MODELING OF TRANSVERSE MOLD SHRINKAGE FOR THE INJECTION MOLDED PARTS WITH A VARIABLE WALL THICKNESS

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Summary

The paper presents empirical research objected to build model of transverse mold shrinkage for HDPE molds with variable wall thickness. The model of fuzzy structure was elaborated. The model's independent variables are: nominal mold's wall thickness, distance from the gate, packing pressure (constant profile) and the profile of mold thickness along direction of polymer flow. Presented model may be used on the designing stage of mold's and runners' geometry. Due to a fuzzy structure, it may be easy altered for approximating other similar injection molding processes. It also seems to be very useful for process optimization in order to secure uniform distribution of shrinkage inside the whole mold by adjusting profile of packing pressure.

Keywords: injection molding, mold shrinkage, modeling, fuzzy logic

Modelowanie skurczu poprzecznego wyprasek wtryskowych o różnej grubości ścianki

Streszczenie

W pracy przedstawiono model skurczu poprzecznego wyprasek wtryskowych, których ścianki mają zróżnicowaną grubość. Zbudowano model o strukturze rozmytej uwzględniający czynniki: nominalny wymiar gniazda formującego, odległość od przewężki, ciśnienie docisku oraz profil grubości ścianki wypraski rozpatrywany wzdłuż drogi płynięcia tworzywa. Opracowany model skurczu jest pomocny na etapie projektowania geometrii wypraski i układu wlewowego formy. Model dzięki strukturze rozmytej jest łatwo modyfikowany i uogólniany na podobne procesy wtryskiwania. Stanowi także podstawę do optymalizacji procesu, zmierzającej do wyrównania wartości skurczu w całej objętości wypraski poprzez dobór ciśnienia w fazie docisku.

Słowa kluczowe: wtryskiwanie tworzyw, skurcz przetwórczy, modelowanie, logika rozmyta

1. The mold shrinkage in injection molding process

The mold shrinkage is a phenomenon of reducing injection molded parts' dimensions, caused by physical transformations of polymer during manufacturing process and afterward. Primary mold shrinkage of thermoplastics,

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which goes inside mould cavity, is caused mainly by reduction of polymer specific volume while cooling stage and by transformations of physical phases. Relaxation of internal stresses inside frozen mold is the reason of aftershrinkage. This process can last even for weeks after mold production.

The mold shrinkage is usually unwanted because it causes part's dimension fluctuations, depress of mold's surface and warpage. It should be considered just during designing stage of mold and mold geometry.

The value of shrinkage can be controlled during injection molding process mainly in a packing phase [1, 2]. During this stage, a reduction of polymer specific volume is compensated by inflow an extra amount of material into nonfrozen core of a mold. The packing is effective until the whole mold is frozen or the polymer in runner system is solidified. The value of mold shrinkage is also strongly related to a temperature of surface of mold cavity [1, 3-5].

So far, the satisfying casual model of mold shrinkage (mold dimensions) as a function of injection molding control variables is unreachable. The main reason of this fact is a very complex mechanism of shrinkage and its directional anizotrophy cased by nonuniform orientation of molecules and polymer chains.

The value of mold shrinkage may be forecasted using empirical relation p–v–T (pressure-specific volume-temperature) [6-8]. However, the practical application of this method is limited, mainly because of dynamic and three-dimensional distribution of polymer temperature and pressure inside frozening mold.

Quite good results in forecasting the mold shrinkage may be obtained using computer simulations [9-11]. These methods are commonly used for optimizing the injection molding conditions and on mould designing stages. But simulations are only sources of particular solutions, so the precise general relationship between shrinkage and process control variables is still unknown.

2. The goal of researches

The main goal of researches was designing the decision algorithms (rules for adjusting control variables of injection molding process), which allow equalizing the value of mold shrinkage inside the whole volume of molded part. The uniform distribution of shrinkage is more important than reduction of its value, because nonuniform shrinkage is the reason of mold deformations, whereas decreasing of linear dimensions may be forecasted and compensated on mold cavity designing stage.

