COMPUTER ANALYSIS OF THE TECHNOLOGICAL PROCESS OF A SELECTED COMPONENT'S PLASTIC INJECTION

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DOI: 10.17973/MMSJ.2022_03_2022004

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The article describes an optimization methods analysis in the technological process of plastic injection using the simulation tool Autodesk Moldflow Adviser. The Polyethylene 120J was the material used in production of the plastic part analyzed. Following the simulations, deficiencies affecting the quality of the final part were identified. Modifications were gradually made both in the cover's design and as changes in the process parameters so as to eliminate the deficiencies identified. In the first step, the value of the injection time was modified based on the results of the analysis of the determination of the ratio of solidified layers at the end of the process of filling the mold cavity. The second type of adjustment required a change in the molding's design. Based on the result of the simulation of forecasting cooling quality, we proposed a change in the wall thickness of selected model elements, specifically the adjustment of the wall thickness of the bolted joint column from 3 to 4 mm. The last adjustment consisted of adjusting the additional pressure profile.

KEYWORDS

computer simulation, plastic injection, polymer, quality prediction.

1 INTRODUCTION

Plastic and rubber products have become an integral part of our lives. However, activities in industrial production, too, need to comply with environmental protection. It is increasingly necessary to implement steps related to separation and recycling of plastic waste, especially in the area of consumer goods. In addition to the problems associated with processing of large plastic waste, plastics may release very small particles - the so-called microplastics. The plastic monomers then enter the drinking water, oceans and animal bodies. A pressing problem to be addressed technologically by the current and the next generation is the elimination of excess plastic waste. Nevertheless, plastics and their composites have an irreplaceable role, for example in car construction [Panda 2019, Petruska 2020]. These materials are increasingly replacing traditional materials in car construction. This is mainly due to their good mechanical and physical properties. They achieve higher strength, thermal and chemical resistance, resistance to UV radiation, etc. The use of such materials also reduces the vehicle weight, which is reflected, among other things, in lower fuel consumption. Plastics used in the vehicle interior muffle noise and vibration. Polymeric materials represent the most important of all materials in terms of production volume and consumption. In competition with conventional materials, especially metals, polymers have largely prevailed due to their ease of processing, low density, and generally beneficial utility-to-price ratio. Much less energy and labor is expended on the production and processing of plastics than on metal processing. Many plastics also have a higher resistance to chemicals than metals [Rusinko 2021].

Thermoplastics and thermoplastic elastomers are most often processed by extrusion (production of semi-finished products) and injection molding (production of final products). Thermosets and non-thermoplastic elastomers are processed by compression molding or by injection molding [Dillinger 2019, Pollak 2019]. One of the oldest plastics processing technologies is pressing. In this technology, the molten material is not moved over a greater distance, so no fluidity is required of it. The advantage of this kind of processing is the operation cycle speed and high production efficiency. This plastic processing technology uses lower pressures. Another plastic processing technology is blow molding. In this case, a plastically moldable blank is inserted into a hollow mold. After the mold is closed, the blank is pressed from the inside onto the mold walls cooled with compressed air. In the next step, the divided mold is opened and the finished product is ejected. The whole procedure is repeated [Dillinger 2019, Pollak 2019].

The most commonly used plastic processing technology is injection molding. The polymer melt is injected under pressure into the mold cavity of the injection mold. The product acquires the shape of the cavity. In the curable resin injection, it is the curing that takes place in the mold, or vulcanization if the material injected is natural rubber. This technology makes it possible to economically produce high-quality products of sufficient precision from a wide portfolio of plastic materials. Typical for injection-molded products is very good dimensional and shape accuracy. The process is automatic. The use of the material is wide-ranging, close to 100%. Recently, the processing of polymeric materials by additive production technologies has become popular. FFF/FDM (Fused Filament Fabrication/Fused Deposition Modeling) technologies represent the most widespread technology in the field. Its principle is based on extruding the molten polymer through a nozzle and this material is then deposited in subsequent layers [Monkova 2020, Dobransky 2021].

