Influence of polymer flow rate, mold cavity volume and injection speed on selected properties of polypropylene molded parts

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Abstract: Influence of the height of the molding cavity and the injection speed for three PP grades with different mass melt flow rate (MFR) on the molded parts mass and longitudinal shrinkage, before and after UV aging, was investigated. It was shown that the mass of the molded parts depends on the flow rate of the material and the volume of the molding cavity, while shrinkage depends only on the volume of the mold cavity and is greater after aging.

Keywords: polypropylene, injection molding, shrinkage, aging.

Wpływ szybkości przepływu tworzywa, objętości gniazda formy i prędkości wtrysku na wybrane właściwości wyrobów polipropylenowych

Streszczenie: Zbadano wpływ wysokości gniazda formującego i prędkości wtrysku dla trzech odmian PP o różnym wskaźniku szybkości płynięcia (MFR) na masę wyprasek oraz skurcz wzdłużny, przed i po starzeniu UV. Wykazano, że masa wyprasek zależy od szybkości przepływu tworzywa i objętości gniazda formującego, skurcz tylko od objętości gniazda formy i jest większy po starzeniu.

Słowa kluczowe: polipropylen, wtryskiwanie, skurcz, starzenie.

The polypropylene (PP) is one of the most used thermoplastic polymers due to its favorable properties, such as low density, high chemical resistance, mechanical strength, ease of processing, and low price of the raw material. It is estimated that polypropylene constitutes 19% of all plastics processed in the world. It is widely used in the packaging, automotive, agriculture, building, construction and for household appliances industries [1–2].

Melt flow rate (MFR) is one of the basic parameters determining the material's ability to flow in the mold and runners [3–4]. During injection molding, a very important parameter is the cycle time, which should be as short as possible. Another parameter of key importance is the injection time. Fast injection speeds lead to rapid filling of the mold, which can result in higher pressures within the cavity, leading to reduced viscosity of the molten material due to shear thinning, allowing it to flow more easily and completely fill the mold. However, it may cause product defects due to, for example, the Diesel effect. During plastic injection air is compressed in the mold cavity and heats up rapidly. It may lead to local overheating of the melted plastic and its degradation, resulting in the formation of a defective moldings [5].

In the literature one can find many articles describing the influence of parameters on the properties of PP moldings [6-24]. Some of them are related to the study of areas of weld lines [6,7]. The properties of PP moldings may vary due to processing parameters and, consequently, the different share of skin and core in the molding structure. Yu *et al.* [8] found that the skin, transition, and core layers showed a gradient distribution along the flow direction. Gipson *et al*. [9] conducted the experiments with two volumes of the molding cavity. The results showed that shrinkage decreases as pressure in the mold increases. The shrinkage relationship remained the same regardless of mold size. Shrinkage can be more accurately determined based on processing pressures and temperatures.

Gao *et al.* [10] investigated β-nucleated iPP injected at different injection speeds. It was shown, that with an increasing injection speed, the impact strength of plastic increases, while the tensile strength decreases. Shearing during plastic flow influences the crystallization of iPP. Rizvi [11] observed, that mold temperature was the most influential parameter during injection molding gover-

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ning the crystallinity and other mechanical properties. Kościuszko *et al.* [12] proved, that the processing conditions like the mold temperature, as well as the post-processing ageing of the isotactic polypropylene, may significantly modify the structure and properties of the PP moldings. Guerra [13] *et al.* showed, that the shrinkage was not influenced by injection molding parameters, but by the warpage. This is the factor that exerts the greatest influence is the geometry of the part, followed by the holding pressure and the post-molding conditions. Pomerleau *et al.* [14] reveal that higher holding pressure leads to lower shrinkage values. The change in injection speed affects the parallel flow shrinkages but significant effect was not observed on cross flow shrinkage. Postawa *et al.* [15] proved, that the most important parameter affecting the shrinkage and weight of molded parts is the holding pressure. Moreover, it is a parameter that can be easily and quickly changed in industrial production. The phenomenon of processing shrinkage is also described in detail in [16]. Maeda *et al.* [17] presents investigations of properties of thin-wall molded PP parts. Authors proved, that parts injected with low speed formed a thicker skin layer compared to the parts obtained at high injection speed. Furthermore, analysis of fracture revealed that a thicker, oriented skin layer in the thin-wall PP sample led to higher fracture toughness. Since polypropylene is often filled with talc, there are scientific works [18-20] describing the influence of processing parameters on the properties, including shrinkage of PP+T moldings. The research on the influence of injection parameters on the properties of iPP moldings, carried out using the analysis of variance (ANOVA) statistical model, was presented in [21]. Authors proved, that the optimum injection condition for the highest tensile properties was: melting temperature 230°C, mold temperature 60°C, holding pressure 8 MPa and cooling time 20 s. Similar studies using ANOVA can be found in [22], which showed that mold temperature is a determining factor of mechanical properties of the polypropylene, together with packing pressure.

