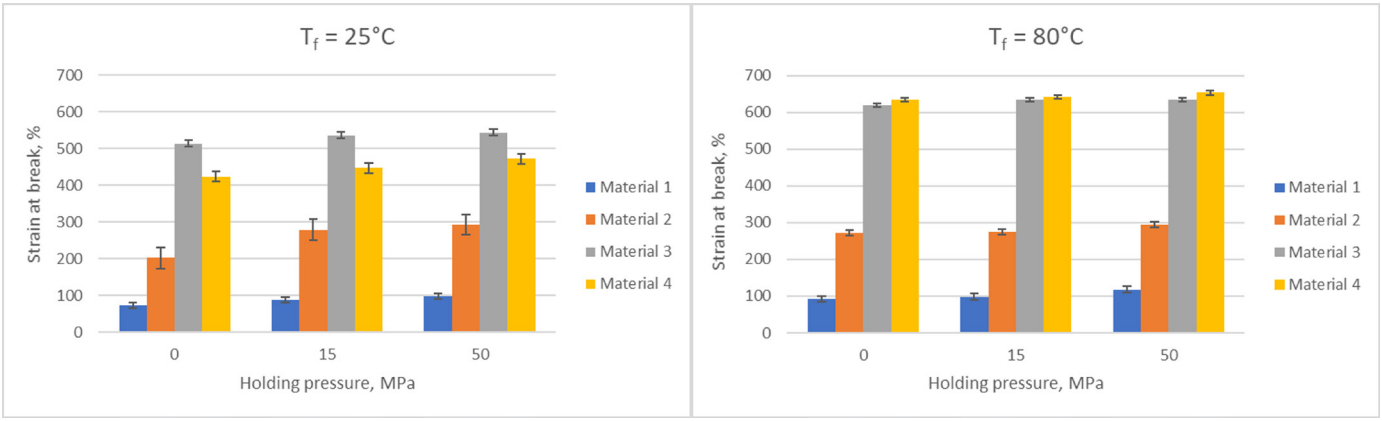

Fig. 5. Averaged values of strain at break for injection speed 20 mm/s

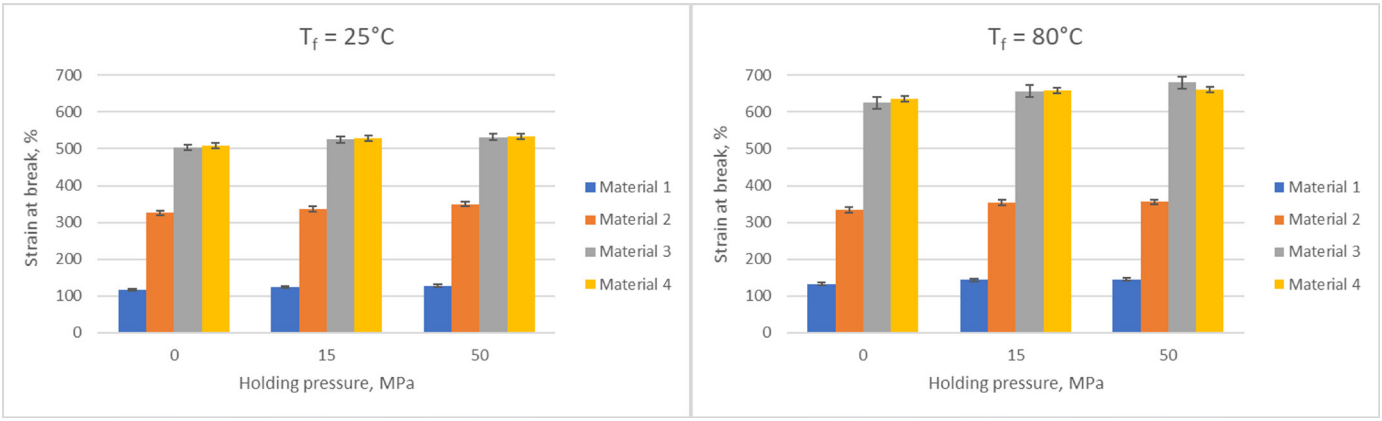

Fig. 6. Averaged values of strain at break for injection speed 80 mm/s

processing conditions, i.e. $T_f = 80°C$, $v_w = 80$ mm/s, $p_d = 50$ MPa. It may be due to the higher degree of structure packing than in samples produced at lower values of processing parameters. Furthermore, it can be observed that for mouldings made of material 1 at $v_w = 20$ mm/s, the tensile strength (Fig. 7) has a similar value and is in the range of 10.5÷13.9 MPa. On the other hand, the samples produced at the speed of 80 mm/s are characterised by higher tensile strength, in the range of 11.6÷14.6 MPa. The increase in mould temperature and holding pressure contributed to a small extent to the increase in tensile strength. Specimens made of material 2 are characterised by a lower tensile strength compared to mouldings of material 1 – for the injection speed of 20 mm/s the values are in the range of 7.6÷12.2 MPa and for the speed of 80 mm/s (Fig. 8) in range from 9.4 to 13.2 MPa. Analogically as before, similar trends were noticed – with the increase of T_f and p_d, the value of σ_M increases. A possible reason for increasing the tensile strength of mouldings with increasing mould temperature is the greater amount of crystalline phase in samples manufactured at a higher value of this temperature. Moreover, for materials with a higher melt flow rate