2 COMPUTER SIMULATION OF PLASTIC INJECTION TECHNOLOGY

Manufacturing process simulation is an important tool for securing concurrent or parallel engineering goals. One of the main goals is to detect defects in the production process in a timely manner, which can take place concurrently with planning, tooling and so on.

In the case of plastic injection technology, a number of tools from the CA (Computer Aided) systems portfolio can be applied, which enables engineers and developers to identify bottlenecks and potential errors in the process of final product design. It is a so-called pre-production analysis capable of detecting potential manufacturing problems such as cold joints, welds, air pockets, as well as optimal inlet placement, optimal settings of technology parameters, and the like.

The type of material used, the technological parameters and the design of the mold, as well as the choice of suitable technological equipment, have a significant impact on the mechanical and physical properties of the finished part.

The overall properties of the ejected plastic part in terms of material selection are affected by the following parameters [Dobransky 2009]:

- the rate of polymer plasticization - should be as short as possible,
- plastics fluidity - must be sufficient and must not change too quickly with temperature,
- sufficient thermal stability of the plastics over the range of processing temperatures - should be as broad as possible,
- internal stress magnitude - the lowest possible is required,
- plastics shrinking - change in the product dimensions with respect to the mold cavity dimensions.

Technological process parameters also have a significant influence on the quality of plastic molding [Dobransky 2009]:

- injection pressure - affects filling speed, closing force, internal stress, shrinkage and orientation;
- melt temperature - depends on the type of material and affects the plastics fluidity, injection pressure, cooling time and thus cycle time, shrinkage, pressure loss and additional pressure value;
- mold temperature - depends on the type of the material used and the nature of the product; affects the flow of plastics, filling speed, cooling time, gloss and surface finish, melt temperature, additional pressure, internal stress, shrinkage;
- the speed of filling the mold cavity - should be as fast as possible, but the temperature of the melt must be controlled to avoid degradation of the mass, the disadvantage is also high orientation of the macromolecules;
- height and duration of additional pressure - affects product dimensions, shrinkage and internal stress.

The plastic injection technology has certain specificities, especially effects of various influences and processes on the product's final properties. From the very start of filling the cavity with molten plastics, production processes are beginning to take place, which can be different in the individual spots of the melt volume. Using computer simulation tools, process engineers can detect and predict the course of the production process and the subsequent properties of the plastic molding. Monitoring important parameters affecting the injection process facilitates activities that lead to better results. Final features of the part can be significantly influenced by the designer alone. This can be done through an optimal wall thickness design, adjustment of the slope of the walls, adjustment of the ribs and the like. The aim of the activities is to minimize possible deformations that negatively affect the overall final product properties. The advantage of using simulations is possible achievement of a good analysis of the basic plastic material behavior during the injection process and optimizing the design of the injection tool based on the results obtained. Using computer aid and setting the optimal solution is very important in product design, as about 70% of production costs are defined at this stage. Such preparation can accelerate the pre-production process and make it economically more efficient for the user and the future processor, which is ultimately highly beneficial.

3 PREDICTION OF THE INJECTION PROCESS QUALITY USING THE AUTODESK MOLDFLOW ADVISER TOOL

Based on the request of our partner (Regada, s.r.o. Presov), we did an analysis of the injection molding process of a selected component (fan cover) for the selected material - Polyethylene 120J - using the Autodesk Moldflow Adviser simulation tool. It is a material known for a relatively high resistance to acids, alkalis and some other chemicals. It is partially crystalline, while the more crystalline it is, the greater its density, mechanical and chemical resistance. Recommended mold temperature values for the material at hand range between 20°C and 95°C. The melt temperature ranges between 180°C and 280°C.