An important aspect in the case of plastics is the aging process, during which the materials lose their original properties, especially due to the influence of UV rays. Paper [23] presents an effect of aging PP samples dyed with pigments of different UV resistance. The investigations revealed a significant impact of aging on the color change, a change in the structure and state of the PP medium surface. Some deterioration of the mechanical properties of PP (for car bumpers) after aging was also demonstrated in the article [24]. The mechanism of polypropylene and polyethylene aging processes was presented, among others, in [25, 26]. Polypropylene undergoes degradation under the influence of UV radiation, during which hydrogen atoms are separated from the methyl group, forming macroradicals.

The aim of this work was to investigate the flow rate of PP depending on its grade and temperature, as well as to evaluate selected parameters of the obtained moldings with different volumes. Different injection speeds (injection velocities) and therefore different injection times were used to obtain the molded parts. The influence of these parameters on the molded parts weight and the secondary linear longitudinal shrinkage and shrinkage after the UV aging process was examined.

EXPERMENTAL PART

Materials

Two polypropylene homopolymers with the trade name Moplen HP456J and HP548R (LyondellBasell Industries N.V., Houston, TX, USA) and their blend (50/50 wt%/wt%) were used. The characteristics of PP grades used are presented in Table 1.

T a b l e 1. Characteristics of used PP grades

Parameter	Moplen HP456J	Moplen HP548R
Density, g/cm^3	0.90	0.90
MFR (230°C/2.16 kg), g/10 min	3.4	23
Vicat softening temperature, (A50), °C	156	154

Methods

MFR was determined using a Dynisco D4003DE load plastometer (Dynisco, Franklin, MA, USA) in accordance with PN-EN ISO 1133-1 standard at temperature of 210, 230 and 250°C and load of 2.16 and 15 kg. The measurement temperature was intentionally increased above the recommendations of PN-EN ISO 19069-1 standard to ensure symmetrical measurement conditions. Weight of samples was measured using a Sartorius CP225 scale with an accuracy of ±1 mg. The research plan is presented in Table 2. The longitudinal shrinkage of the molded parts was evaluated using a Vis Sylvac System digital micrometer with an accuracy of ±0.01 mm. The research plan is presented in Table 3. Secondary longitudinal shrinkage was evaluated 72 hours after injection of the molded parts, as well as shrinkage after the aging process.

Injection molding

Injection molding was performed using a KM65-160 C4 machine (Krauss-Maffei, Parsdorf, Germany) at three dif-

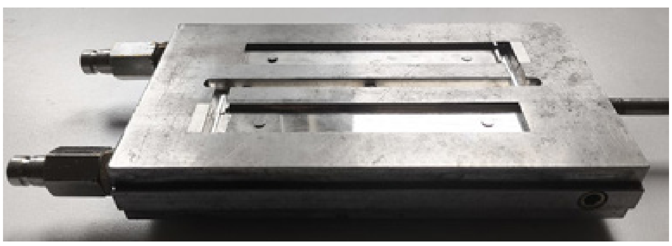

Fig. 1. Mold with cavities

T a b l e 2. Research plan regarding the weight of molded parts

Injection speed, cm^3/s	PP type
34.5	HP456J
34.5	HP548R
34.5	HP456J+HP548R (50/50)
54.5	HP456J
54.5	HP548R
54.5	HP456J+HP548R (50/50)
54.5	HP456J+HP548R (50/50)
74.5	HP456J
74.5	HP548R
74.5	HP456J+HP548R (50/50)

T a b l e 3. Research plan regarding the longitudinal shrinkage

Injection speed cm^3/s	PP type	Cavity height mm
34.5	HP456J	1.5
34.5	HP456J	4.0
34.5	HP548R	1.5
34.5	HP548R	4.0
34.5	HP456J+HP548R (50/50)	3.2
54.5	HP456J	3.2
54.5	HP548R	3.2
54.5	HP456J+HP548R (50/50)	1.5
54.5	HP456J+HP548R (50/50)	4.0
54.5 (C)	HP456J+HP548R (50/50)	3.2
54.5 (C)	HP456J+HP548R (50/50)	3.2
74.5	HP456J	1.5
74.5	HP456J	4.0
74.5	HP548R	1.5
74.5	HP548R	4.0
74.5	HP456J+HP548R (50/50)	3.2

ferent injection speeds (34.5, 54.5, and 74.5 cm^3/s) for three different cavity heights (1.5 mm, 3.2 mm, and 4 mm), using a two-cavity mold with replaceable inserts, shown in Figure 1. The mold was water-cooled using a Tempro Plus 140 thermostat (Wittmann). The mold cavity was 150 mm long and 20 mm wide. The increased cavity height allowed for an increase in the volume of injected material. With the speed change, the injection time was varied to achieve 99% cavity filling when switching to holding pressure. A total of 27 mold series were obtained. Constant injection temperature (230°C), holding pressure (50 MPa), holding time (20 s), cooling time (20 s), mold temperature (20°C) was used. Variable process parameters are presented in Table 4.

