Research Article

RESEARCH ON THE CONTENT AND FILLER TYPE ON INJECTION SHRINKAGE

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ABSTRACT

The paper presents the phenomenon of injection shrinkage. The definition of shrinkage and shrinkage types are presented. The main factors affecting shrinkage value of injection-molded part are discussed. Based on the experimental tests conducted using injection-molded parts made from polypropylene filled with glass fiber and talc, the dependence of injection-molded part shrinkage on filler content and selected parameters of the injection molding process has been determined.

Keywords: polymer processing, injection molding, shrinkage, filler, composite injection-molded part.

INTRODUCTION

The injection molding is one of the most important manufacturing processes for producing parts made of polymer materials. There are many different variants of this process, all of them characterized by cyclical nature. Injection molding can be used to process practically all kinds of polymer materials, particularly thermoplastic and thermoset materials, but also rubber compounds, liquid silicones and composite materials. As a result of injection molding, an injection-molded part is produced; depending on both the injection molding process variant employed and the polymer used, the injection-molded part is characterized by a very wide range of functional and strength properties as well as variations in shape, structure, dimensions and production accuracy [2, 4, 9, 19].

Injection-molded part design is predominantly affected by the following factors: polymer type, processing method and molding conditions, tool design and the processing capacity of injection molding machine . All these factors directly or indirectly affect the final dimensions, structure and shape of the injection-molded part, its consistency with the tolerance range adopted during the design process and molding anomalies (material and surface defects) that are significant from a user's point of view [6, 12, 18].

SHRINKAGE AND ITS TYPES

Shrinkage is defined as the decrease in the volume or dimensions of a plastic part relative to the volume or corresponding dimensions of the mold cavity, with the decrease occurring both during the final stage of the process and within a specified time period after the process [4, 6, 12].

Shrinkage of plastic materials can be classified according to several criteria. With regard to time and place of occurrence, shrinkage can be divided into primary shrinkage and secondary shrinkage. Primary shrinkage means the decrease in part dimensions during cooling (for thermo-

plastics) or hardening (for thermoset plastics) in the mold cavity and shortly after demolding. It is conventionally assumed that primary shrinkage lasts 16 hours [4, 9, 12]. Secondary shrinkage is defined as the change in the volume and dimensions of a molded part as a function of time that occurs even after primary shrinkage and approaches, at the same time, a constant value. The sum of primary shrinkage and secondary shrinkage is called overall shrinkage [4, 12, 16].

With regard to changes in the geometric dimensions of a polymer product, shrinkage can be divided into the following categories: linear, volumetric, mean, longitudinal and transverse. Linear shrinkage is the decrease in a given linear dimension of an item relative to the corresponding linear dimension of the mold cavity, usually expressed as a percentage. Moreover, it should be mentioned that there is also a term "actual shrinkage" which takes into account the thermal expansion of cavity material that occurs during processing [1, 4, 5].

Owing to variations in the orientation of polymer macromolecules, shrinkage values differ depending on the direction measured; consequently, transverse shrinkage and longitudinal shrinkage can be distinguished. Transverse shrinkage refers to the linear dimension transverse to the direction of polymer flow in the mold cavity, while longitudinal shrinkage is the linear shrinkage measured along the flow direction. Transverse shrinkage is lower than longitudinal shrinkage. The difference between the values of transverse shrinkage and longitudinal shrinkage is called anisotropic shrinkage [4, 8, 12, 16].

Another criterion used to classify shrinkage concerns processing methods. For this reason, the term "technological shrinkage" has been coined, which can encompass, among others, injection molding shrinkage, compression shrinkage, extrusion shrinkage and casting shrinkage [4, 9, 12, 15].

