Improving the quality of the molded polymeric parts by reducing the residual stress

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Abstract: - The paper presents a method to increase the quality of molded polymeric parts using CAE technology by reducing the residual stresses. In order to find the best parameters of the molding process which lead to a minimum level of the residual stresses several studies were performed. Parts made of polymeric materials may be also simulated in order to minimize the residual stresses. We consider that a high degree of confidence of the simulating software results may be achieved only if they are cross-checked with the results of some experimental studies. Computer Aided Engineering analysis provides insights useful in designing parts, molds and molding processes. Using this method we can obtain information such as polymer melt filling patterns, weld line and air trap locations, required injection pressure and clamp tonnage, fiber orientation, cycle time, the final part shape and deformation and mechanical properties of molded parts. CAE technology helps us save time, money and raw material, as well as cuts scrap, reduces the rejection rate, improves product quality and ensures a smaller time-to-market. It is a useful method to approach most of the molding problems.

Key-Words: - Polymeric material, molded parts, CAE analysis, residual stress, experiment, numerical model

1 Introduction

Thermoplastics are usually processed in the molten state. Molten polymers have very high viscosity values and present shear thinning behavior. As the rate of shearing increases, the viscosity decreases, due to alignments and disentanglements of the long molecular chains. The viscosity also decreases with increasing temperature. In addition to the viscous behavior, molten polymers exhibit elasticity. These include stress relaxation and normal stress differences. Slow stress relaxation is responsible for frozen in stresses in injection molded and extruded products. The normal stress differences are responsible for some flow instabilities during processing.
The quality of the final part is a complex concept which may be approached from different points of view. Research offers the instruments employed to define the best strategies for the effective production of molded polymers: materials and parameters of the molding process. Nowadays science offers both numerical and experimental methods to investigate the phenomena related to the molding process. Interdisciplinary approaches which use the results of both experimental and simulation results are the most accurate methods of investigation.
CAE - Computer Aided Engineering - was widely adopted and proved to be an important tool for part and mold designers and for other engineering studies, [4]. Design and process variables are evaluated beforehand using computer simulation and experimental data. This way, potential defects are identified and eliminated in the design phase. Moreover, design can be refined and even optimized according to the simulation results. Thanks to the highly efficient proposed methodology, a typical integrated 3D analysis of part with hundred thousand elements can usually be finished on an ordinary PC within one day. Programs like Mold Flow offers powerful tools to simulate the molding process in the free surface approximation, [1].
In this paper, a numerical model based on Finite Element Method is presented, model which was successfully applied in an injection molding filling simulation.

2 Numerical simulation

According to Shoemaker, numerical simulations have an important role in the injection molding process, as in several other scientific problems. Commercial software, such as MoldFlow offers powerful tools to simulate the molding process based on the free surface approximation. They provide a quantitative description of the part behavior, the user being allowed to customize the polymer properties. Thus, MoldFlow Plastics Insight MPI/Flow simulates the filling and packing phases of the injection molding process to predict the flow behavior of thermoplastic melts, so that the high quality final products may be manufactured under effective

conditions. The program allows the user to choose the best parameters of the molding process.
The proper polymeric material and molding parameters, such as injection pressure, injection points and locations of air evacuation which influence the quality of the final object have an important role in the injection molding process. The numerical simulations employed to validate very expensive mold designs also eliminate risks and avoid losses.
The polymeric part geometry discretization is presented in figure 1, the corresponding injection mold having two cavities. The characteristics of the discretization mesh are presented in table 1.
The material is an acrylonitrile butadiene styrene (ABS) produced by Daicel Chemical Industry, CevianV510. Its physical characteristics were previously measured using the strain gage technology.

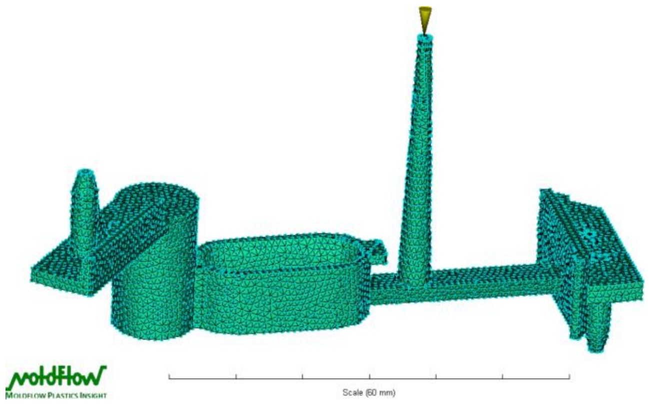


Fig. 1 The mesh of the polymeric parts

Table 1 The characteristics of the discretization model

Total volume of the part [cm^3]	5.37046
Total aria of the part [cm^2]	62.4348
Number of laminae across thickness	20
Melt temperature convergence tolerance [^oC]	0,2
Mold - melt heat transfer coefficient [$W/m^2 \cdot {}^oC$]	25000

