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Numerical Analysis of Injection Molding Of Polypropylene Parts with Glass Fibers

Dzanko Hajradinovic[1], Hazim Basic[2], Marin Petrovic[1]
[1]Department of Mechanics, Faculty of Mechanical Engineering, University of Sarajevo, Sarajevo, Bosnia and Herzegovina
[2]Department of Machinery Production Engineering, Faculty of Mechanical Engineering, University of Sarajevo, Sarajevo, Bosnia and Herzegovina
Corresponding Author: Dzanko Hajradinovic

Abstract: *This paper demonstrates the process of plastic flow during the injection molding of polypropylene with glass fibers. The work is performed on 3D model of requested work piece utilized in automotive industry by using CAD/CAE/CAM software packages (CATIA, VISI Vero, Autodesk Moldflow). The focus of research is aimed at the analysis how the geometry of the cavity will be filled during the injection process for one constitutive relation of the material. Constitutive relationship of the material used for the numerical simulation is outlined. The analysis includes two different parts. Results related to air traps, clamp force, deflection, fill time, pressure at the end of fill, weld lines and time to reach ejection temperature are presented.*
***Keywords** -CFD, constitutive model,injection molding, glass fiber, polypropylene*

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I. INTRODUCTION

Injection molding as a massive production process has expanded over the last couple of decades in the world's industrial production [1]. The most significant application is in food, construction and automotive industry. Injection molding is one of the most important and the most complex processes when using polymers. By polymer injection process, ready-made multi-functional products of extremely complex structure are obtained, made within close tolerance field. Such products may vary in sizes (from extremely small to large) and masses (from few grams to several dozens of kilograms) [2].

Injection mold design of polymers represents an enormous challenge for a designer in modern age. The designer is required to design a tool in a very short time that will be able to produce a large number of pieces (from 200 000 to 1 million), by using minimum expenditure of material, time, energy and money. Tools thereby should endure high temperatures and large loads, and products should be injected very fast, usable and with the demanded quality. The speed of injecting a part, or the quality in sense of weld lines, burning of the part, warpage, tolerances can be solved in the construction process of tool. The key guidelines for the design of the tool gives the mold flow analysis of the part. The importance of the mold flow analysis lies also in the prediction of the cooling time which is related to the number of parts that can be produced in one hour or one working day. Due to a large number of influential parameters, there still has not been developed a unique mathematical model that would encompass the entire process of injection molding. However, mathematical models do exist focusing on individual segments, such as: arrangement of pieces in molds, fluid flow, heat conduction, cost-effectiveness etc. Injection molding of polymers has reached its sudden expansion by the application of computers and CAD/CAE/CAM (**C**omputer-**A**ided **D**esign / **E**ngineering / **M**anufacturing) software packages, especially due to complexity of products [3-6]. This paper gives an insight how the numerical analysis of the material flow can lead to a better design of an injection molding tool for two different parts.

II. MODEL GEOMETRY AND MATERIAL PROPERTIES

3D models of requested work pieces, made out of PP GF 30 (**P**oly **P**ropylene with **G**lass **F**iber 30%) polymer, are shown in Figure 1. Models are referred as work piece #1 and work piece #2. Based on these models, geometry for injection molding of series from 250 000 to 1 000 000 pieces is analyzed. Considered work pieces are of relatively large size dimensions (~100x210x140 mm).

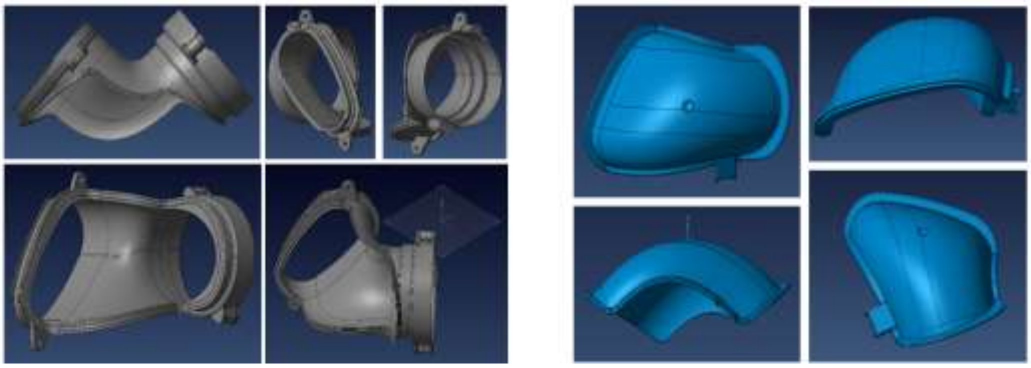


Figure 1: 3D model of work piece #1 (left) and #2 (right)

For the purpose of investigating the behavior of PP GF 30 material during the simulation of injection molding process, using numerical methods, it is important to know physical, mechanical and thermal properties of used polymers, which are given in Table 1.