The following process parameters were configured to run the simulation:

- mold temperature - 40°C
- melt temperature - 220°C
- injection pressure - 180 MPa

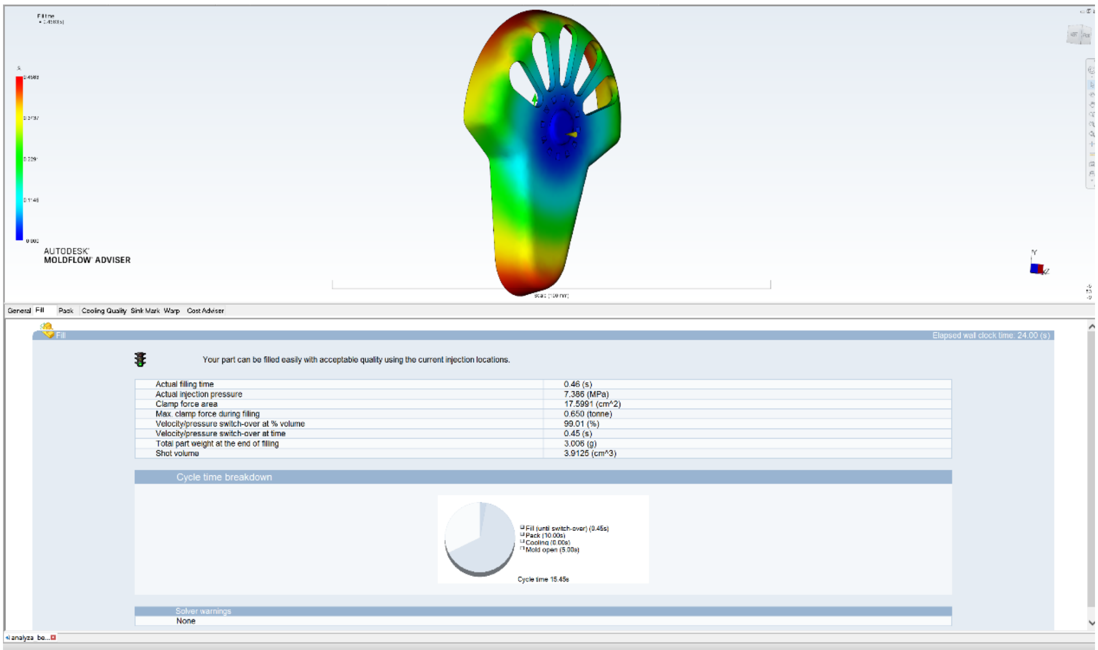

Figure 1. Result of mold cavity filling time analysis

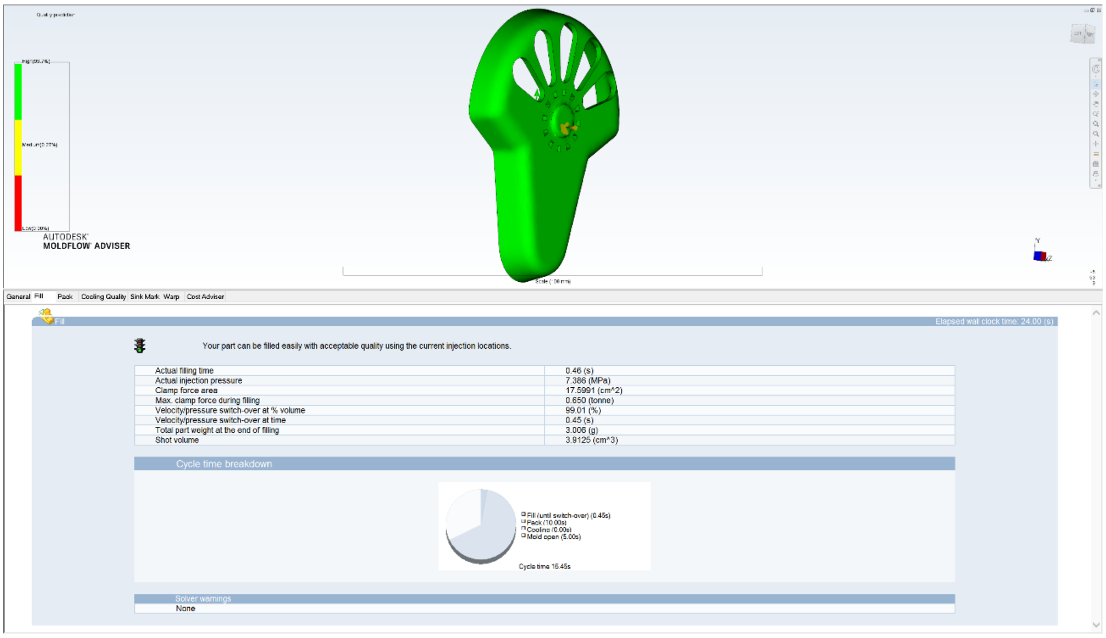

Figure 2. Analysis of the quality and reliability of the mold cavity filling process

3.1 The mold cavity filling time

The results of the filling time analysis show the position of the face of the molten material flow at regular intervals during the cavity filling (Fig. 1). The areas that fill last are shown in red. In the case of a particular model, all traces of plastic flow reach the end of the part at the same time. The ends of the part are highlighted in red. The colored contours are evenly distributed, the contour spacing expresses the speed at which the polymer flows. The wide spacing of the contours represents fast flow, while the narrow spacing expresses the slow process of the part filling. The contour spacing on the model is broad (fast flow), which is also confirmed by the cavity filling time - 0.46 s.

3.2 Quality prediction and injection pressure analysis

The simulation shows a preliminary estimate of the quality of the part's mechanical properties and appearance. In this analysis, the model can have three colors. The green color represents high quality, the yellow color - the possibility of quality problems and the red color foreshadows clear problems with the quality of the molding. The result of the analysis in the specifically investigated case at hand confirmed high quality of the process implemented (Fig. 2).

At the beginning of the filling, the pressure in the whole mold is zero or 1 atm (at absolute pressure). The pressure will start to rise in certain places only when the advancing melt reaches the given place. Subsequently, the pressure rises continuously due to the melt moving in the mold. The pressure gradient is the difference in pressure divided by the distance between the two spots. Like water, the polymer moves from higher to lower pressure