The injection simulation was done using Mold Flow Plastics Insight software, which allows us to determine a specific variation parameter during the ongoing process.
For the best injection process, the following parameters were chosen:
- maximum machine clamp force, $F_i = 7{,}0002 \cdot 10^3$ tonne;
- maximum volume filled, $V_i = 2 \cdot 10^4 cm^3$;
- maximum injection pressure, $P_{i\max} = 180 MPa$;
- maximum machine injection rate, $Q_{i\max} = 5 \cdot 10^3 cm^3/s$;
- machine hydraulic response time, $t_{rh} = 1 \cdot 10^{-2} s$.

3 Case study - Application of the results for the finite element model to a mechanical part

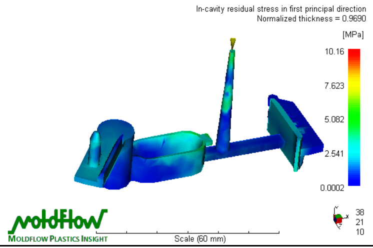
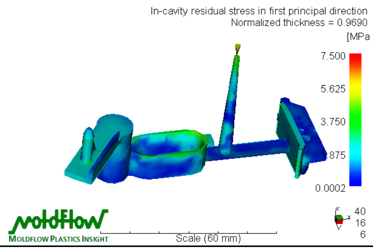
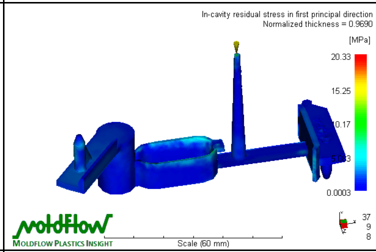
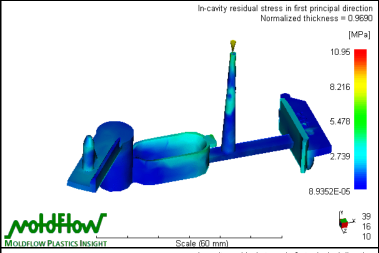
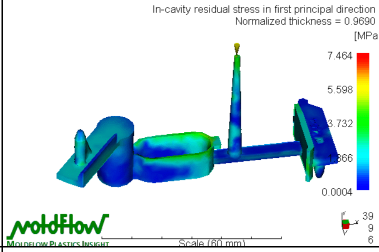
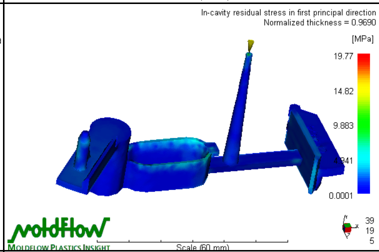
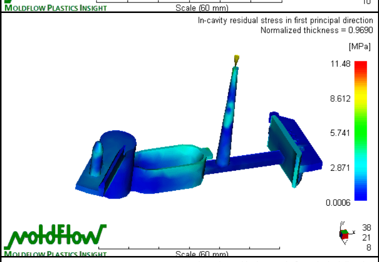
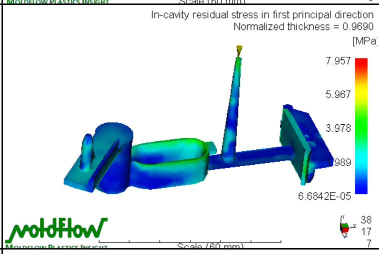
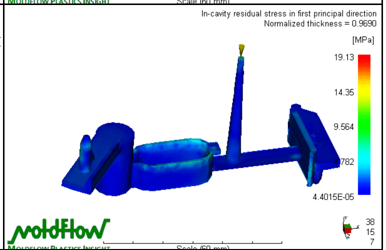
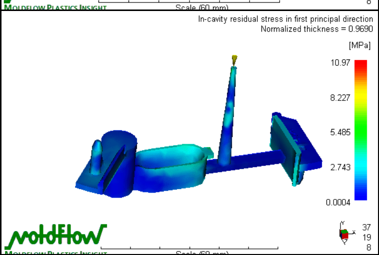
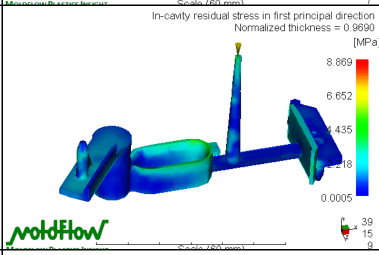
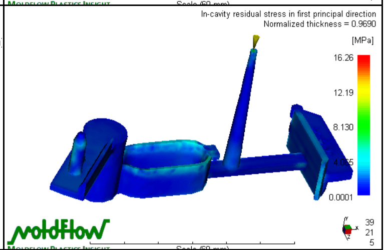
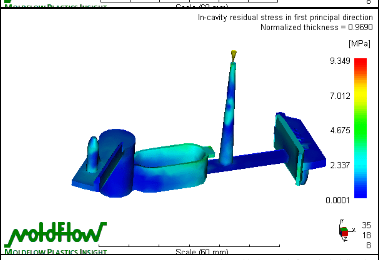
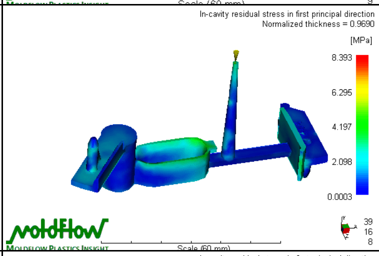
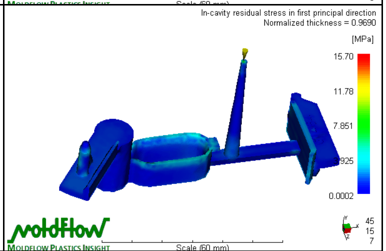