Table 1: Characteristics of PP GF 30 for injection molding - Hostacom G3 U01 102297

Percentage of shrinkage of material (%)	Temperature of melting $T_{t,p}$ (℃)	Melt flow index MFI $\left(\frac{g}{10\,min}\right)$	Density ρ $\left(\frac{g}{cm^3}\right)$	Viscosity $\left(\frac{cm^3}{g}\right)$
0,7	170	14	1.12	119
Mold temperature (℃)	Injection rate	Nozzle Temperature (℃)	Thermal conductance $\left(\frac{W}{Km}\right)$	Specific heat $\left(\frac{J}{g \cdot K}\right)$
30 - 70	Slow	240	0.3	1.41

III. Mathematical Model

To simulate a behavior of the material related to the properties and type of simulation, different constitutive relationships are used. The basic constitutive relationship for polymer materials is the relationship of the generalized Newtonian fluid. This relationship is given in equation (1), representing the Newton viscous force law:

$$\boldsymbol{\tau} = \eta \cdot \dot{\boldsymbol{\gamma}} + (\lambda \nabla \cdot \mathbf{u})\mathbf{I} \tag{1}$$

where η is a dynamic viscosity, $\dot{\boldsymbol{\gamma}}$ is a rate of deformation tensor, I is unit tensor and λ is a dilatational viscosity. The rate of deformation tensor is given by equation (2) as follows:

$$\dot{\boldsymbol{\gamma}} = 2\dot{\boldsymbol{\varepsilon}} = \nabla u + (\nabla u)^T = \begin{bmatrix} 2\frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} & \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} & 2\frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \\ \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} & \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} & 2\frac{\partial w}{\partial z} \end{bmatrix} \tag{2}$$

For different materials in the constitutive relationship only the dynamic viscosity as a property has different models.

For material flow of polymers during the injection process an often used model is the Cross model. This model is given by the following equation:

$$\eta = \frac{\eta_0}{1 + \left(\frac{\eta_0 |\dot{\gamma}|}{\tau^*}\right)^{1-\bar{n}}} \tag{3}$$

where τ^* is a shear stress at the transition between Newtonian and power law and η_0 is Newtonian zero viscosity.

Combination of this model shown in the equation (3) and the WLF model shown in equation (4) gives the WLF Cross model, which is the widest used model in injection molding. It is given by equation (5) [1]:

$$\eta_0 = D_1 \exp\left(\frac{-A_1(T - (D_2 + D_3 P))}{A_2 + T - D_2}\right) \tag{4}$$

The WLF model is a zero shear viscosity model and it can more exactly reflect the variation of melt viscosity with temperature and pressure.

$$\eta = \frac{D_1 \exp\left(\frac{-A_1(T-(D_2+D_3P))}{A_2+T-D_2}\right)}{1+\left(\frac{D_1 \exp\left(\frac{-A_1(T-(D_2+D_3P))}{A_2+T-D_2}\right)|\dot{\gamma}|}{\tau^*}\right)^{1-\bar{n}}} \quad (5)$$

where A_1,A_2,D_1,D_2 and D_3 are material characteristics. Very often used model in injection molding can also be Arrhenius formula, which is outside of scope of this paper.