Statistica software (StatSoft Inc., Krakow, Poland) with the DoE (Design of Experiments) module was used to develop the research plan and analyze the results. Due to the accuracy of the measurements, samples from only one molding cavity of the two-cavity mold were used in the tests. During the ageing, the obtained samples were then subjected to accelerated UV ageing in the Atlas UV Test device equipped with eight fluorescent lamps (wavelength 313 nm UV-B). The radiation intensity was 0.76 W/m^2, the UV ageing time was 600 h, which corresponds to 2 years of ageing in a natural environment.

RESULTS AND DISCUSSION

MFR analysis

From the Pareto charts (Fig. 2) regardless of the load (2.16 kg; 5 kg), the type of material has the greatest influence on the MFR. The second important parameter is the temperature. The MFR increases with the increase in temperature, which is obvious.

The analysis of the mass melt flow rate (MFR) for various types of PP, including the HP456J and HP548R (50/50) blend, is presented in Figure 3a. The analysis showed significant differences depending on temperature and load. At a load of 2.16 kg and a temperature of 210°C, the MFR for Moplen HP456J was 2.1 g/10 min, while at a temperature of 250°C it increased to approxi-

T a b l e 4. Injection molding variable parameters

Cavity height, mm	Injection speed v_i, cm^3/s	Injection time t_i, s		
		HP456J	HP456J+HP548R (50/50)	HP548R
1.5	34.5	0.95	0.90	0.85
	54.5	0.6	0.56	0.54
	74.5	0.45	0.42	0.4
3.2	34.5	1.2	1.11	0.85
	54.5	0.74	0.68	0.54
	74.5	0.54	0.5	0.38
4	34.5	1.35	1.2	0.55
	54.5	0.83	0.75	0.36
	74.5	0.6	0.53	0.26