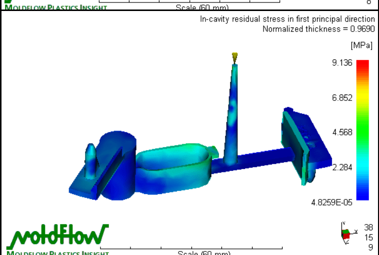
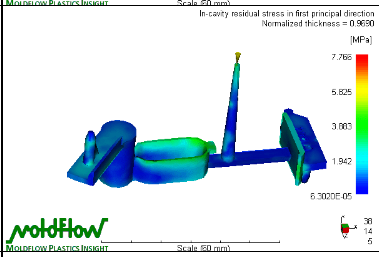
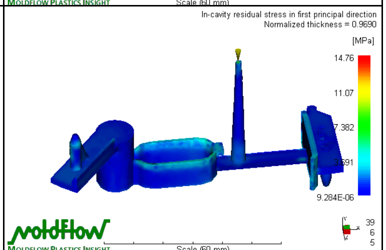
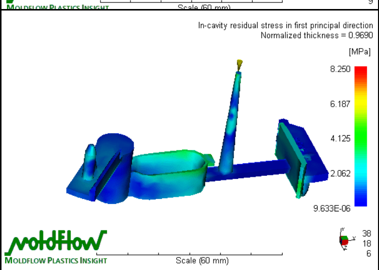
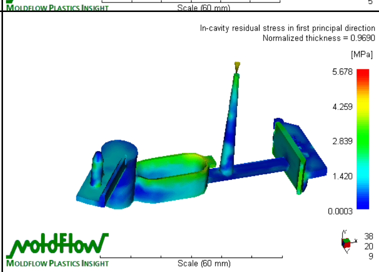
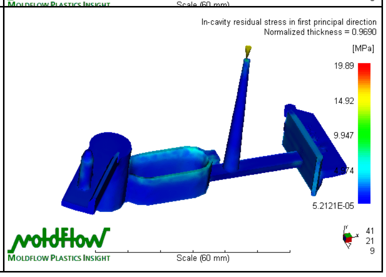
Moldflow Plastics Insight can precisely estimate the cycle time, pressure and volume. This research method offers the following information: polymer melt filling patterns, weld line and air trap locations, required injection pressure and clamp tonnage, fiber orientation, cycle time, final part shape and deformation, and mechanical properties of molded parts.
While the part is still constrained in the mold cavity, the internal stress that accumulates during solidification is referred to as in-cavity residual stress. This in-cavity residual stress is the cause of the post-ejection shrinkage and warping of the part.
The optimum simulation offers the best parameters according to the most suitable polymeric material. This method predicts the internal stress development during molding process, leading to improved molding technological parameters.
A comparative study was performed by simulating molding for several melting temperatures, the values of the stresses being presented in table 2.