Relations describing the motion of the fluid in the cavity related to the thermodynamics of the fluid and the injection process are the continuity, momentum and energy equations given by equations (6), (7) and (8) as follows [1]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (6)$$

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = \nabla \cdot (\sigma) + \rho f \quad (7)$$

$$\rho c \frac{\partial T}{\partial t} + c\nabla \cdot (\rho T u) = \nabla \cdot (k \cdot \nabla T) + \tau_{xx}\frac{\partial u}{\partial x} + \\ + \tau_{yx}\frac{\partial u}{\partial y} + \tau_{zx}\frac{\partial u}{\partial z} + \tau_{xy}\frac{\partial v}{\partial x} + \tau_{yy}\frac{\partial v}{\partial y} + \tau_{zy}\frac{\partial v}{\partial z} + \tau_{zx}\frac{\partial w}{\partial x} + \\ + \tau_{zx}\frac{\partial w}{\partial y} + \tau_{zz}\frac{\partial w}{\partial z} + S_i \quad (8)$$

IV. Results And Discussion

Injection molding of polymers is extremely complex process due to mutual activity of a large number of parameters (temperature, volume flow, pressure etc)[9-11]. Therefore, it is almost impossible to investigate these problems by analytical analysis of the behavior of polymers during and after injection. By the occurrence of qualitative computers and software packages supporting numerical simulations, solution of this problem has become significantly simpler.

In this paper, by means of numerical analysis, problems of flow of PP GF30 have been solved using CFD (**C**omputational **F**luid **D**ynamics) method and gathered appropriate results. Autodesk Moldflow software package [12] was used for this analysis, including the following modules: Design Adviser, Gate Location, Molding Window, Fill + Pack, Runner Adviser & Runner Balance, Cool and Warp.

4.1 Flow analysis

This part of paper shows the filling and flow behavior of the material in the cavity of the two parts. Results of the analysis are shown in Figure 2 and Figure 3.

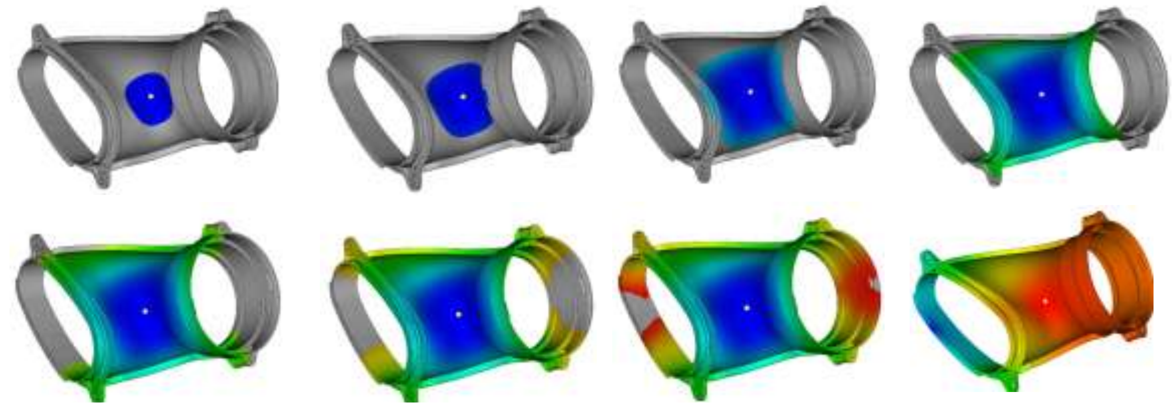
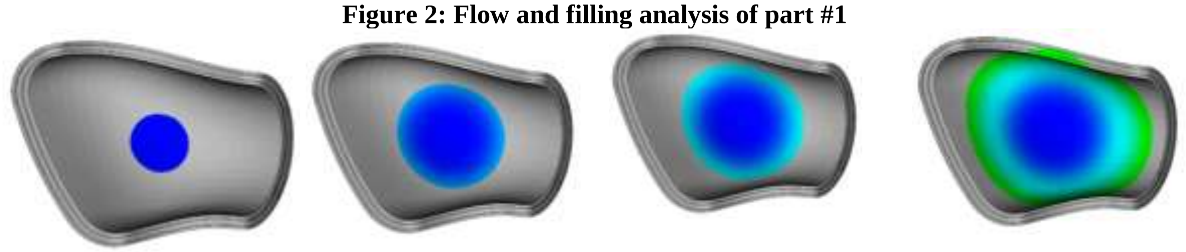


Figure 2: Flow and filling analysis of part #1



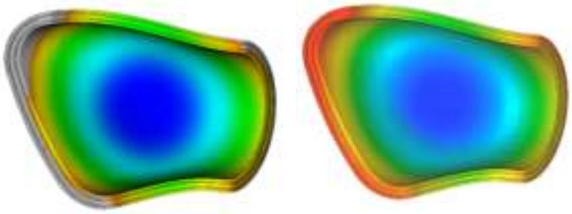


Figure 3: Flow and filling analysis of part #2

It is noticeable from performed modelling that the flow and filling analysis return satisfactory results for the interaction of polypropylene parts with glass fibers and materials used for molds.