The relationship of change in part dimensions to time is called shrinkage characteristic curve. Basic characteristic curve describes one of the processing methods (injection molding, compression or casting), encompassing the time period from the moment the mold cavity is filled with the polymer melt until secondary shrinkage is over. A comprehensive characteristic curve applies to the main processing method for producing a part (e.g. injection molding), taking into account an additional processing method performed at elevated temperature in order to

minimize the risk of shrinkage and to ensure the dimensional stability of the part (e.g. heat treatment). This characteristic curve encompasses the time period from the moment the mold cavity is filled with the polymer melt until the additional processing technique is over, which is considered identical to the end of secondary shrinkage. Examples of visual interpretation of shrinkage characteristic curves for an amorphous plastic and a semicrystalline material are shown in Figure 1 and Figure 2 [4, 6, 16].
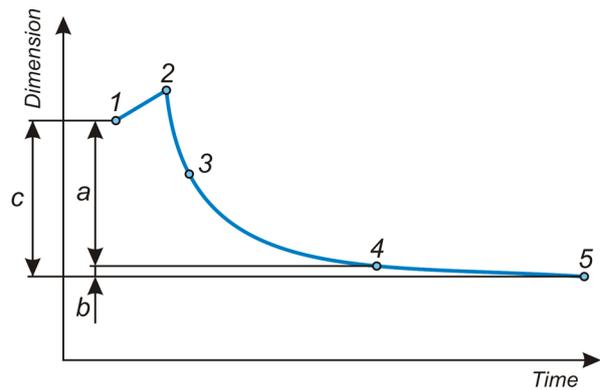
Fig. 1. Basic characteristic curve of shrinkage for amorphous part: a – primary shrinkage, b – secondary shrinkage, c – overall shrinkage, 1 – mold cavity dimension at initial cavity filling temperature, 2 – dimension of mold cavity heated by polymer, 3 – part dimension after demolding, 4 – part dimension after primary shrinkage, 5 – part dimension after secondary shrinkage [9]
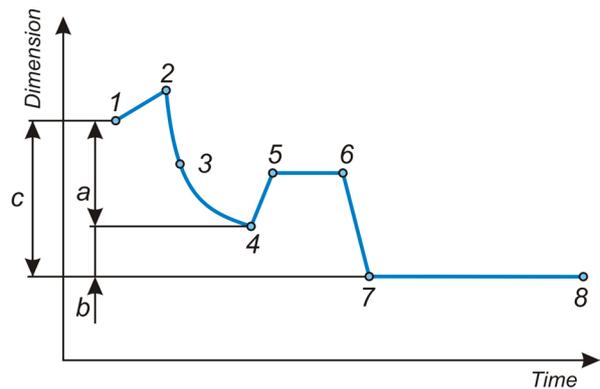
Fig. 2. Comprehensive characteristic curve of shrinkage for semicrystalline part: a - primary shrinkage, b – secondary shrinkage, c – overall shrinkage, 1 – mold cavity dimension at initial cavity filling temperature, 2 – dimension of mold cavity heated by polymer, 3 –part dimension after demolding, 4 – part dimension after primary shrinkage and at the beginning of heat treatment, 5 and 6 – part dimensions during heat treatment, 7 – part dimension after heat treatment, 8 – part dimension after secondary shrinkage [9]

FACTORS AFFECTING SHRINKAGE

With its origin in physiochemical phenomena, shrinkage is affected by many factors that can be grouped according to the following: [1, 4, 9, 12, 20]:

- polymer material (density, molecular weight, crystalline or amorphous structure),
- part (shape, dimensions, dimensional accuracy and tolerance range),
- processing conditions (polymer temperature, mold temperature, product cooling and cooling method applied),
- tool design (flow system design, mold cavity shape),
- physical or chemical treatments applied to the molded part (normalizing, annealing, chlorination).

The effect of processing conditions on mold shrinkage is difficult to determine. When thermoplastics are processed by injection molding technique, shrinkage is mainly caused by the decreasing temperature of the polymer being processed in the final stages of the injection cycle, and it depends on technological parameters of the process (temperature, pressure, time and cooling conditions) as well as on the parameters of subsequently employed thermal and thermo-chemical treatments. In contrast, when thermoset plastics are processed by compression method, compression shrinkage is significantly affected by chemical processes that occur in the polymer being processed at the final stages of the compression cycle [4, 5, 12].