The knowledge of relationship between mold shrinkage and main variables of process, as well as a mold geometry, is necessary for successful control of this unwanted phenomenon. The object of research described in this paper was elaboration of model of transverse mold shrinkage S_p for noncomplex HDPE mold as a function of nominal wall thickness d_n, distance from the gate x and packing pressure p_d:

$$S_p = f\,(d_n\,,\,x\,,\,p_d) \tag{1}$$

where transverse mold shrinkage was defined as ratio of difference of the mold cavity dimension d_n and real mold dimension d relative to d_n:

$$S_p = (d_n - d) \,/\, d_n * 100\% \tag{2}$$

Because of multidimensional character of formulated problem, complexity of shrinkage mechanism, as well as dynamic and spatial nature of physical phenomena, authors decided that model (1) should be built using experimental methods.

3. The object of study

The requested model of mold shrinkage (1) was elaborated for a set of thin-wall beams, which walls had intentionally profiled thickness (Tab. 1). The molds were manufactured from HDPE (Borealis BL2571). The polymer was injected into the mould cavity at the shorter side of beam, through the cuboid gate of 15 mm wide, 2 mm high and 2 mm long. The bottom wall of the mould cavity was designed as replaceable bar, which allowed manufacturing beams of different thickness profiles. The mold had two identical, symmetrically oriented cavities and runners (Fig. 1).

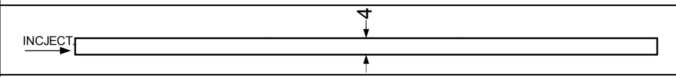
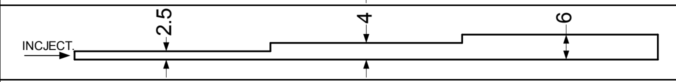
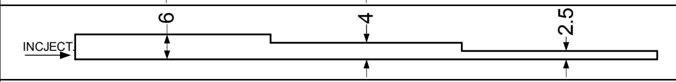
Beams of shapes specified in tab. 1 were chosen in order to explain the potential influence of thickness profile to distribution of shrinkage along direction of polymer flow (longer axis of beam).

The injection molding process was running on a single-screw machine Krauss Maffei KM 65-160 C1. Values of main control variables, unchanged during experiment, were presented in Tab. 2.

4. Empirical results

Four pieces of each type of beam from Tab. 1 were injected for a constant value of packing pressure p_d. The experiment was performed for $p_d = 15$, 30 and 50 MPa. Values of transverse mold shrinkage were measured in three points located along the axis of a beam (Tab. 1). These points correspond to centers of beam's segments of different thickness. The distance of measurements from the injection gate was accordingly: x = 25, 75 and 125mm.

Table 1. Nominal dimensions of injection molded beams for mold shrinkage study

<table>
<tr><th>Mark</th><th>Dimensions</th><th>Thickness profile</th></tr>
<tr><td>4–4–4</td><td>
</td><td>constant</td></tr>
<tr><td>2–4–6</td><td>
</td><td>ascending</td></tr>
<tr><td>6–4–2</td><td>
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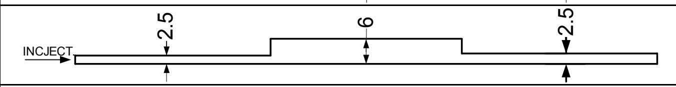
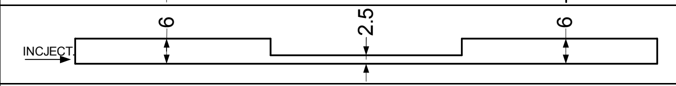
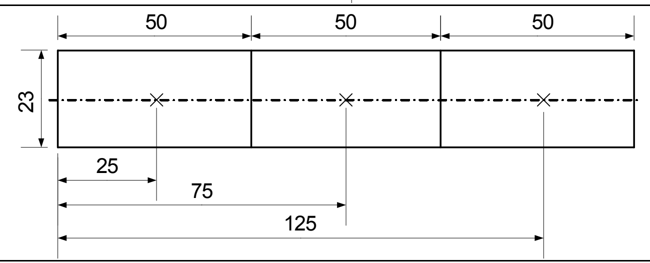
<tr><td>2–6–2</td><td>
</td><td>thin–thick–thin</td></tr>
<tr><td>6–2–6</td><td>
</td><td>thick–thin–thick</td></tr>
<tr><td></td><td>
</td><td>x marks indicate thickness measurement points</td></tr>
</table>