4.2 Ejection time

This part of paper shows a time length needed to reach ejection for analyzed parts. Results of the analysis are shown in Figure 4.

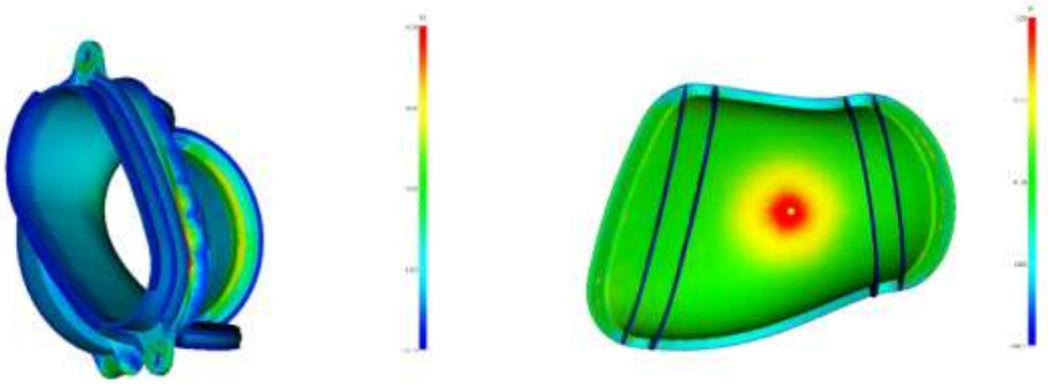


Figure 4: Time to reach ejection of parts #1 (left) and #2 (right)

The time needed to reach ejection amounts to 33.25 seconds for part #1 and 12.25 seconds for part #2. The time for the second part is shorter, which can be expected because of the volume and dimension of this part. These findings have significant importance as they offer information about the parts productivity.

4.3 Welding lines

Weld lines are weak spots in the integrity of parts due to structural load. This part of paper shows weld lines for analyzed parts. Results of the analysis are shown in Figure 5.

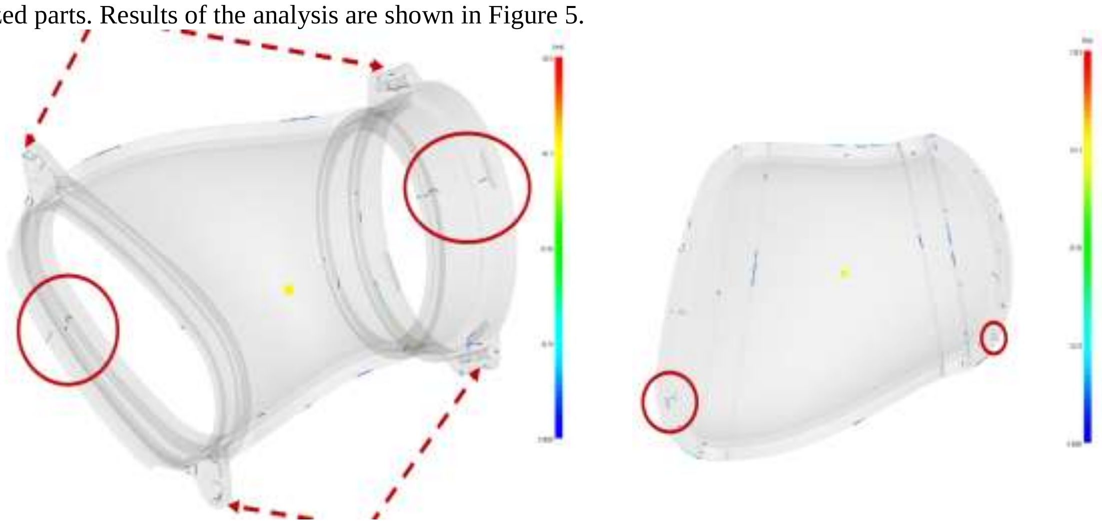
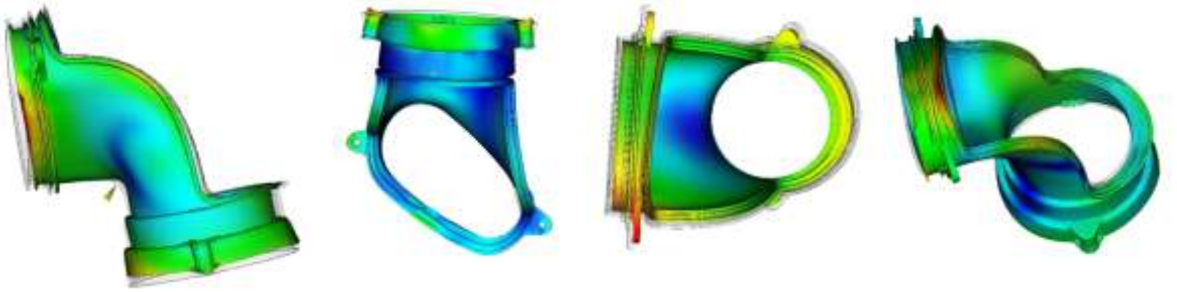