spots. This is why the maximum pressure is found around the inlet and the minimum pressure at the ends of the mold cavity. The magnitude of the pressure and the pressure gradient depends on the resistance of the polymer in the mold. This occurs because the high-viscosity polymer needs more pressure to fill the cavity. During the filling phase, large differences in pressure distribution must be avoided. These differences are indicated by inflated contours. In the case of "Dual Domain" analysis, the pressure at the points where the plastic ends should be zero. In the case of the imported 3D model, the maximum pressure is 7.386 MPa at the inlet (red) and 0 MPa at the ends of the model (blue).

3.3 Ratio of solidified layers at the end of the filling process

The result of this simulation foretells the ratio of the thickness of the solidified layer at the end of the filling process. It ranges from 0 to 100%. A higher value indicates a thicker solidified layer and a higher flow resistance. The polymer is considered solidified when the temperature drops below the transition temperature (for Polyethylene 120J, this temperature is 112°C). The ratio of solidified layers is generally very low near the inlet and at the end of the flow. The maximum ratio of solidified layers at the end of the filling process should be less than 20% - 25%. At higher values, it will be very difficult to eject the part from of the mold. In this case, the maximum value of the solidified layers ratio is 32.17%, which is unsatisfactory.

This problem can be solved by reducing the injection time. When setting process parameters, the injection time is configured for automatic setting. In this case, it is advisable to use the "Molding window" analysis when selecting the injection time. This analysis recommends an injection time range between 0.16 s and 0.47 s. At this point, it is necessary to adjust the injection time value and completely repeat the whole analysis and check all the results. After verification of several values, the value of the optimal injection time was set at 0.30 s (Fig. 3).

