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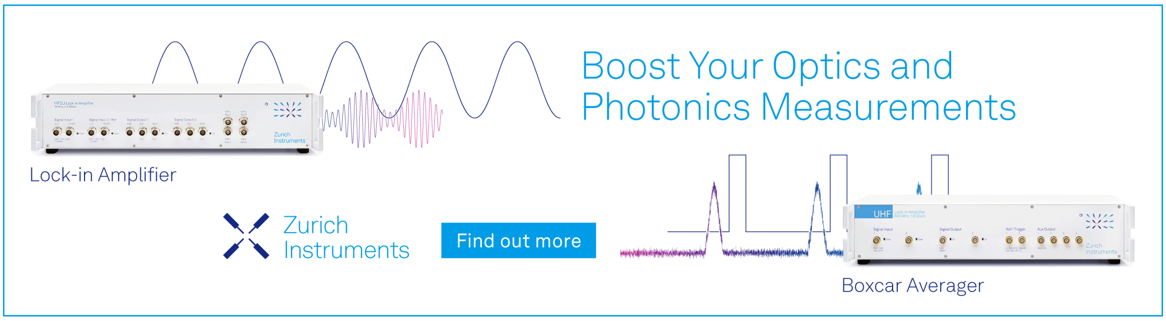

Shrinkage, Warpage and Residual Stresses of Injection Molded Parts

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Abstract. The shrinkage and warpage behavior of injection molded parts is very complex. By using a new measuring method it was shown for the first time that the warpage can be classified as warping and distortion. In general, warpage can only be reduced substantially by a sufficiently high volumetric compensation in the holding pressure phase.

INTRODUCTION

Injection molding allows to produce geometrically complex parts at low cost in a single process step. [1] During and after production, changes in the produced part´s shape can occur, caused by shrinkage, volume contraction and thus warpage. [2] In many publications shrinkage and volume contraction unfortunately are not distinguished. The term "volume contraction" describes the volume decrease while the term "shrinkage" describes the polymer chains´ reorientation and thus relaxation while the volume keeps constant. This paper uses "contraction" and "shrinkage" in the above mentioned manner.

The contraction and warpage behavior of the plastic parts has to be taken into account during the design and manufacturing phase of injection molds. Therefore, the mold shapes are generally made larger than the specified part dimensions. The prediction of contraction and warpage behavior is very complex. Nowadays contraction can already be predicted very well, but this is not true for warpage.

The influence factors on warpage are still far less understood. Thus, very cost-intensive mold changes are often necessary until the specified part shape is achieved.

STATE OF ART

The contraction and warpage of a plastic part are usually listed together in the literature. Contraction describes the dimensional deviation of a plastic part to the mold and is a normalized value, which can be determined for each plastic on standard specimen [3]. For warpage, however, the situation is different. In the German standard DIN 16742, warpage is defined as the sum of deviations in form, position and angle of the part due to a flexural warping, and torsional. An anisotropic contraction causes residual internal stresses in the part, which leads to warpage. [4] Due to the cooling of the part, a residual stress gradient as shown in Figure. 1 (a) occurs. After demolding, an anisotropic contraction over the wall thickness leads to a deformation of the part shape (Figure. 1, b). Thus a stress equilibrium is reached. [5, 6, 7]

If homogenous contraction is present in all spatial directions, it can be assumed that only a very small warpage and residual stress occurs. This makes clear that the effects on the contraction behavior have to be considered separately before investigating the warpage. In this work, the different influencing factors on the contraction are distinguished into material-dependent, process-dependent and shape-dependent contraction.

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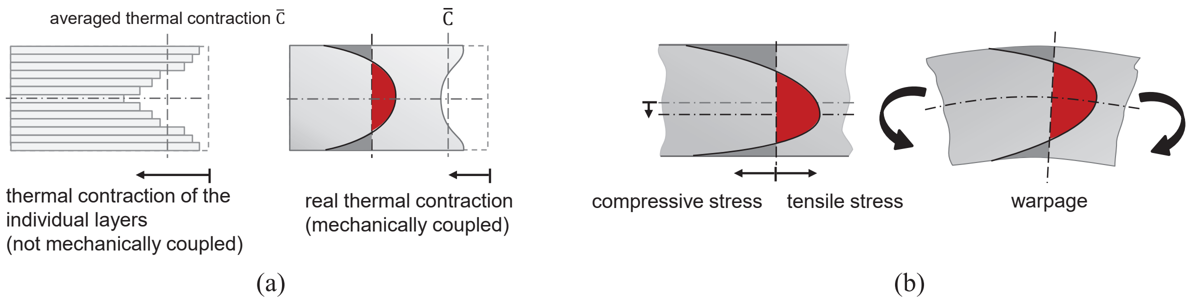


FIGURE 1. Residual stresses due to cooling effects. [5, 6]

The **material-dependent contraction** behavior can be shown by means of a pvT-graph. The contraction of semi crystalline thermoplastics is higher than that of amorphous plastics because of the crystalline phase. The reason is a lower free volume in the solid state, which is caused by the tight crystalline arrangement of the polymer chains [8].