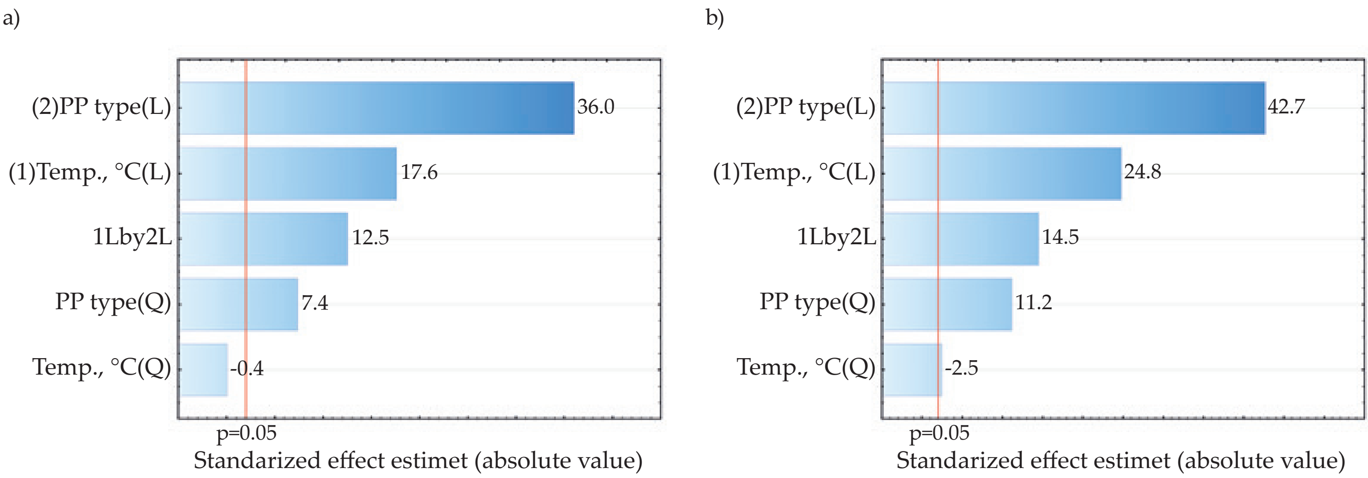

Fig. 2. Pareto analysis for MFR under load: a) 2.16 kg, b) 5 kg

mately 6.5 g/10 min, an increase of 310%. In the case of Moplen HP548R, at 210°C the MFR was 17.2 g/10 min, while at 260°C it increased to 43.1 g/10 min, an increase of approximately 250%. The HP456J/HP548R (50/50) blend showed an MFR of 8.4 g/10 min at 210°C, which increased to 15.5 g/10 min at 250°C, an increase of 185%. As the temperature increases, the viscosity of the polymer decreases, making the material more fluid. In this case, the dependence of MFR on temperature is linear. An increase in temperature can lead to a significant increase in MFR, but the rate of this increase may vary depending on the type of polymer. Polymers differ in activation energy and viscosity, which affects how the MFR varies with temperature. At a 5 kg load (Fig. 3b), the MFR for Moplen HP456J was 11.8 g/10 min at 210°C and increased to 33.7 g/10 min at 250°C, an increase of 285%. For Moplen HP548R, the MFR was 58.9 g/10 min at 210°C and increased to 152.8 g/10 min at 250°C, an increase of 259%. The HP456J/HP548R (50/50) blend had an MFR of 27.7 g/10 min at 210°C, which increased to 62.8 g/10 min at 250°C, an increase of 267%. Figure 3 shows that with increasing MFR, the flow rate increases at higher temperatures. Also, in this case the dependence of MFR on temperature is linear. This suggests that higher temperature leads to greater fluidity of the molten polymer. In summary, the shear viscosity of molten polypropylene is temperature dependent according to the Arrhenius equation [27], indicating greater fluidity at higher temperatures. MFR is a measure of the ability of the molten polymer to flow under a fixed pressure and can be an indirect measure of molecular weight. A low melt flow rate may correspond to a high molecular weight [28].

Molded parts weight analysis

Since it is obvious that moldings with different volumes have different weight, analyses were performed separately for each height of the molding cavity. The Pareto analysis (Fig. 4) showed that the type of polypropylene, and therefore its flow rate, has the greatest impact on the weight of molded parts. The injection speed had much less impact on the sample weight.