It has been established that crystalline materials are more prone to shrinkage than amorphous materials [1, 8, 11]. The shrinkage phenomenon has been best investigated for the injection molding process, hence the majority of dependences describing the effect of molding conditions on shrinkage value have been formulated with regard to injection-molded parts. Table 1 lists values of linear primary shrinkage for the most important polymer materials [16].

Polymer materials with higher density exhibit higher shrinkage. It is particularly important in the case of polyolefines, polyamides and polyacetals. Polymers with lower density crystallize to a lower degree due to their stronger chain branching, which leads to lower shrinkage. Shrinkage decreases with the increase in melt flow rate [1, 4, 14].

Injection molding parameters, in particular pressure and holding time as well as mold temperature and cooling time, have a significant ef-

Table 1. Value of linear primary shrinkage [16]

Polymer type	Shrinkage value [%]
Polystyrene	0.5 – 0.7
ABS resins	0.4 – 0.6
Low-density polyethylene	1.0 – 1.5
High-density polyethylene	2.0 – 4.0
Polyamide	1.2 – 3.0
Poly(vinyl chloride)	0.1 – 0.4 hard
	1.0 – 3.5 soft
Polypropylene	1.0- 2.0
Poly(methyl methacrylate)	0.4 – 0.8
Polycarbonates	0.4 – 0.8
Polyoxymethylene	3.0 – 5.0

fect on shrinkage [1, 4, 11, 13]. Generally, if the injection pressure, holding pressure and injection temperature increase, injection shrinkage of thermoplastics decreases, whereas increasing mold temperature and injection rate leads to increased shrinkage. If the holding time is too short, which is usually the outcome of premature freeze-off, or if the holding pressure is too low, depressions or shrinkage cavities can occur. If the holding pressure is too high, it results in excessive increase in polymer pressure and its packing in the mold cavity, leading to scratches and cracking of the injection-molded part [1, 4, 5, 11]. The temperature of the mold cavity surface and the wall thickness of the molded part determine the cooling rate uniformity. With extending the cooling time and increasing the wall thickness of the molded part, the heat transfer becomes slower, so, as a consequence, the molecule chains have more time to level up the stresses, while semicrystalline materials have more time even for crystallization [3, 4, 10]. Although the increase in the mold temperature leads to the increase in overall shrinkage, the fraction of primary shrinkage is then so low that sufficient dimensional accuracy of the molded part can still be obtained [3, 5, 6, 19].

The injection-molded part design and the way of polymer feed determine shrinkage uniformity in particular fragments of the molded part. The non-uniformity of wall thickness leads to different shrinkage values, which induces internal stresses and warpage [4, 11, 17, 20]. With very thin walls of molded parts, strong macromolecule orientation and anisotropic shrinkage occur. Shrinkage is clearly lower if the molded part does not have any sharp edges, for example in the place where the bottom changes into a side

wall. This is due to the fact that rounded shapes facilitate polymer flow, which results in lower pressure losses [6, 9, 12].

The design of the injection mold is critical to shrinkage uniformity in the injection-molded part. The most commonly mentioned design factors that affect shrinkage value are as follows: the number and arrangement of mold cavities, flow path length, type of a gating system as well as the place where the polymer is forced into the mold cavity, cross section and shape of pinpoint gates as well as the arrangement of temperature adjusting channels. Parts molded in multi-cavity molds are characterized by considerable variations in shrinkage values. Shrinkage increases along the polymer flow direction in the mold injection channels with the increase in the distance of the mold cavity from the central injection channel. This is due to the decrease in the pressure along the polymer flow path. Shrinkage is lower in the vicinity of the ingot than at the distant edge of the molded part; for this reason, many injection points are used to level out shrinkage value [6, 12, 20].

Anisotropic shrinkage of polymer materials without fillers is relatively low, particularly in the case of amorphous materials. The anisotropy of filled materials mainly depends on the filler content and shape, the shape and dimensions of the molded part, the way of forcing polymer into the mold cavity (which is connected with mold cavity filling and filler orientation), as well as the dimensions and shape of the pinpoint gate [3, 7, 13, 14].