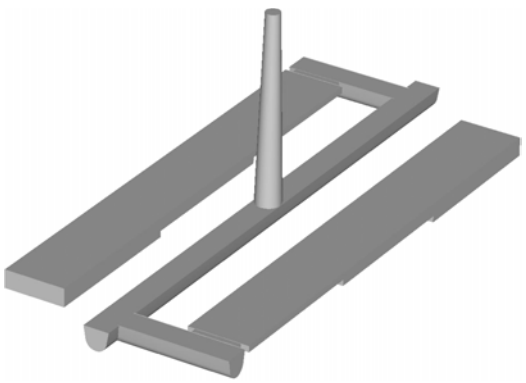


Fig. 1. Injection molded mold (model) for shrinkage study

Table 2. Values for main control variables of injection molding process in described experiment

Process variable	Value
Mold temperature T_f	60 ^oC
Injection (polymer) temperature T_t	230 ^oC
Injection speed v_w	21 cm^3/s
Packing pressure p_d	15; 30; 50 MPa
Packing time t_d	45 s
Cooling time t_{ch} (counts from the end of packing phase)	60 s
RPM of screw n_s	150 min^{-1}
Back pressure p_u	15 MPa

Thickness of mold's segments was determined by semiautomatic device with electronic transducers. The resolution of measurements was 0,001 mm. The results of mold shrinkage were presented on Fig. 2. A negative value of shrinkage means, that thickness of a molded beam was greater than

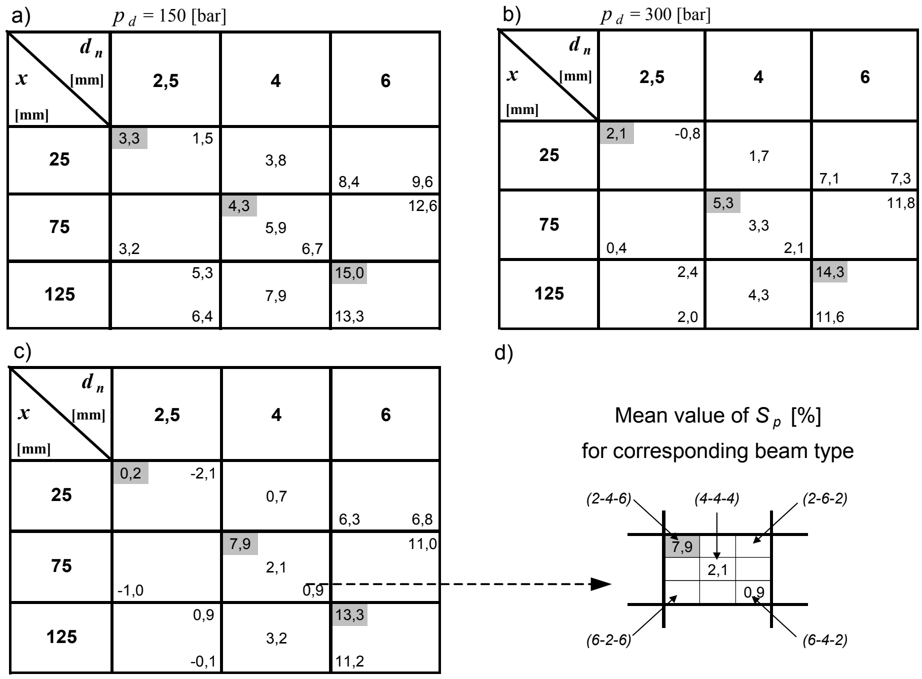


Fig. 2. Transverse mold shrinkage (mean values in %) against nominal wall thickness d_n and distance from the gate x for three values of packing pressure p_d : a) 150 MPa, b) 300 MPa, c) 500 MPa, d) explanation of results presentation

corresponding size of mold cavity – the “overpacking” phenomenon appeared, typical for high values of packing pressure.