Figure 5: Weld lines of parts #1 (left) and #2 (right)

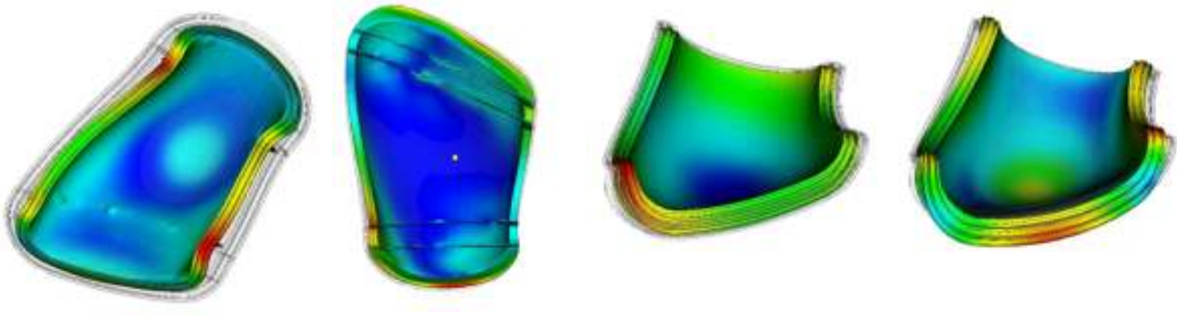
From Figure 5 it is possible to determine position where the material forms the weld line after separation of flow. This is quite significant information and needs to be taken into account during parts construction depending on final usage of the parts and their function within an assembly. Being weak spots in the integrity, these zones are not permitted to be subjected to high structural loads.

4.4 Deformation and warpage parts

Deflection and warpage of the parts in the mold design process are important to be considered, so that the necessary tolerances of the part are reached. This part of paper shows a deformation and warpage of the two parts. Results of the analysis are shown in Figure 6.



a) b) c) d)



e) f) g) h)

Figure 6: Deformation and warpage of parts #1 (a, b, c, d) and #2 (e, f, g, h)

Figure 6 a) and e) shows all effects of the deflection of part #1 and part #2, whereas b) and f) show the corner effects. Figure 6 c) and g) shows the differential shrinkage, whereas d) and h) show orientation effects on deflection of two analyzed parts. In order to achieve necessary tolerances of the part, heating up the mold in observed target regions or cooling in other regions is advisable, optimizing the part after the first tryout of the mold.

4.5 Air traps

This part of paper shows air traps of two analyzed parts. Results of the analysis are shown in Figure 7.

a) b) c)

Figure 7: Air traps of parts #1 (a, b) and #2 (c)

Potential air traps of part #1 are shown in Figure 7 a) and b), whereas Figure 7 c) shows potential air traps of part #2. From this analysis it is evident that all air traps lie on the separation line of the part. It is therefore advisable for the tool designer to make air ventilation close to these regions.

4.6 Clamping force

This part of paper shows the magnitude of the clamping force needed to inject analyzed parts. Results of the analysis are shown in Figure 8.