As additional substances, e.g. fillers, are introduced into the material at different stages of processing, they significantly change both the properties of products obtained and the process itself. As far as the injection molding process is concerned, fillers, both as powders and short fibers, exert a positive impact as they lead to the reduction in injection molding shrinkage and the dimensional stability of the injection-molded part. Depending on injection molding conditions and the structure of the injection-molded part, the application of fibrous fillers can result in distinct fiber orientation, which leads to anisotropic shrinkage. The addition of fillers can, however, deteriorate the operational conditions of the injection molding machine deteriorate, exerting an erosive impact on the barrel and screw surfaces; what is more, some fillers impair the rheological properties of plastics and make polymer flow difficult [4, 7, 13].

A detailed discussion of the effect of individual factors on the shrinkage phenomenon is beyond the scope of the present paper. However, the problem has been thoroughly presented in the literature [4, 8, 9, 11]. To give an example of the effect of selected factors on shrinkage value, the dependence of primary injection shrinkage on injection pressure and side gate dimensions for highly crystalline polyoxymethylene called Duracon M140-44 is shown in Figure 3 [10]. To give another example of the effect of selected factors on shrinkage value, the dependence of difference of primary injection shrinkage on wall thickness and gate size for highly crystalline polyoxymethylene Duracon M270-44 is shown in Figure 4 [10].
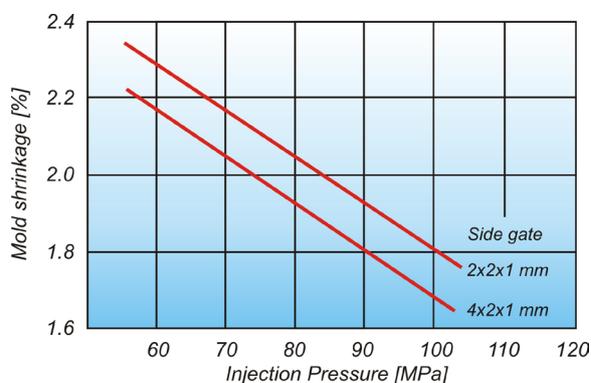
Fig. 3. Dependence of primary injection shrinkage on injection pressure and side gate dimensions for highly crystalline polyoxymethylene Duracon M140-44 [10]
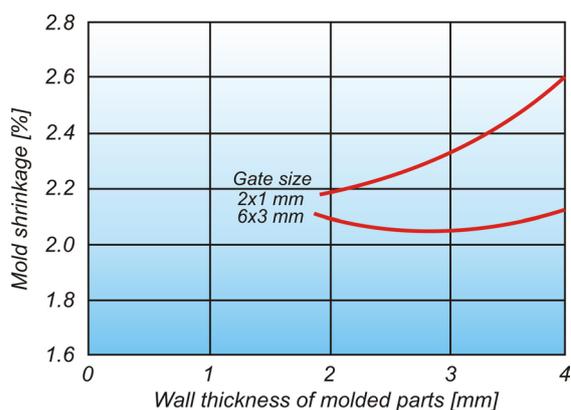
Fig. 4. Dependence of difference of primary injection shrinkage on wall thickness and gate size for highly crystalline polyoxymethylene Duracon M270-44 [10]

EXPERIMENTAL TESTS

To conduct the experimental tests investigating the effect of filler type and content as well as of selected parameters of the injection mold-

ing process on linear shrinkage value, injection-molded parts in the shape of tensile test specimens were used. The injection-molded parts were obtained using a laboratory screw injection molding machine, with variable factors being: injection time set to 4 and 6 seconds, cooling time set to 15, 30 and 45 seconds, respectively. The injection-molded parts were made of polypropylene, marketed under the name of Moplen EP440G, manufactured by Basell Orlen Polyolefins. The fillers used included: short glass fiber, as a ready PP/GF concentrate, and talc, also in a form of a ready PP/T concentrate. For injection, polymer batches containing: 10%, 20%, 30%, 40% and 50% of glass fiber, 10%, 20%, 30% and 40% of talc, and pure propylene without filler, were used. The temperature in particular heating zones of the plasticizing system was increased from 220 °C to 240 °C, reaching 245 °C in the injection nozzle. The tool used was a two-cavity injection mold thermostated at a temperature of 50 °C. Neces-

sary for further calculations of linear shrinkage, the dimensions of the mold cavity were as follows: length L = 152.00 mm, width H = 20.15 mm and thickness B = 4.00 mm.