Comparison of shrinkage values for beams of the same nominal thickness d_n and distance from gate x, but belonging to beams of different thickness profiles (inside each separate frame of tables in Fig. 2) shows, that shrinkage values are similar to others excluding case of beam of 2–4–6 profile (shaded values). Fig. 3 shows graphs for mean values of transverse mold shrinkage of corresponding beam’s segments for moldings of following thickness profiles: 2–6–2, 4–4–4, 6–2–6 and 6–4–2, i.e. excluding results for 2–4–6 beam.

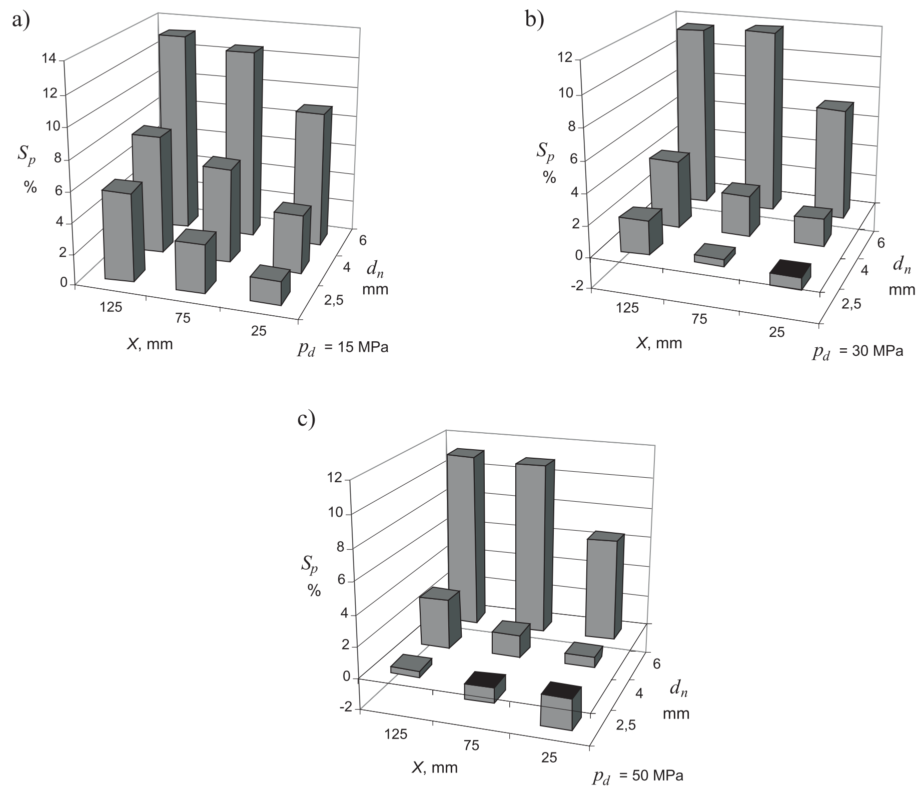


Fig. 3. Mean value of transverse mold shrinkage S_p for beams’ segments of following thickness profiles: 2–6–2, 4–4–4, 6–2–6 and 6–4–2, i.e. excluding results for 2–4–6 beam for various pressure p_d: a) 15 MPa, b) 30 MPa, c) 50 MPa

Fig. 4 presents mean values of shrinkage for 2–4–6 beam’s segments manufactured for three different packing pressure levels. This was the only case of beam thickness profile, where “nontypical” tendency of shrinkage increase against rising packing pressure inside middle segment (d_n = 4 mm) was observed.