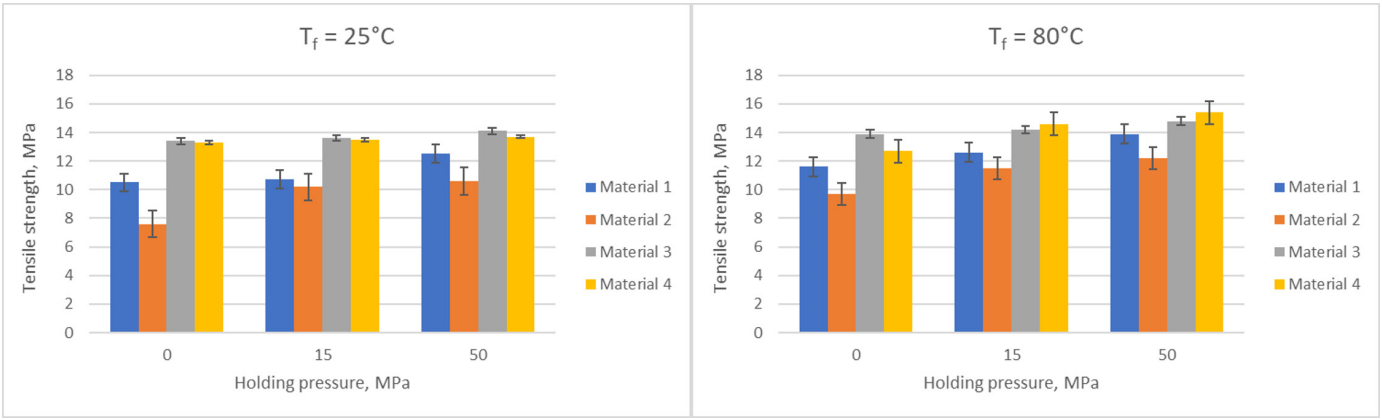

Fig. 7. Averaged values of tensile strength for injection speed 20 mm/s

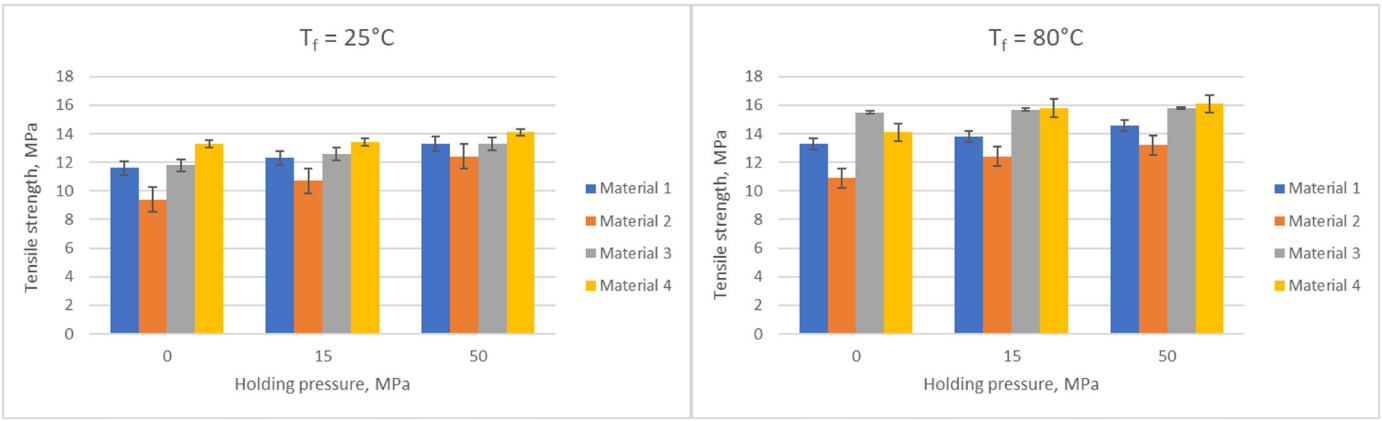

Fig. 8. Averaged values of tensile strength for injection speed 80 mm/s

(marked as 3 and 4), an increase in tensile strength was observed at higher injection moulding parameters. Only for mouldings 3, the σ_M range shows the reverse tendency in relation to the injection speed – at a speed of 80 mm/s, a smaller discrepancy in the results between individual tests was observed and values lower than for v_w = 20 mm/s.

4. Conclusion

The conducted tests and analysis of the obtained results allow to demonstrate the important influence of the process parameters: holding pressure, mould temperature and injection speed on changes in mechanical properties as well as weight and dimensions of mouldings made of low-density poly(ethylene) and low-density linear poly(ethylene) regranulates. It was observed that the holding pressure was the most important parameter determining the change of properties of injected mouldings. The influence of mould temperature and injection speed is secondary. Correlation was found between the processing parameters, which in some cases had a greater effect than each factor independently.

Due to the fact that in recent years the voices have been raised about the greater use of plastic waste, in particular from the packaging industry (e.g. films), therefore the presented results are of a utilitarian nature. They show the differences between processed materials with different melt flow indexes.

A slight influence of the injection speed and the mould temperature on the changes in the mass and dimensions of the moulded parts was pointed out. A greater effect on these values was observed during the variation of the holding pressure during injection. In the case of mouldings produced without holding phase, a significant dispersion of mass and dimensions was observed, which may indicate that the process is less repeatable, probably because of the lack of this holding phase, which reducing processing shrinkage phenomenon has a key influence on dimensional accuracy.

In the tensile strength studies, it was found that the samples made with higher injection parameters were characterised by higher values of maximum force, tensile strength, strains at break and maximum force. This may indicate obtaining a greater macromolecular orientation during the flow in the mould, which in turn contributes to obtaining better strength properties. Additionally, the viscoelastic properties of thermoplastics and the possibility of influencing to some extent the density of moulded parts through processing conditions are responsible for this. The observed changes are caused not only by the processing conditions but also by the characteristics of the injected material (different value of the mass flow rate). Furthermore it can be observed that the optimal parameters of the injection process

have an impact not only on the strength properties of used materials, but also on the mass and geometric properties of obtained moulded parts, i.e. their thickness and width.

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