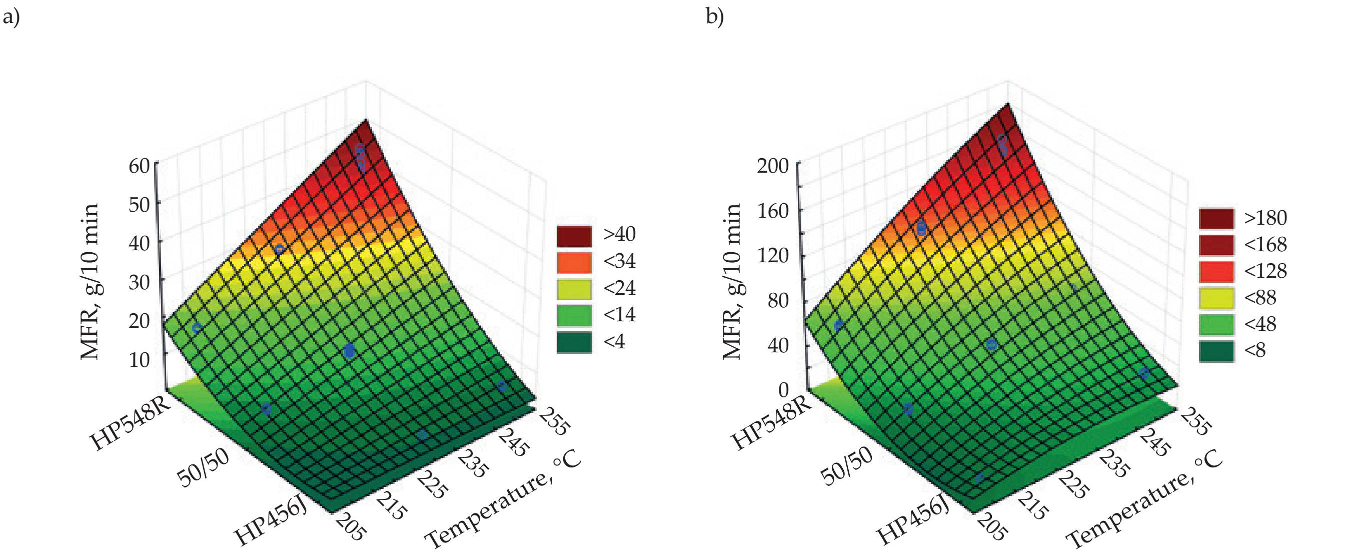

Fig. 3. Effect of PP type and temperature on MFR under load: a) 2.16 kg, b) 5 kg

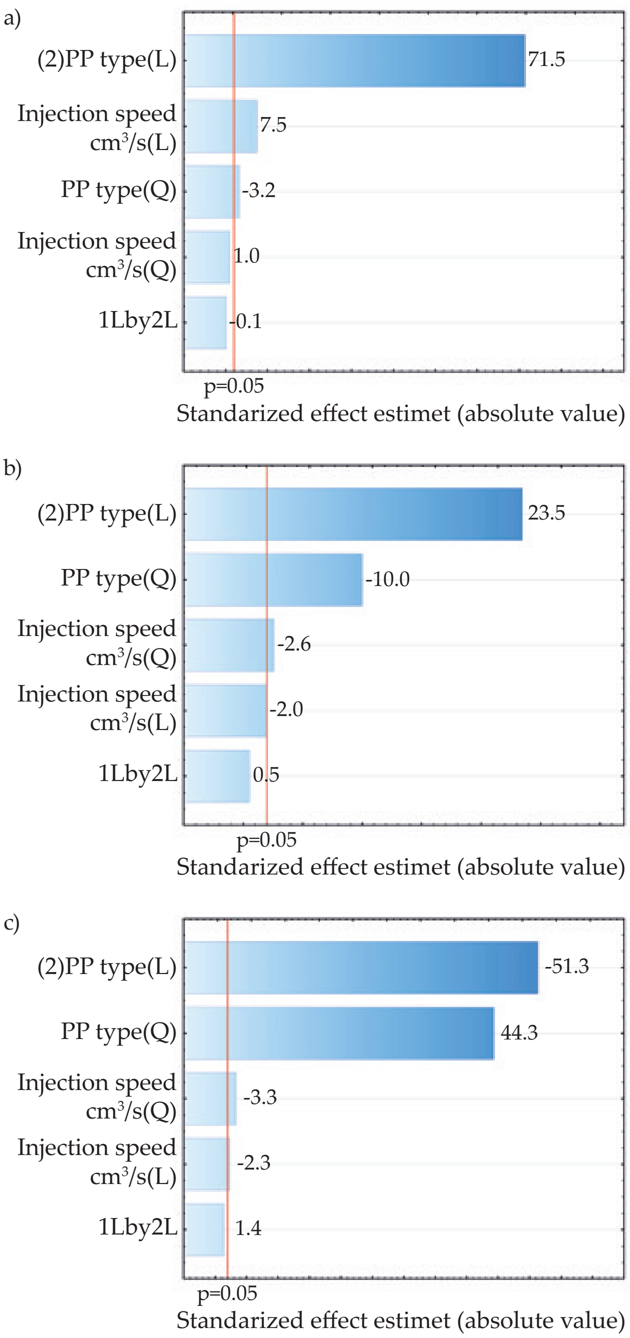

Fig. 4. Pareto analysis of molded parts weight depending on the height of the molding cavity: a) 1.5 mm, b) 3,2 mm, c) 4 mm