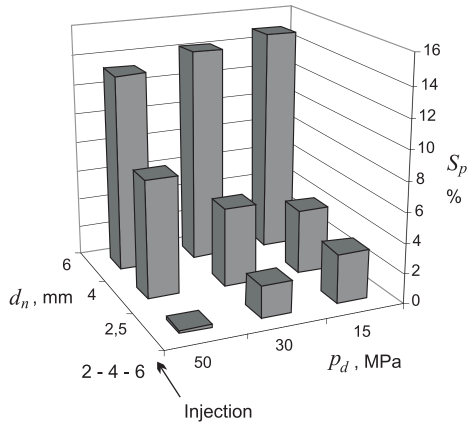


Fig. 4. Mean value of transverse mold shrinkage S_p for beam of ascending thickness profile 2–4–6

5. Discussion of the results

The analysis of experiment results presented on Fig. 3, i.e. excluding results for 2–4–6 beams, leads to the following conclusions:

- The transverse shrinkage is strongly related with thickness of beam segment. Increase of thickness causes considerable rise of shrinkage value.
- The value of mold shrinkage increases with a distance from the gate for a constant level of packing pressure (nonprofiled packing phase). In the case of the thickest mold (d_n = 6 mm) this relationship is valid only for the parts located nearest to the gate (approximately 1/3 of beam length).
- Increase of packing pressure causes decrease of transverse mold shrinkage for segments of small and medium thickness, regardless of a distance from the gate. The influence of packing pressure to shrinkage for the thickest segments is minimal.
- The separate discussion had to be done for the case of beam of rising thickness profile 2–4–6 (Fig. 4), were shrinkage increases against rising packing pressure inside middle segment of the beam. Probably, this effect may be explained by polymer flow inside nonfrozen core of the mold from middle segment towards the thickest segment. Simultaneously, the limited flow of frozening material through the least thick segment is not enough to compensate shrinkage inside middle segment. This phenomenon will be verified in computer simulations of injection molding process.

6. Transverse mold shrinkage model

Described experiment showed, that the values of shrinkage for molds of different thickness profile are similar. The exception is the case of beam with increasing thickness 2–4–6 (Fig. 2). Authors decided, that model for approximation the relationship (1) should include additional criterion – the thickness profile Δd_n along direction of polymer flow (i.e. along beam axis):

$$S_p\,(d_n\,, x\,, p_d\,, \Delta d_n) \tag{3}$$

where Δd_n is a difference between thickness of segment located the farthest from the gate and a thickness of segment beside the gate (e.g. for 2–4–6 molding the thickness profile is: Δd_n = 6 mm – 2.5 mm = 3.5 mm).

Fuzzy logic theory was applied in order to built required model (3). Fig. 5 and fig. 6 show the basic components of the model. For independent variables d_n, x, p_d three linguistic variables (LV) were defined: **S**mall, **M**edium, **B**ig. Profile of thickness Δd_n has following LV: **D**escending, **C**onstant, **A**scending. Membership functions are triangular. Fig. 5c presents LV and membership functions for independent variable S_p.