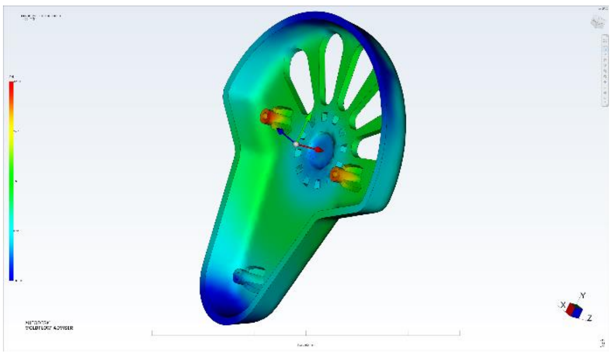

Figure 3. Result of the analysis of the ratio of the layers' solidification at the end of the filling process before adjusting the process parameters

3.4 *Analysis to determine the occurrence of air bubbles, welds, and depressions*

Air bubbles form where the melt is trapped and compresses the air or gas between two or more converging flows. A typical result of air bubbles is a small hole or stain on the part's surface. Air bubbles are acceptable if they are located in places which are not required to be visually perfect. The inspected part model has air bubbles on the inside, in places that get filled last (Fig. 4). These air bubbles are not a serious flaw.

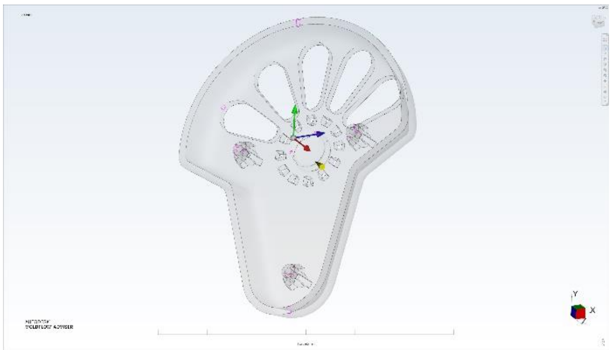

Figure 4. Analysis to determine the occurrence of air bubbles

Welded joints are formed at the intersections of converging faces of melt flows. The presence of welds may indicate a structurally critical point or surface defect. Welded joints cannot be avoided in two cases, namely when the flow face splits around the hole and then merges again, or when the component has several inlet orifices. A "good quality" weld usually occurs if the melt temperature at the weld is not less than 20°C below the injection temperature.

Weld joints are not only a visual defect, but they can also reduce strength of the part by 10 to 20%, depending on the place of their occurrence. From the technological point of view, the type of polymer, the melt temperature, and the injection rate influence the weld joint strength (Fig. 5) [Dobransky 2009].

Depressions are visual defects on the surfaces of injected parts. A similar flaw are unwanted cavities in the walls of the injected parts. They affect the appearance of the component, as well as its mechanical properties. Lighter colors and a decorative finish tend to make depressions less visible. If it is not possible to eliminate or reduce these defects, they can be hidden by adding design elements, such as the use of a rough-textured coating.

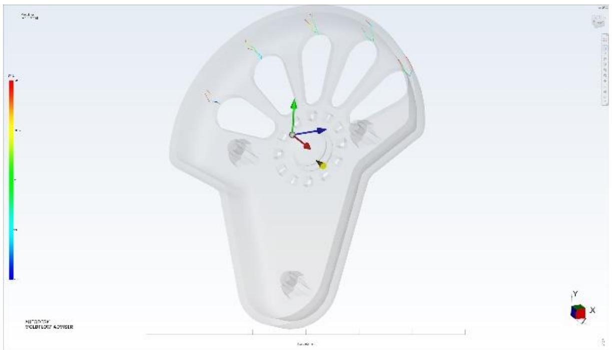

Figure 5. Localization of weld joints

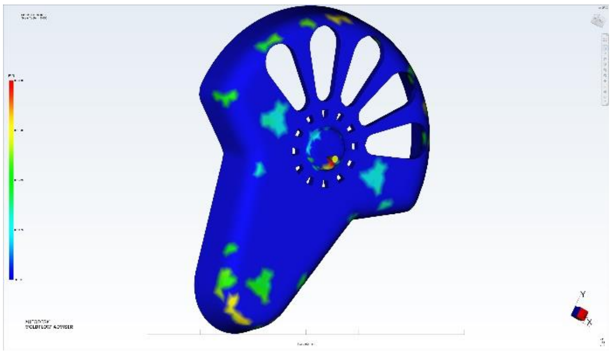

Figure 6. Occurrence of depressions in the investigated model

The investigated plastic cover has a maximum depression value of 0.0438 mm. Less than 1% (0.82%) depressions were identified in the model. The average depression depth is around 0.02 mm (Fig. 6).