The **process-dependent contraction** is influenced by a large number of different factors. In addition to the injection mold design and the positions and shape of the filling points and cooling channels, the process parameters have to be considered. Each of these factors influences the material characteristics during the injection molding process. [9, 10]

The shape of an injection-molded part has a decisive influence on the contraction behavior of the plastic. Depending on the part shape and mold concept, different dimensions and tolerances can be reached. In the withdrawn German standard DIN 16901 as well as in the current German standard DIN 16742, the **shape-dependent contraction** is divided into tool-specific dimensions and non-tool-specific dimensions [4]. The non-tool-specific dimensions must also be further differentiated into two types of contraction. Overall, there are three types of a shape-dependent contraction. The free contraction only occurs in the thickness direction. In this case the plastic can contract unhindered. Longitudinally and transversally to the flow direction of the plastic there is an internal contraction hindrance due to already cooled edge layers. The result is a hindered contraction. An additional external contraction hindrance is caused by a contraction of the plastic on mold cores or undercuts. The freezing material is fixed in the mold and cannot contract further. This results in so called prevented contraction. [2]

EXPERIMENTS AND MATERIALS

For the investigation of the contraction and warpage behavior, a semi-crystalline polypropylene of the type BJ368MO from Borealis AG, Vienna Austria, was used. A low viscosity and good nucleation behavior ensures a homogeneous contraction and a symmetrical stress profile caused by cooling effects. Two plates of 60 mm x 60 mm were used: In Figure. 2 the left plate used for determining the contraction according to DIN EN ISO 294-3 is shown. An identical plate with additional ribs at the edges, which cause a prevented contraction, is shown on the right. The experiment was carried out on an injection molding machine Arburg Allrounder of type 370S 700-100 / 70 from Arburg, Loßburg Germany, with a screw diameter Ø d = 25 mm. The used mold was designed as an injection compression mold. This allows a simple variation of the part thickness t. For each thickness the height position of the diaphragm runner was adjusted accordingly (0.75 x t). In addition, two pT-sensors (p1, p2) were integrated for process monitoring.

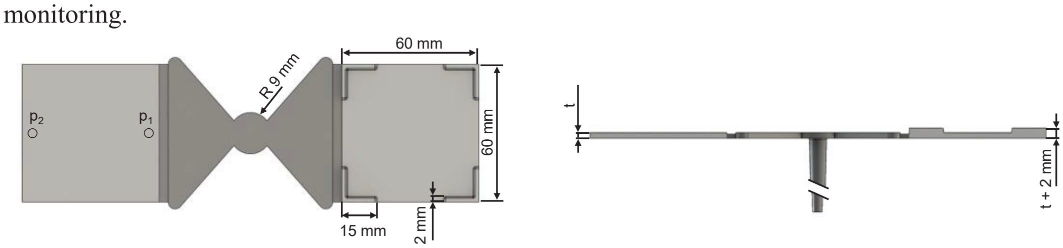


FIGURE 2. Used part shape.

The experiments include all relevant process parameters (Table 1). For this purpose a fractional factorial centrally composed design with 83 process variations was used. The injection volume flow of the machine (cm³/s) was varied for each part thickness. This allows to realize the same melt front speed in the cavity for all part thicknesses.

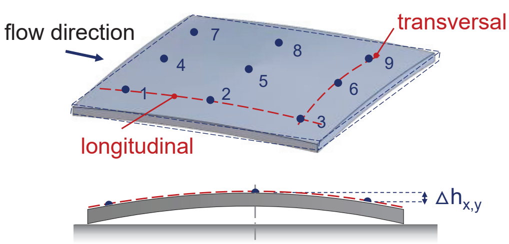
TABLE 1. Used process conditions.

Parameter		Unit	-α	0	α
thickness	t	mm	1	2,5	5
melt temperature	ϑ_{me}	°C	210	235	260
mold temperature	ϑ_{mo}	°C	20	50	80
melt front speed	v_f	mm/s	150	500	850
holding pressure	p_h	bar	50	175	300
holding pressure time	t_h	s	1	4,5	8
ejection temperature	ϑ_E	°C	90	105	120

Measurement Methods

The contraction was determined according to the standard. A measurement of the warpage according to the standard is not possible yet for the lack of a standard. Till today, a standard measurement method for the warpage does not exist. Therefore, a new measurement method was developed with this work.