Corresponding to the dimensions of the mold cavity, the actual geometric dimensions of the injection-molded parts produced with particular batches, differing in filler type and content and obtained at different injection parameters, were measured with an accuracy of 0.01 mm by means of an electronic measuring device. The measurements were made three times: immediately after demolding (to analyze primary shrinkage), after twenty-four hours and after one week (to analyze secondary shrinkage). Following the preliminary calculations, the length L of the injection-molded part, as the longest dimension of the examined product, was used for further presentation of the results.

Figure 5 and Figure 6 offer examples of the charts illustrating the change in the dimension L of the injection-molded part after demolding as a
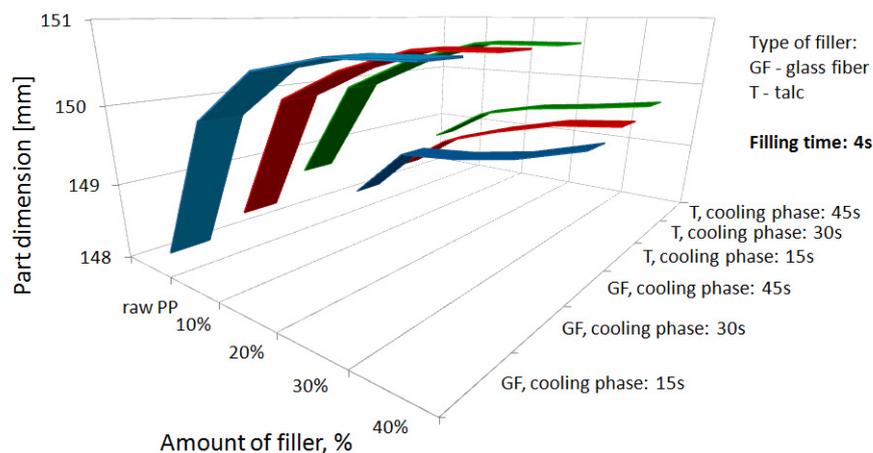
Fig. 5. Change in the dimension L of the glass fiber-filled part and talc filled part after demolding, depending on the filler content and cooling time of the part in the mold. The part was produced at filling phase time of 4s