3.5 *Forecasting the cooling quality*

The results of the cooling quality analysis show where the heat tends to accumulate, mainly due to the shape and thickness of the part. The simulation result shows how the heat leaves the hot part naturally and how it flows towards the model's ends.

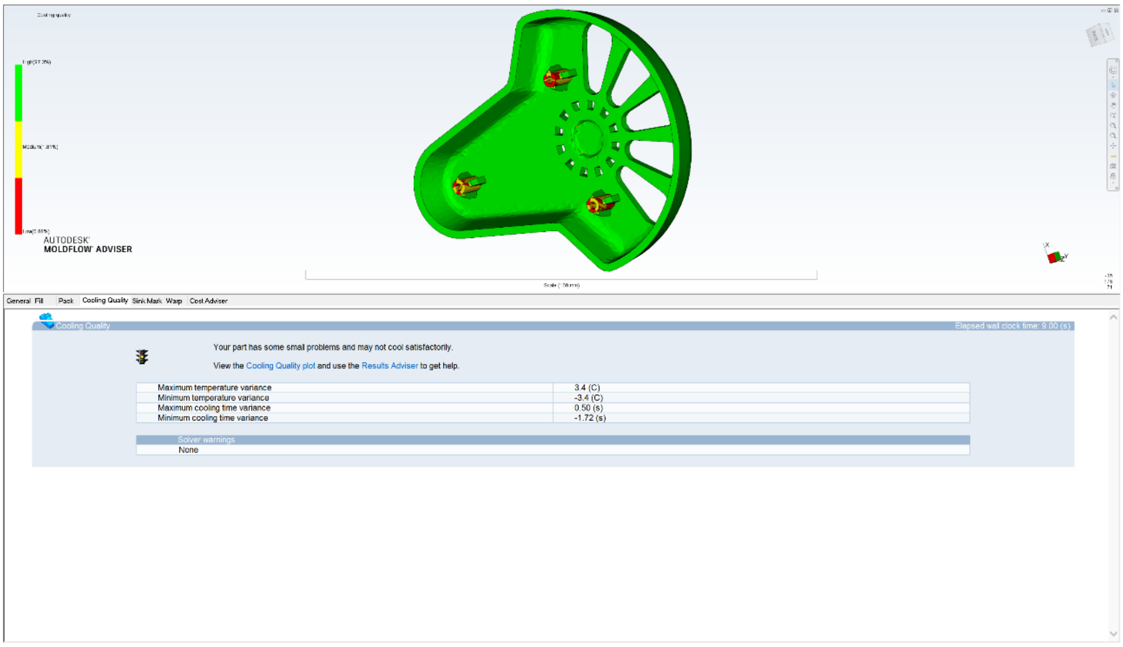

Figure 7. Result of the cooling quality analysis of the plastic molding

Two main factors influence cooling time: melt temperature and mold temperature. These parameters can be optimized to achieve high quality outputs. The simulation also serves the purpose of designing and optimizing the tempering system. The cooling time is proportional to the wall thickness. In the process of designing a plastic molding, it is advisable to avoid walls that would be too thick in order to achieve an economically acceptable cooling time of the molding. Thickness of a part should be as uniform as possible.

The results are graphically represented in three colors: green, yellow and red. The computer model indicates the following values: green - 97.3%; yellow - 1.81% and red - 0.86% (Fig. 7). The ratio of yellow to red is not extremely high, but it is still possible that surface defects and deformations may appear on the part (Fig. 7). This problem can be solved by adjusting the wall thickness in red areas.

3.6 Analysis of volume shrinkage upon molding's ejection

Shrinkage represents a change in the volume during solidification of polymer melts, the main cause of which is its compressibility, thermal expansion, and contraction of plastics. In partially crystalline polymers, crystallization changes also take place.