Table 2 The parameters of injection process

	Numerical simulation						
	1	2	3	**4**	5	6	7
Polymeric material	ABS	ABS	ABS	**ABS**	ABS	ABS	ABS
Mold temperature, [^oC]	50	50	50	**50**	50	50	50
Melt temperature, [^oC]	200	210	220	**230**	240	250	260
Fill time, [s] mesh=3	2.589	2.433	1.965	**1.734**	1.508	1.391	1.280
Fill time, [s] mesh=2	2.334	2.430	2.078	**1.736**	1.508	1.396	1.285
Fill time, [s] mesh=1	2.365	2.328	1.973	**1.738**	1.513	1.289	2.947

The results of the simulation, presented in table 3, are compared one to the other in order to notice the variation of the residual stresses with respect to melting temperature and the mesh size.

Table 3 The residual stresses for the different sizes of the mesh and for different melt temperatures

Melt temp.	$\Delta x = 3\,mm$	$\Delta x = 2\,mm$	$\Delta x = 1\,mm$
T=200°C			
T=210°C			
T=220°C			
T=230°C			
T=240°C			
T=250°C			
T=260°C			

This method allows us to check the confidence of fill, the fill time, the pressure drop result, the injection pressure, the flow front temperature, the weld lines and the air traps. Figure 2 presents the main regions of the part. Initially zone E was not considered, being considered a local area of a larger region, but the specific values of the residual stresses are high in this area, so it must be identified separately. Table 4 presents the value of the overall residual stress for each region and for each melting temperature.

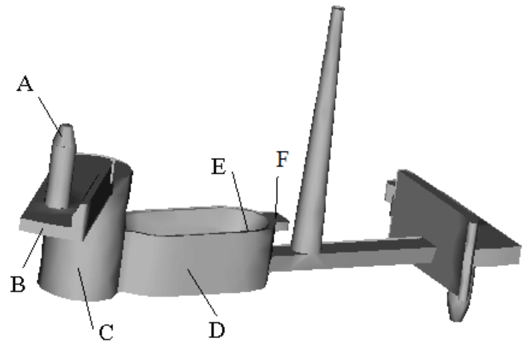


Fig. 2 Identifying the regions of the part

Table 4 The maximum residual stresses in the regions of the part

Polymeric material	Mesh	Numerical simulation	Melting temperature, [^oC]	Region					
				A	B	C	D	E	F
ABS	3	1	200	2.329	1.906	0.78	1.482	4.023	3.176
		2	210	2.054	1.598	0.636	1.14	3.88	2.967
		3	220	1.675	1.397	0.44	1.107	3.589	2.632
		4	**230**	**1.532**	**1.269**	**0.323**	**0.958**	**3.501**	**2.514**
		5	240	1.753	1.364	0.581	0.974	3.311	2.532
		6	250	1.813	1.252	0.784	1.332	3.616	2.955
		7	260	1.891	1.85	0.825	1.547	3.629	3.109
ABS	2	1	200	2.032	1.719	0.781	1.407	3.967	2.969
		2	210	1.711	1.41	0.467	1.189	3.88	2.955
		3	220	1.492	1.392	0.397	1.16	3.513	2.755
		4	**230**	**1.328**	**1.236**	**0.318**	**0.924**	**3.411**	**2.402**
		5	240	1.574	1.224	0.525	1.124	3.672	2.623
		6	250	1.456	1.133	0.685	1.133	3.721	2.907
		7	260	1.422	1.765	0.818	1.302	3.904	2.943
ABS	1	1	200	1.896	1.604	0.729	1.313	3.938	2.871
		2	210	1.625	1.375	0.375	1.125	3.875	2.775
		3	220	1.375	1.125	0.375	1.083	3.417	2.417
		4	**230**	**1.225**	**1.016**	**0.308**	**0.875**	**3.125**	**2.071**
		5	240	1.375	1.125	0.375	0.876	3.375	2.125
		6	250	1.395	1.128	0.625	0.925	3.575	2.375
		7	260	1.417	1.75	0.81	1.083	3.583	2.75

4 Results and discussion

In order to analyze the data, we must draw the residual stress with respect to the temperature melt for each region, the diagrams being presented in figure 3, [2].