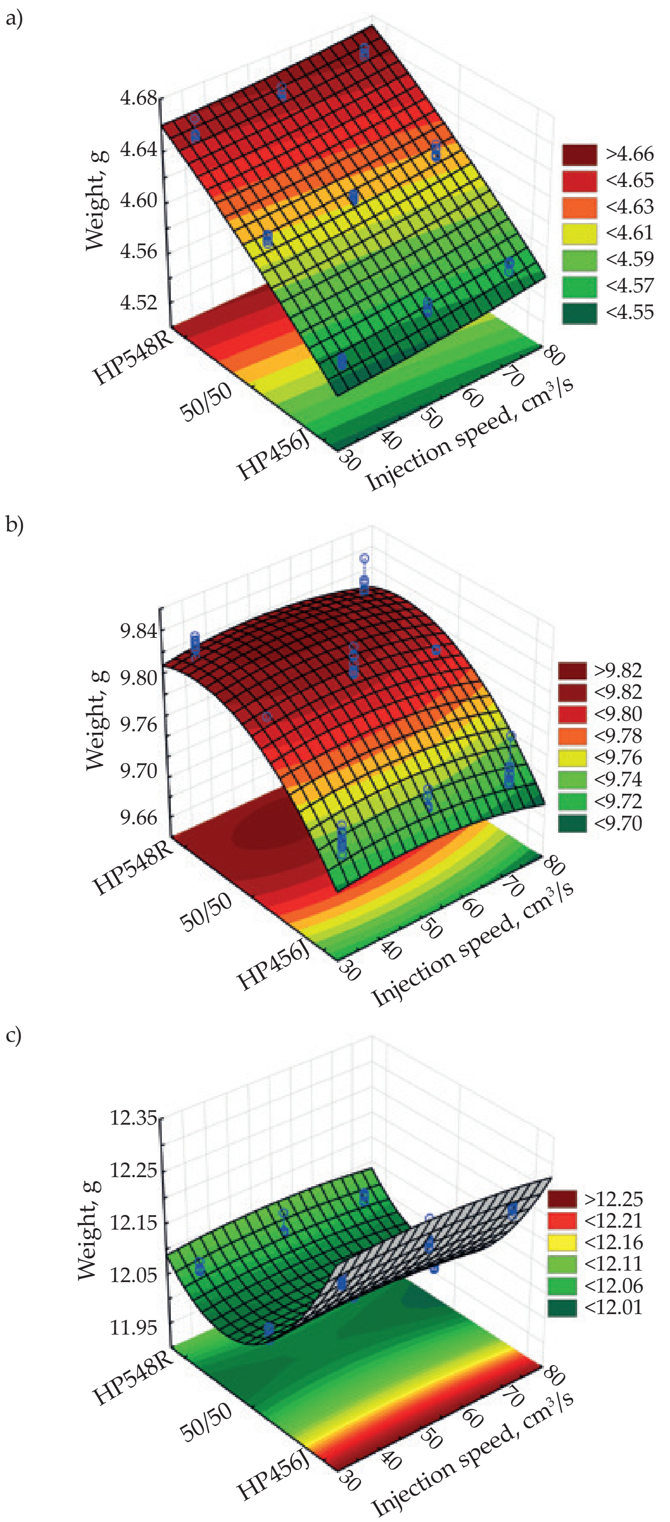

Fig. 5. Change of molded parts weight in function of PP type, injection speed and cavity height: a) 1.5 mm, b) 3.2 mm, c) 4 mm

The results of the molded parts weight at different injection speed and molding cavity heights as well as different PP flow rates had different characteristics (Fig. 5).

In the case of samples with a mold cavity height of 1.5 mm (Fig. 5a), the weight of the moldings increases with the increase in flow rate and, to a small extent, with the increase in injection speed. In the case of the HP45J material, the weight of the moldings was on average 4.56 g and HP548R 4.66 g, which means an increase in the weight of the moldings by 2.2%. A material with a high flow rate easily fills the mold cavity, and a higher flow rate intensifies the shearing of the material. For moldings with a molding cavity height of 3.2 mm, also with the increase in the PP flow rate, the weight of the moldings increases from 9.74 g to 9.82 g (an increase of 0.8%), but this change has different characteristics (Fig. 5b). In the case of these samples, it can also be seen that the injection speed has a slight effect on the weight change, but for these samples the weight decreases with the increase in injection speed. For samples with a thickness of 4 mm (Fig 5c), a completely different effect of the material flow rate on the weight

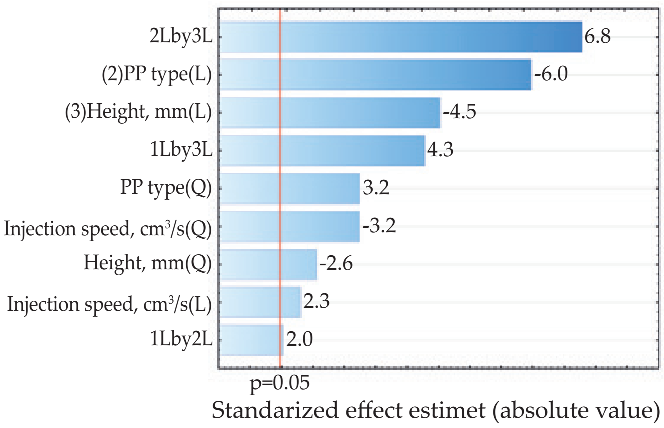

Fig. 6. Pareto analysis of molded parts shrinkage

of the moldings is visible. Samples from the slowly flowing HP456J have a weight of approx. 12.25 g, from the mixed one 12.03 g, and from the fast-flowing HP548R 12.07 g. The difference between the extreme samples is 1.8%. The difference between the trends of samples 1.5 and 3.2 and 4 mm may result from the fact that in a large-volume molding cavity, the material solidifies more slowly, which makes it possible to pack a larger amount of material during pressing and produce a greater degree of crystallinity. The difference in the crystallization kinetics of the tested polypropylenes, and therefore changes in the density of the material, may result in such a different tendency to change the weight of the molded parts.

Shrinkage analysis

Pareto chart (Fig. 6) show that the correlation between the type of PP and the height of the molding cavity has the greatest impact on the linear longitudinal secondary shrinkage of the molded parts, and the correlation between the type of material and the height of the molding cavity has the greatest impact on the secondary linear shrinkage of the molded parts. As three parameters increase: polymer flow rate, mold cavity volume and injection speed, shrinkage decreases.