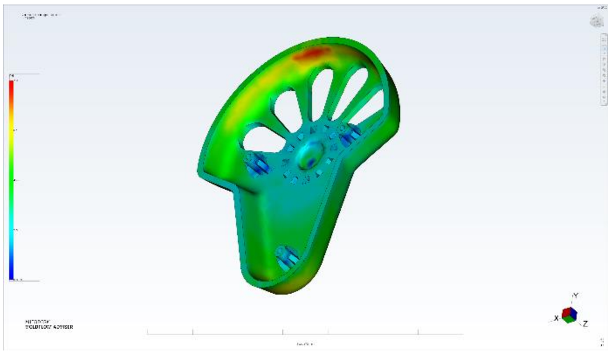

Figure 8. Volume shrinkage upon the molding's ejection

Volume shrinkage upon the mold ejection represents a reduction in local volume between the end of the cooling phase and the time when the part is cooled to ambient temperature (approximately 25°C). The results of this analysis can be used to detect depressions in the model. High values of shrinkage may indicate depressions or so-called empty spaces inside the part. Shrinkage values should be uniform throughout the model. This is important for determining the additional pressure value, which will ensure a good structure and visual integrity of the component. In the investigated model, the value of the maximum volume shrinkage is 7.966% (Fig. 8), which is a relatively high value. This value can be reduced by adjusting the profile of the additional pressure. After the adjustment, this value was significantly lower. The value of volume shrinkage after adjustment was 2.26%.

4 EVALUATION AND DISCUSSION OF RESULTS

In the case of the given design of the fan cover and the recommended settings of the technological parameters' values for the given type of material, the applied simulation analyses confirmed the existence of certain deficiencies, which, however, should not have a significant impact on the product's function and appearance properties. Nevertheless, modifications were gradually made both in the cover's design and as changes in the process parameters so as to eliminate the deficiencies identified. In the first step, the value of the injection time was modified based on the results of the analysis of the determination of the ratio of solidified layers at the end of the process of filling the mold cavity. Adjusting the injection pressure depending on the injection time has two effects. As the injection time increases from zero, the pressure required to extrude the molten material decreases. Also, as the injection time increases, the temperature of the polymer decreases due to heat transfer to the mold, which causes the viscosity and thickness of the solidified layer to increase - which in turn increases the injection pressure [Dittrich 2019, Dobransky2021].

Table 1. Summary of analysis results for the plastic cover reference model before and after adjustments

	No adjustment	1st adjustment	2nd adjustment	3rd adjustment
Filling time [s]	0.46	0.34	0.34	0.34
Forecasting filling reliability of the mold cavity formy [%]	100	100	100	100
Quality forecast (green, yellow, red) [%]	99.7	99.6	99.6	99.6
	0.27	0.44	0.38	0.38
	0	0	0	0
Injection pressure [MPa]	7.38	8.11	8.18	8.18
Temperature at the face of the flow [°C]	217.1 - 220	218.9 - 220	219 - 220	219 - 220
Ratio of solidified layers at the end of the filling process [%]	32.17	24.23	15.74	16.12
Depressions [mm]	0.044	0.043	0.04	0.005
Cooling quality (green, yellow, red) [%]	97.3	97.3	100	100
	1.81	1.81	0	0
	0.86	0.86	0	0
Volume shrinkage upon ejection [%]	7.9	6.9	6.55	2.26
Deviations in geometry displacement [mm]	0.33	0.32	0.32	0.13
Total cycle time [s]	15.45	15.34	15.34	12.34

The second type of adjustment required a change in the molding's design. Based on the result of the simulation of forecasting cooling quality, we proposed a change in the wall thickness of selected model elements, specifically the adjustment of the wall thickness of the bolted joint column from 3 to 4 mm. The last adjustment consisted of adjusting the additional pressure profile.