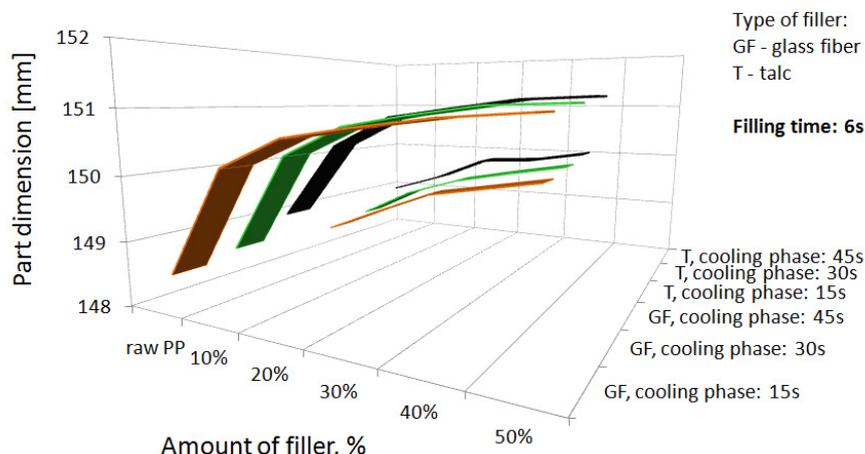
Fig. 6. Change in the dimension L of the glass fiber-filled part and talc filled part after demolding, depending on the filler content and cooling time of the part in the mold. The part was produced at filling phase of 6s
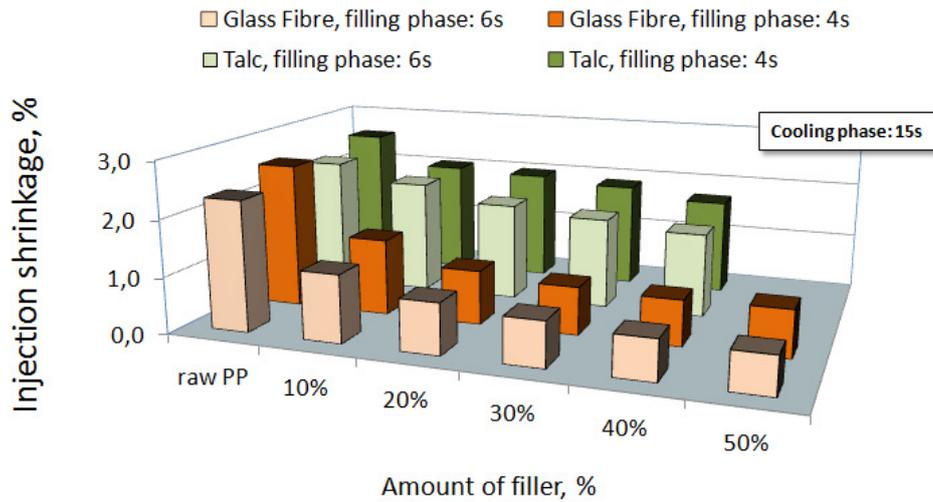
Fig. 7. Effect of the filler type and content on the linear injection shrinkage of polypropylene injection-molded parts produced at filling phase time of 4s and 6s also with a cooling phase time of 15s
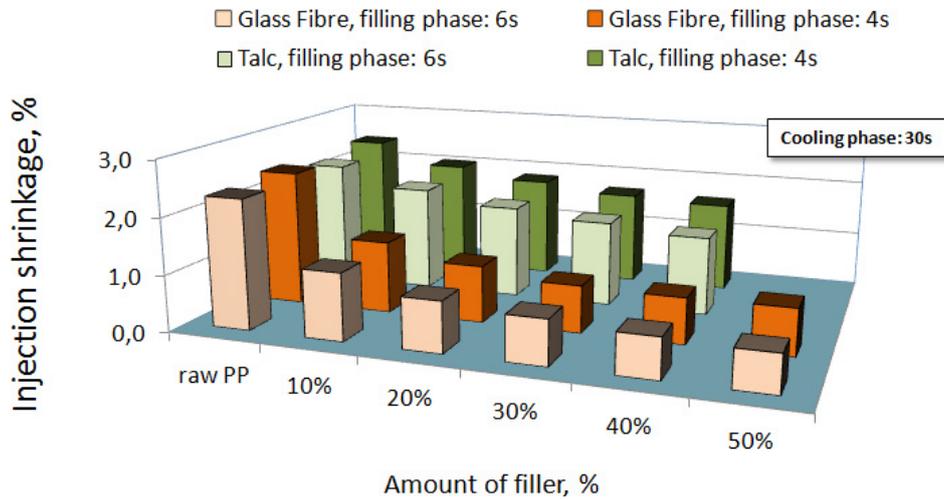
Fig. 8. Effect of the filler type and content on the linear injection shrinkage of polypropylene injection-molded parts produced at filling phase time of 4s and 6s also with a cooling phase time of 30s
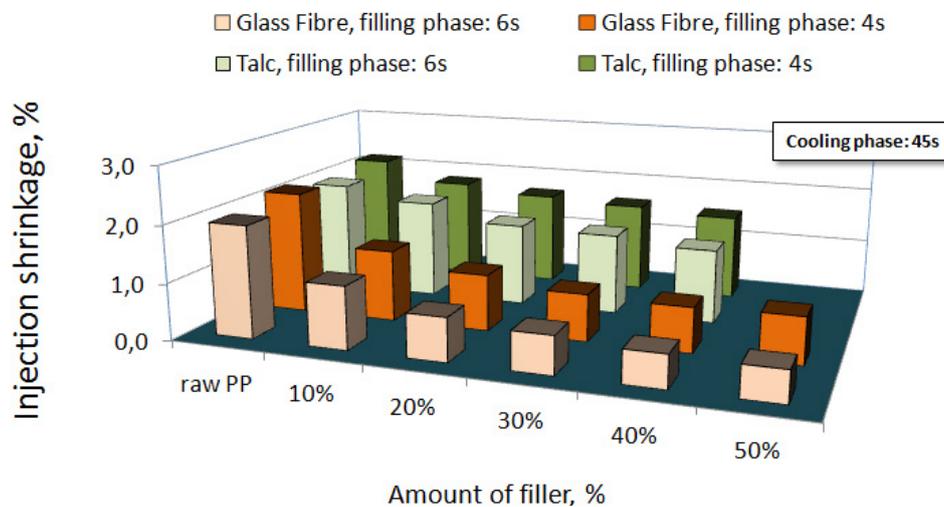
Fig. 9. Effect of the filler type and content on the linear injection shrinkage of polypropylene injection-molded parts produced at filling phase time of 4s and 6s also with a cooling phase time of 45s