Analyzing the shrinkage of injection molded parts depending on the type of PP and injection speed (Fig. 7), molded parts made of free-flowing PP HP456J exhibit

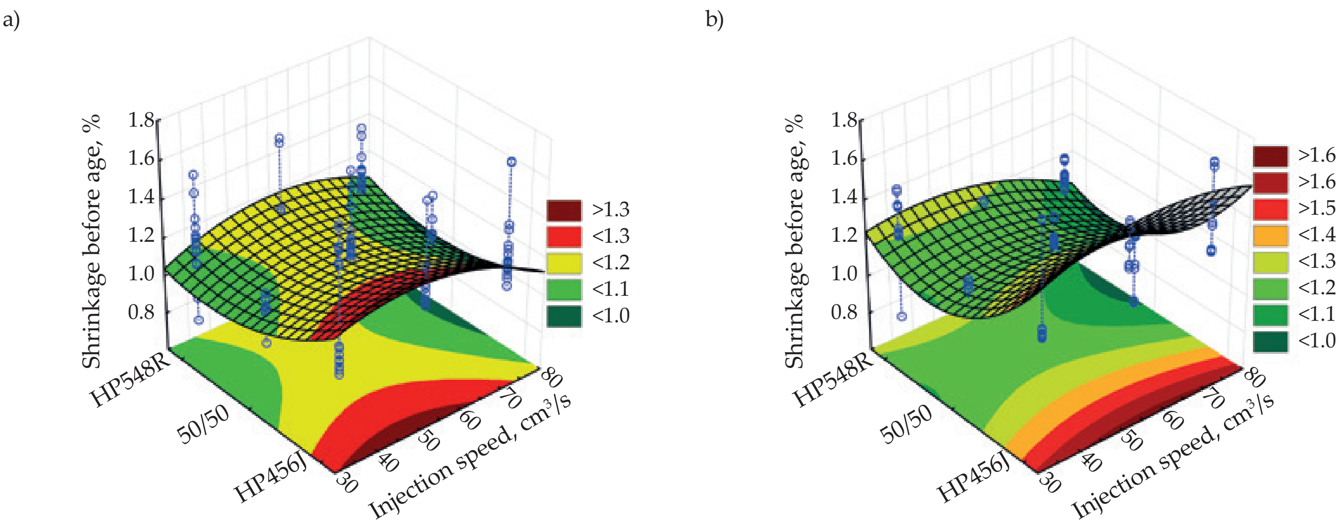

Fig. 7. Change of shrinkage of molded parts in function of PP type and injection speed: a) before ageing, b) after aging

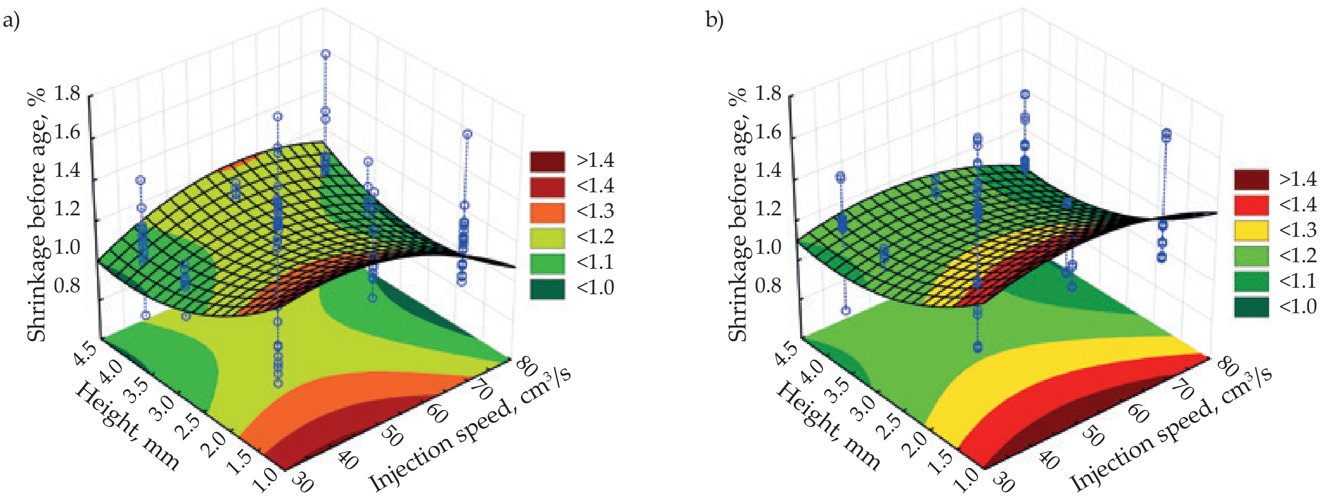

Fig. 8. Change of shrinkage of molded parts as a function of the cavity height and the injection speed: a) before ageing, b) after aging