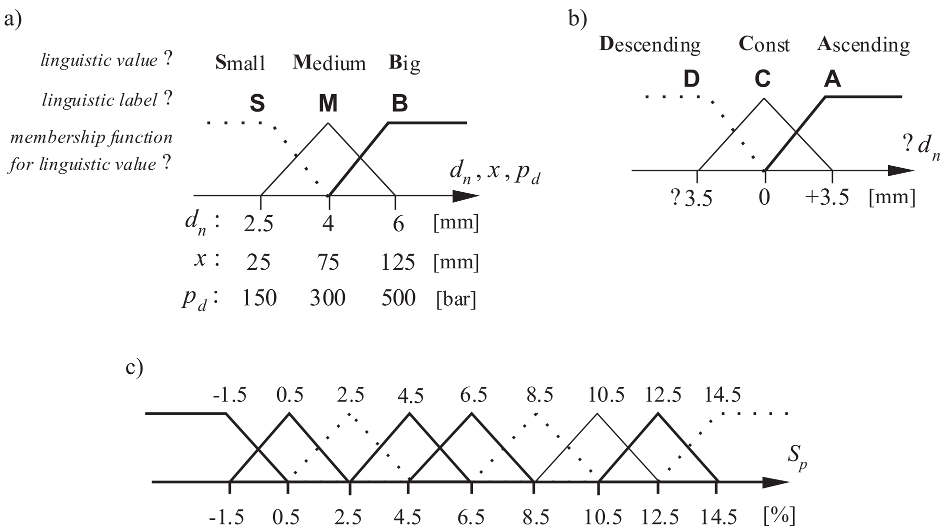


Fig. 5. Fuzzy variables of transverse mold shrinkage model $S_p\,(d_n\,, x\,, p_d\,, \Delta d_n)$:
a), b) independent variables, c) output variable

Fuzzy rules of the model have the following general form:

if d_n is ... **and** x is ... **and** p_d is ... **and** Δd_n is ... **then** S_p is ... ,

where dots in predicates (before “than”) should be replaced with linguistic variables of corresponding independent variables and “S_p is” (the successors) should be followed by LV for shrinkage. The complete set of model’s rules ($3 \times 3 \times 3 \times 3 = 81$ rules) is shown in graphical way on Fig. 6.

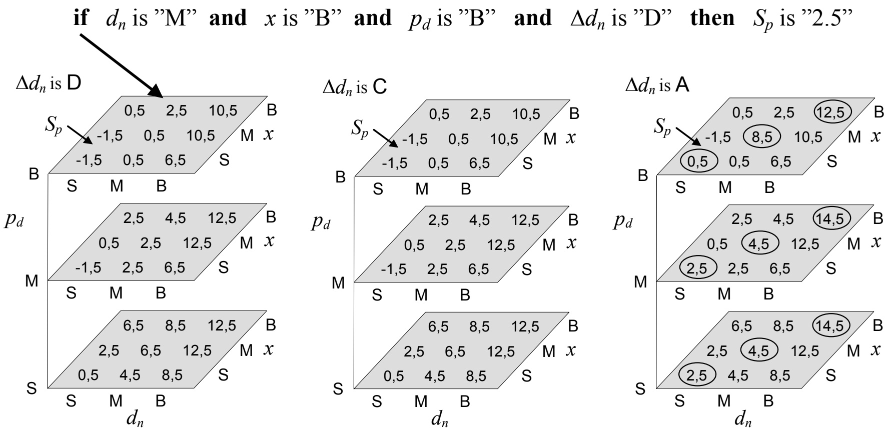


Fig. 6. Graphical presentation of complete set of fuzzy rules for model $S_p(d_n, x, p_d, \Delta d_n)$. Circles indicate linguistic labels in successors of rules, which were built based on empirical results for beam of ascending thickness profile 2–4–6 (Δd_n is **A**scending)

The Mamdani’s method of reasoning [12, 13] was applied (typical fuzzy logic controller) for described fuzzy model. Center of area (COA) defuzzyfication algorithms was used because of its good approximation features. All numeric procedures for the model implementation and reasoning mechanism were implemented in C programming language.

7. Conclusions

The empirical model of transverse mold shrinkage for HDPE molds with variable wall thickness was built. The model includes following independent variables: nominal wall thickness, distance from the gate, packing pressure (constant profile) and the profile of mold thickness along direction of polymer flow. Fuzzy structure of the model makes it more universal and allows altering it for other similar injection molding processes.

The described model may be used on the designing stage of mold's and runners' geometry. It also seems to be very useful for process optimization in order to secure a uniform distribution of shrinkage inside the whole mold by adjusting profile of packing pressure.

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