function of the injection time and cooling time of this part. Figure 5 offers a comparison between the change in the lengths of the parts filled with glass fiber and talc that were produced at an injection time of 4 seconds, while Figure 6 presents the variations in the dimensions of the parts produced with the injection time set to 6 seconds. Extending the injection time and cooling time led to increasing the values of the investigated linear dimensions, whereas the differences between the corresponding dimensions were the more clear, the lower the filler content. Figure 7, Figure 8 and Figure 9 present the effect of the injection time and cooling time on the values of linear injection shrinkage, depending on the filler type and content.

Increasing the filler content led to decreased shrinkage, this effect being most visible for the glass fiber-filled part whose shrinkage sometimes decreased nearly twice, compared to the shrinkage of the part without any filler. The addition of talc resulted in decreased shrinkage, too, yet the decrease was not as considerable as in the case of glass fiber. With glass fiber, the decrease in shrinkage could be observed when the filler content was changed from 10% to 20%, and then to 30%. A further increase of the glass fiber content in polypropylene did not cause any visible decrease in shrinkage. As for the talc filler, the decrease in shrinkage was not as considerable as the one observed for glass fiber, and it proceeded at a uniform rate along with increasing the talc content in the material.

The extension of the injection time, which enables higher polymer packing in the mold cavity, affected the increase in the part dimensions more than the extension of the cooling time of the part in the mold.

CONCLUSIONS

Given both the complexity of the injection molding process for polymer materials and a relatively high number of factors that affect the process and its results, it is necessary that polymer properties, tool design and machine processing capacity be known in order to determine the optimal conditions of injection molding. The performed experimental tests were undertaken to investigate selected problems of the injection molding process, including factors such as changes in properties of the polymer being processed (filler type and content) and changes in some relatively

easily adjustable injection parameters (injection time and cooling time of the part in the mold). The phenomenon of injection molding shrinkage of polymer materials, which changes both the shape and dimensions of the molded part, is one of the fundamental problems to be solved at the stage of both tool design and parameter selection for this processing method. The conducted analysis of injection molding shrinkage has demonstrated that shrinkage value can be effectively affected if injection molding conditions are selected properly, within the processing capacity of the injection molding machine; if necessary, it is also possible to modify the processing properties of polymers in order to produce molded parts with the desired geometric and strength properties. Both increasing the filler content in the polymer to a given value and extending the injection molding time (by increasing the injection time and cooling time) led to a clear decrease in injection molding shrinkage and, as a result, increased the dimensional accuracy of the injection-molded parts obtained, which means better production quality and enhanced applicability of such parts.

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