As shown in Tab. 1, the filling time changed only during the first adjustment. The time of filling the mold cavity was reduced by more than ten seconds. Filling reliability in all analyses was 100%. The results of the quality forecast did not differ much. The largest change occurred at the mean (yellow) value. The injection pressure also did not change significantly. The difference between the maximum and minimum temperature at the face of the flow was the smallest after the second and the third adjustment. The ratio of solidified layers at the end of the filling process was too high in the first analysis, so it was necessary to change the process parameters. After the second adjustment, the value of the monitored ratio was satisfactory. In the third adjustment, this value slightly increased. The largest difference in the results of the depression analyses occurred in the third modification, where their size decreased to 0.005 mm from the initial 0.044 mm. Cooling quality problems were still present after the first adjustment, so changes to the model had to be made. After the model change, the results improved. Visible results of volume shrinkage occurred only during the third adjustment, where it was necessary to change the additional pressure profile (see. Fig. 9). Deviations from geometry displacement were the same after the first and second adjustments. After the third adjustment, this value dropped to 0.13 mm. The total cycle time was visibly reduced only following the third adjustment, as the additional pressure time was reduced by 3 seconds.

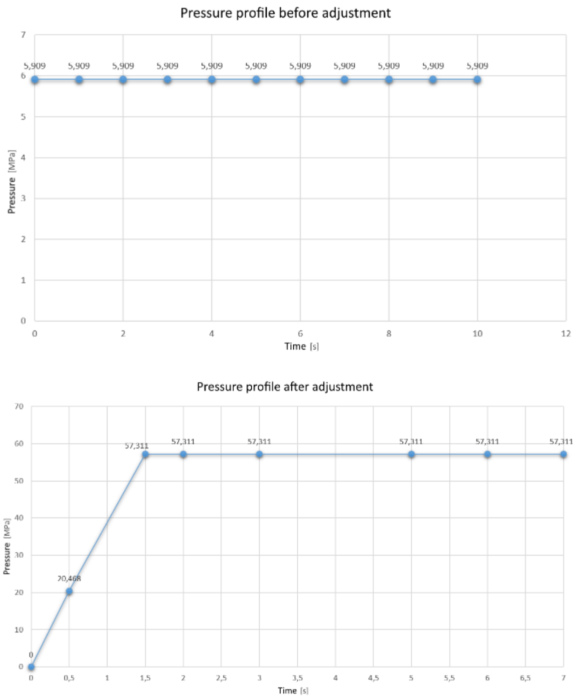

Figure 9. Changing the pressure profile before and after adjustment

5 CONCLUSION

In cooperation with our partner, we ran a simulation of the plastic injection process in the Autodesk Moldflow Adviser. The partner's request was to optimize the process parameters for the selected Polyethylene 120J (Prime Polymer Co Ltd). Through simulation analyses, deficiencies were identified and subsequently eliminated through both adjustments to design and technological parameters. The premise that through simulation of the production process it is possible to verify the correctness of the selected design, technology, and the entire production process, has been confirmed. The issue of costs in connection with the design of the mold, which can be minimized by the application of simulation tools, is also important. And last but not least, the issue of reducing pre-production times, which can be rapidly reduced through a parallel engineering approach, has been proven as well [Fedorko 2015].

The technology of plastic injection has certain specifics, especially in terms of the effects of various influences and processes on the product's final properties. From the very start of filling the cavity with molten plastic, production processes are beginning to take place, which can be different in the individual spots of the melt volume. Using the production process simulation tools, the course of the manufacturing process and the properties of the plastic molding can be detected and predicted.

Computer simulation tools can detect defects of the selected material and its behavior. Monitoring important parameters affecting the injection process facilitates activities that lead to better results.

The final features of the part can be significantly influenced by the designer alone. By designing the optimum wall thickness, adjusting the slope of the walls, adjusting the ribs and the like. The aim of these activities is to minimize possible deformations that negatively affect the overall properties of the final product.

ACKNOWLEDGMENTS

The authors thank the Ministry of Education of Slovak Republic for supporting this research by the grant VEGA 1/0051/20 (Research in field of reverse engineering deployment into diagnostics of hard-to-reach places).

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