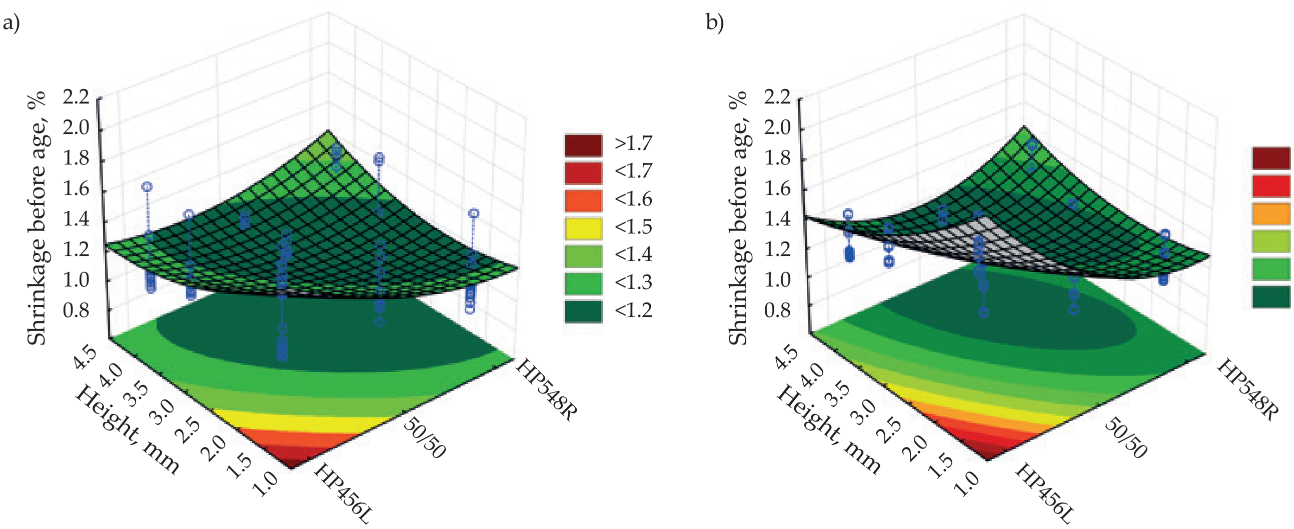

Fig. 9. Change of shrinkage of molded parts in function of cavity height and PP type: a) before ageing, b) after aging

greater shrinkage. After the ageing process, the shrinkage is greater.

Comparing the relationship between the height of the mold cavity and the injection speed (Fig. 8), the molded parts with a smaller thickness have a larger longitudinal shrinkage than the molded parts with a thickness of 4 mm. Moreover, after the aging process, the shrinkage is larger.

A similar analogy occurs when comparing the molded parts in terms of material flow rate and mold cavity height (Fig. 9). Particularly in the case of HP456J and a mold cavity height of 1.5 mm, the shrinkage increased from 1.27% to 1.87% after ageing.

The average linear shrinkage of all molded parts before the aging process was 1.19%, which increased to 1.29% after the aging process.

CONCLUSIONS

It was shown that the greatest influence on the flow rate is the polymer's mass flow rate, followed by temperature. Therefore, it is not possible to significantly increase the flow rate of a low MFR polymer by simply increasing the injection temperature. The weight of the molded parts always depends on the volume of the cavity, which is obvious. In the case of different heights of the molding cavity, the relationship between the weight of the molded parts and the flow rate of PP is not always linear. There can be many reasons for this, e.g., different degrees of crystallinity, so this phenomenon requires further research. The studies carried out have shown that the injection speed has little effect on the weight of molded PP parts. The linear longitudinal shrinkage depends on the injection volume (mold cavity height and polymer MFR) and, to a lesser extent, on the injection speed. As the polymer flow rate, mold cavity volume and injection speed increase, the linear shrinkage of molded parts decreases. The aging process slightly increases the shrinkage of PP injection molded parts. The results showed that the most important parameters influencing the properties of injection molded parts are the type of material and the volume of the molding cavity. The injection speed had only a minor effect.

Authors contribution

P.P - conceptualization, methodology, writing-original draft, visualization, supervision, writing-review and editing, validation; T.G. – writing-review and editing, supervision, validation, visualization; Ł.H. - investigation, methodology, validation.

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Conflict of interest

The authors declare no conflict of interest.

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