The height of the plate was determined tactilely at nine measuring points (see Fig. 3). Thus, a characterization of the warpage as the maximum difference in height is possible. In addition, the surface shape (eq. 1) or the surface profile in one direction (eq. 2) can be described with a polynomial function of second degree. As a reference for the tactilely determined warpage values, the warpage was additionally measured optically. For this purpose the plates were scanned with a 3D scanner ATOS Core 135 from GOM, Braunschweig Germany.



$$h_{(x,y)} = a_0x^2 + a_1xy + a_2y^2 + a_3x + a_4y + a_5 \quad (1)$$

$$h_{(x)} = ax^2 \cdot bx + c \quad (2)$$

FIGURE 3. Warpage measurement method.

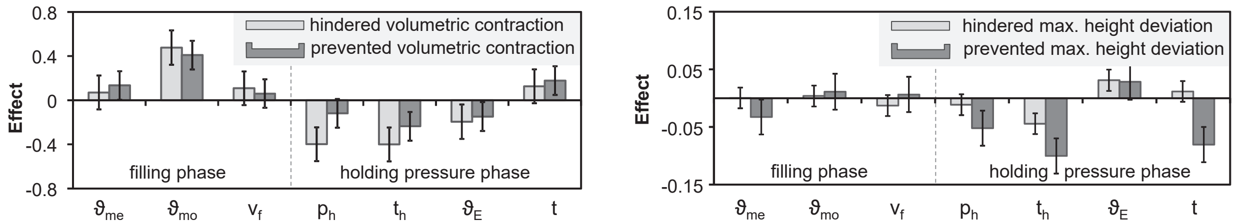
RESULTS AND DISCUSSION

Contraction

The contraction of injection molded plastic parts depends, as already mentioned, on a large number of influential factors. The effect analysis of the process parameters on the volumetric contraction of the two plates is shown in Fig. 4, a. The graph reads as follows: When changing the value of a parameter by 1, the dependent variable changes by the value of the respective effect coefficient. The total volumetric contraction of all process conditions consists of approx. 22–28 % longitudinal contraction, 18–24 % transversal contraction and 50–60 % thickness contraction. This means that the volumetric contraction is predominantly influenced by the thickness contraction. It is found that the parameters of the holding pressure phase – which affect the compensation of the volume contraction – have a significant influence on the volumetric contraction (Figure 4 a). The influence of the process parameters is nearly identical for both plate shapes. The hindered contraction is not fixated in the mold and therefore is influenced more strongly by the process parameters.

Warpage

The effect analysis of the maximum height deviation shows that it is influenced primarily by the parameters of the holding pressure phase, too (Figure 4 b). It can be assumed that the warpage mainly results from an insufficient volumetric compensation. The plastic melt freezes on the exterior walls immediately and forms a dimensionally stable frame. When the effect of holding pressure is insufficient (time and pressure), not enough plastic melt will flow into the mold cavity, resulting in the outer frame being deformed. Thus, increased warpage occurs. Unlike the findings on contraction presented above, it can be seen that even though volumetric contraction is similar, the effects on the height deviation of the two shapes differ clearly. The prevented contraction shows much higher process dependence than the hindered contraction. The plastic is additionally fixed longitudinally and transversally to the flow direction. This three-dimensional fixation of the plastic melt inside reacts more sensitively to the parameters of the holding pressure phase.



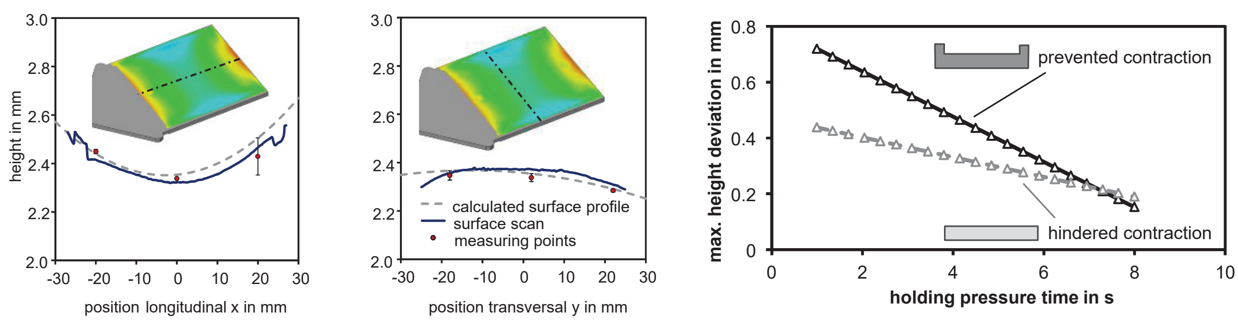
(a) (b)

FIGURE 4. Process-dependent effect analyses to the volumetric contraction (a) and max. height deviation (b).