According to the figures 2, 3 and table 4, one can notice the following connections:

• the part has no symmetry, so we cannot apply considerations subsequent to this property, regarding this phenomena (filling, cooling, residual stress apparition);

• in the analysis we shall consider maximum analytical values displayed by the program at the upmost boundary of the range of stresses (table 3); these values are computed on theoretical bases and they are not large enough to be significant for the study of the part; having a low degree of relevancy for the regions of the part, the analysis is focused on the maximum residual stresses of the regions previously identified in figure 3 where significant higher values can be found;

• region D is the largest region of the part and it is the first region filled with melt; the range of stresses in this region is 0.875 up to 1.547 MPa; the stresses have no significant variations with respect to the melting temperature; in this area the largest stresses are in the neighborhood of region E, but the effective values are not large enough to be considered;

• region E is located between region F and D; the largest values of the residual stresses are recorded in this region, the range being from 3.125 MPa up to 4.023 MPa;

• region F has the smallest volume; the range of stresses in this region is 2.071 MPa up to 3.176 MPa;

• region C is connecting region D to regions B and A; the range of stresses is 0.308 MPa up to 0.825 MPa; these values are the smallest in comparison with the other regions; for all the input data considered in the study, we may notice that stresses have no large variations in this region;

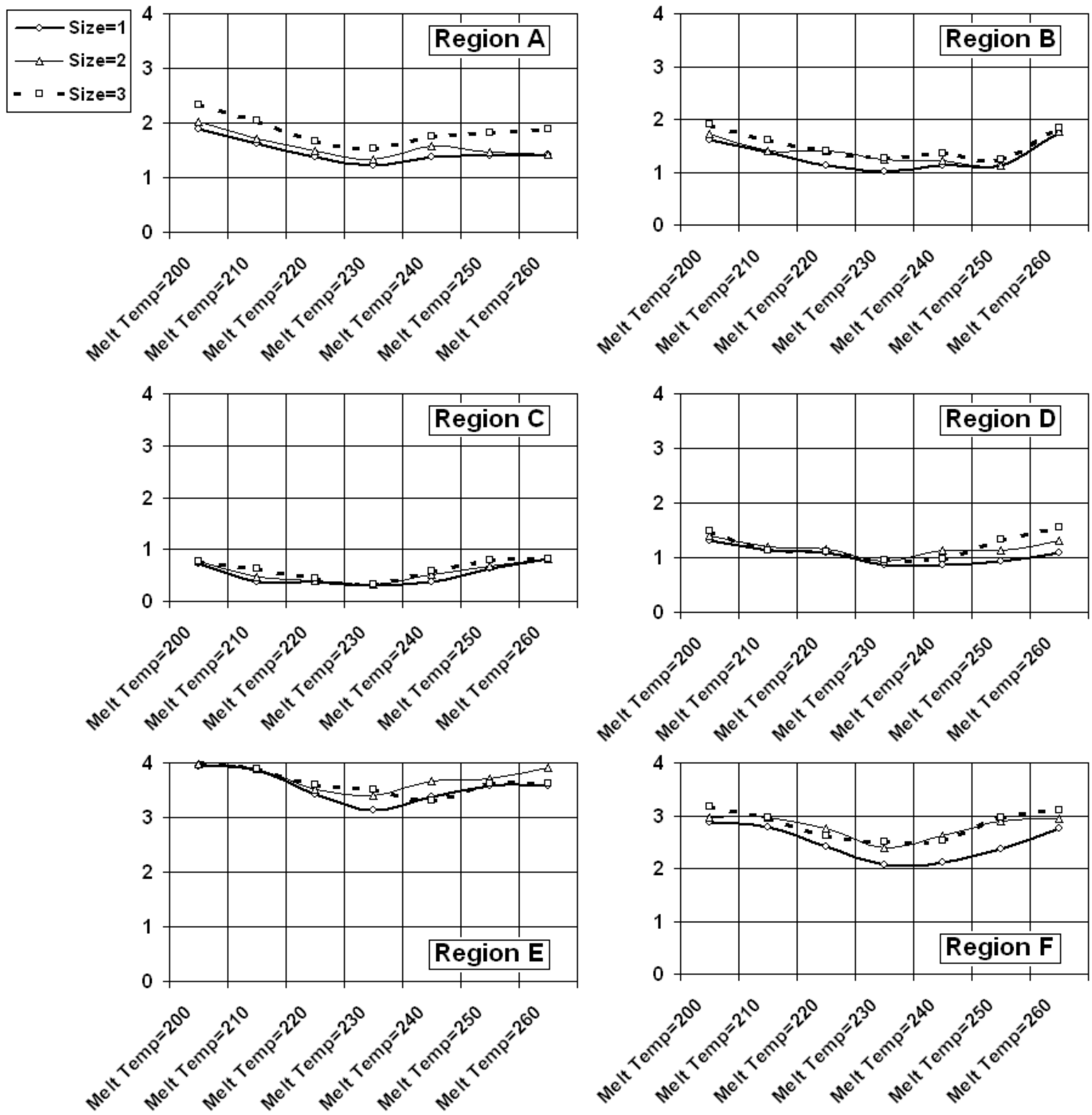


Fig. 3 Variation of the overall stresses for each region of the part, with respect to the melting temperature

• region B is located between region C and region A; the range of the stresses is 1.016 MPa up to 1.906 MPa; the stresses have no large variations in this region;
• having a remote location, region A is the last region filled with melt; one can notice variations of the residual stresses; the range of the stresses is 1.225 MPa up to 2.329 MPa; the maximum values of the stresses are noticed to the upmost end of the region and at the lowest end, which is at the boundary of region B.

Based on previous remarks, we can derive the following general conclusion:
• overall the residual level of stresses is low, hence from this point of view there is no need for a better design;