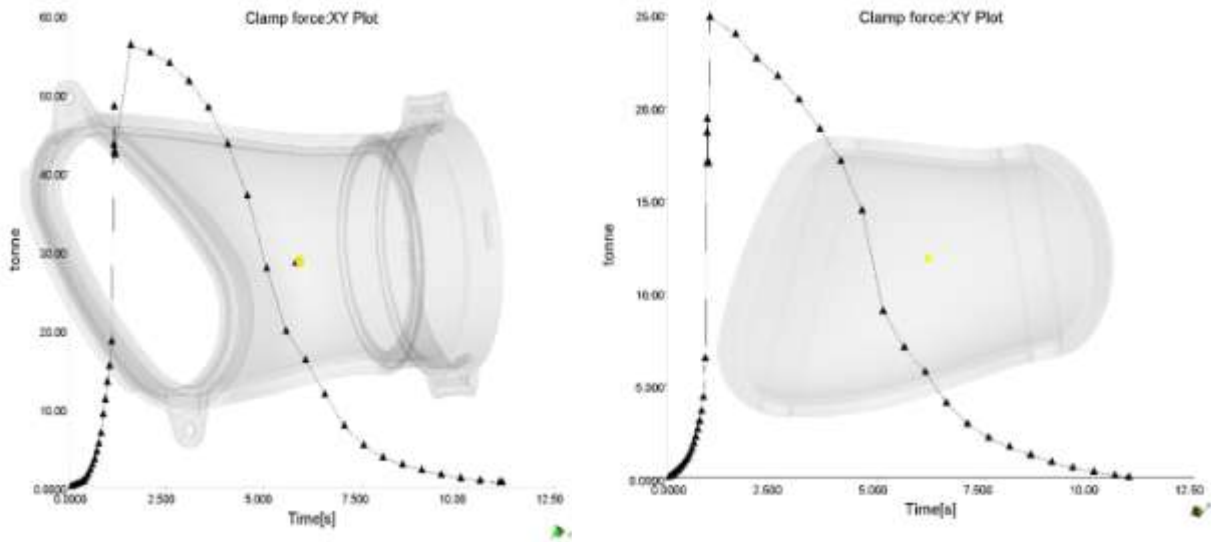


Figure 8: Clamping force for parts #1 and #2

Figure 8 indicates that the necessary clamping force for part #1 is approximately 57 tones and for part #2 approximately 25 tones. Therefore, in order to inject both parts, the lowest necessary clamping force amounts to 82 tones.

V. Conclusions

Designing of tools in practice is mostly based on experience of a designer and many measures are practically selected without considering mathematical models. Results obtained by the analyses performed in this paper confirmed close relation between experiential decisions on one side and mathematical models and numerical simulations on the other side. Mathematical models are being in larger scope implemented in solvers of different numerical analyses software packages. Although such packages are relatively simple to use, interpretation of obtained results has become one of the most demanding and the most complex tasks for modern designers. Therefore, the aim of this paper was to demonstrate results obtained by numerical analysis in relation to the decision made when choosing the injection machine and designing the injection mold. The following conclusions may be drawn based on the findings from investigation performed:

- Flow and filling analysis proved satisfactory results for the interaction of polypropylene parts with glass fibers and materials used for molds;
- Ejection time analysis results have shown significant importance offering information about the parts productivity, showing filling up the mold within the time period satisfactory for the production. Cooling period for part #1 was found to be shorter than for part #2. This information can be used to decide if the two parts will be injected separately in two molds or together in the same mold. If one mold injection is selected, the second part will be at a lower temperature than the first part, which should be considered due to the potential larger deflection or warpage of the part;
- Analysis have shown positions of the weld lines after separation of flow, which is quite significant information and needs to be taken into account during parts construction. Depending on final usage of the parts and their function within an assembly, weld line zones as weak spots in the integrity are not permitted to be subjected to high structural loads;
- Deflection and warpage of the parts in the mold design process are important to be considered, so that the necessary tolerances of the part are reached. This can be done by heating up the mold in target regions or cooling in other regions, optimizing the part after the first tryout of the mold;
- Analysis has revealed that all air traps lie on the separation line of the part and it is therefore advisable for the tool designer to make air ventilation close to these regions;
- Clamping force offers the information about the type of injection machine needed to inject the parts. This information is related also to dimensions of the parts and future dimensions of the mold.

Based on the findings from this paper, future work shell concentrate to the specific design segments of the mold. Different constitutive material models can be used to compare their influence on currently obtained results.

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