A more detailed analysis of the height warpage is possible with the new measurement method. The simplified function (eq. 2) was used to evaluate the warpage. This function comprises only half as many factors as the surface function. This new method allows a more precise classification of the warpage. a describes a flexural warping, which is arched and can be mapped with a square function with high accuracy. On the other hand, b describes a torsional warping which is expressed by a twisted surface pattern. The final parameter c is a thickness value and depends completely on the thickness of the part.

The measuring points of the central process settings and the respective calculated surface profile according to eq. 2 as well the surface scan of the optical measuring system are shown in Fig. 5,a. It can be seen that the simplified calculated surface profile describes the surface course very well. For the following investigations, an average of each of the three curves in longitudinal and transversal direction of the flow was used.

The new measuring method is explained in detail for the example of the holding pressure time at the central process settings of the experimental design. Figure 5 b, shows the maximum height deviation of the two plate shape at different holding pressure times. With an increasing holding pressure the height deviation decreases due to an improved volumetric compensation.

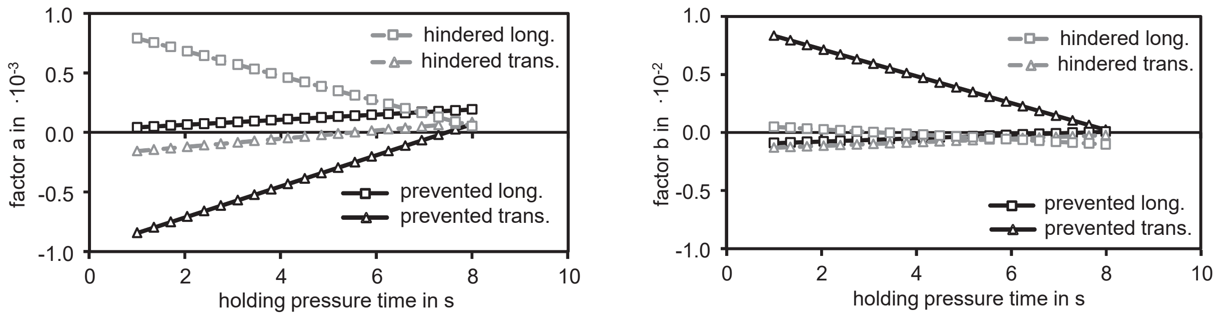


(a) (b)

FIGURE 5. Comparison of the used measurement methods (a). Influence of the holding pressure time on the max. height deviation (b).

The parameters a and b (eq. 2) allow a more detailed view on the type of warpage (Fig. 6). In the case of hindered contraction the b-values longitudinal and transversal to the flow direction are almost zero (Fig. 6, b). Also the a-value transversal to the flow direction is very low. So the height deviation is caused by a parabolic warping (a-value) along the flow length. It is shown that an increasing holding pressure time reduces the value of a. Also the longitudinal contraction decreases due to the increased holding pressure time.

In the case of the prevented contraction Fig. 6, b shows very high b-values. Additional high a-values are shown in Fig. 6, a. This means that a flexural warping and additional torsional warping appearances. The influence of the holding pressure time can be clearly demonstrated. Furthermore it can be seen that a is negative. That means that the deflection of the plate is not concave, like before, it is convex. This shows that the warping of the hindered contraction occurs in opposite direction to the prevented contraction. This example shows the difficulty of the predictability of warpage. Despite a comparable contraction in both cases, the warpage behaves contrarily in its amount, shape and direction.



(a) (b)

FIGURE 6. Influence of the holding pressure time on the factor a (a) and b (b).

CONCLUSIONS

Within this work it was shown that the holding pressure phase has a significant influence on the contraction and warpage behavior, especially of unfilled semi-crystalline plastics. Generally, a slight warpage results from a slight contraction. However the type of injection mold has to be taken into account.

Depending on the mold concept the contraction can occur as a free contraction, hindered contraction or prevented contraction. In addition to the dimensional deviations, the shape and orientation of the molded part can be altered by the warpage. By using a new measuring method it was shown for the first time that the warpage can be classified as flexural warping and torsional warping. The prevented contraction, in particular, results in an increased warpage which depends on the process parameters markedly. In general, warpage can only be reduced substantially by a sufficiently high volumetric compensation in the holding pressure phase.

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