• every region has a specific range of stress values an analysis for each region was therefore necessary;
• in each region the range of values of the residual stresses is narrow; thence the results are convergent, furthermore, we have a stable and accurate model;

• for the extreme values of the melt 200oC and 260oC, especially for 200oC, we record the largest values of the stresses, so according to our analysis the technological conditions may be properly adjusted;
• according to figure 3, the larger the size of the mesh, the larger resulting stresses; even the running time of the application necessary to solve a version with a small size of the mesh is significantly larger, it is paramount to have an overview onto the state of stresses and the variation of the stresses for all the sizes of the mesh.

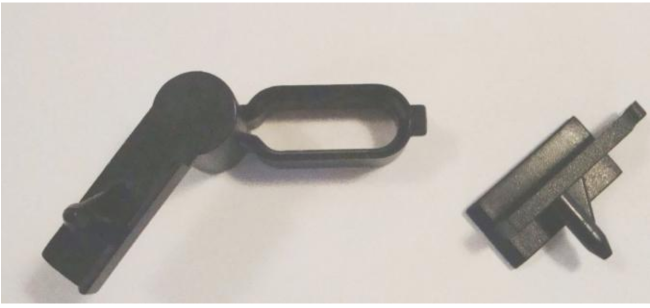


Fig.4 ABS molded parts

In order to have accurate results and significant conclusions, the part was studied using different mesh sizes and under several technological conditions. The results of the study consist not only in the scientific and technological information for a given part, but also of the methodology, [3], which may be applied in practical conditions for a wide range of parts manufactured from the same material and for various technological constraints. In this way, the decision making process to be performed in an upper level can rely on accurate information.

5 Conclusion

Most of the stresses in plastic parts occur during the compensation phase. By controlling flow, melt temperature and minimizing the residual stresses, it is possible to design high quality parts. The study presented in the paper uses dedicated CAE software, Mold Flow Plastics Insight.
The results of the study are accurate and can be used for further research, such as:
• study of the stresses in running conditions, the part being loaded with nominal mechanical and thermal loads;
• study of the sensitivity of the finite element model with respect to various variables;
• study of the part for a mold having a new location of the runner system;
• study regarding the necessity to perform annealing or quenching operations of the part;
• optimization of the assembly which uses the part.

6 Acknowledgement

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The mold and the mold model (fig 4) were designed and manufactured at Matris Metal Plast, Bucharest.

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