Thermal specification of 3D printed injection moulds made from PA12GB

K Raz, Z Chval, M Habrman, A Milsimerova

University of West Bohemia, Regional Technological Institute, Univerzitni 8, 306 14 Pilsen, Czech Republic
kraz@rti.zcu.cz, zdchval@rti.zcu.cz, mhabrman@rti.zcu.cz, anetam@rti.zcu.cz

Abstract. This paper deals with the usage of the injection mould made from the plastic material. This technology is rapidly decreasing the time, necessary to the production of the prototype. This attribute takes nowadays a key role in the industry, especially in the automotive. Technology of using injection moulds from the plastic material (produced by additive technologies) has advantages in the decreasing of the time demands and cost reduction during the production of the prototype part. Unfortunately, plastic moulds have worse surface quality, lower lifetime of the mould (measured in number of produced parts) and more difficulties of moulding process regulation with respect to the metal moulds. This paper is focused on the injection process and it is describing the thermal distribution and specification of the comparable plastic specimen during injection into the metal and plastic mould. The results are the temperature and cycle-times comparisons. The effectivity of cooling is also compared in this work. It is obvious, that the plastic mould has worse results compared to the metal mould. However, this is clearly balanced by the speed of production and price of plastic mould. The prototype of the plastic mould was made from the material PA12GB with usage of 3D printer HP MJF4200

1. Introduction
Technology of injection molding is one of the most commonly used production technologies in the industry. It is used mainly in the automotive sector, which is the driving force of the world economy. The main disadvantage of this technology is the complexity (financial and time) of moulds. There are high financial and time claims and this is problem mainly during production of prototypes. These moulds are standardly produced by machining on CNC machines.[1,2] The plastic injection technology is theoretically based on the technology of die casting and it is a cyclic-repeated technology. Injection molding is used for the production of final end products and also for production of plastic prototype parts, which are used to verify the functionality of the designed product. [3,4]

2. Usage of the Additive technologies during production of injection molds
Additive technologies are currently used mainly in the production of prototypes. The main advantage with respect to the conventional machining is the significantly lower price and faster delivery time of the injection mold. The disadvantages are following: lower surface quality, limitations of the shape caused by the higher friction between the part and the mold and finally, the plastic mold has lower lifetime. [5] The lifetime of the mold itself can be considered as less the one hundred of injection molded parts (considering FDM or SLA printers). [6,7] This number has to be considered with respect to the complexity of the cavity shape. This service life is affected by the used additive technology. The
industrial method HP Jet Fusion 4200 was used in this research. This method achieves better mechanical properties and homogeneity of the material compared to other printers. [8] The service life of this plastic molds can be up to three hundred parts (with respect to the shape of part and with decreasing quality of parts). The best surface quality can be achieved using the stereolithography method with printing from photopolymeric resin. [9,10] The disadvantage of these molds is their higher fragility and lower durability and higher susceptibility to damage. [11]

3. Design of the mold with replaceable cavity from plastic or aluminium
The mold was designed as a modular design with replaceable inserts (cavities) from various materials (Aluminium or PA12GB). For injection molding technology was used the Arburg 470EG. It is an electric injection molding press with innovative drive solution. It is using spindle gears, servomotors with automatic regulation of closing force. It is ensuring the stability of the process and minimizing the time of mold installation and maintenance. [12,13] The press has following parameters:
Distance between tie bars: 470 x 470 mm
Clamping force: 1 000 kN
Clamping plate dimensions: 637 x 637 mm
Maximal material volume: 144 cm$^3$

The insert was produced in two material variants which are compared in this research (3D print from PA12GB and machined from aluminium). Both variants have the same geometry without any reductions or drafts. All other parts are produced from steel or aluminium by conventional machining. The principle of the designed modular mold (only the moving half, the stationary half doesn’t have a cavity) is described in the following figure.

Figure 1. Design of the movable half of the mold with replaceable cavities

4. Parameters of the injection molding process
A simple part (specimen for the tensile test) was selected for the analysis. Mechanical properties of the material (tensile test) will be tested in the following research with the respect to the material of cavity. The injection process has following parameters:
• Polypropylene was the injected material with and injection temperature 240 °C
• The mould temperature is an ambient temperature 25°C. The mould doesn’t have cooling and preheating system in the current design.
• The injection time is 0.5s
• The cooling time is 60s for the plastic cavity and 10s for the aluminium cavity
The material of the plastic insert has following properties:
- Powder Melting Point: 186°C
- Density of part: 1.3 g/cm³
- Tensile strength: 30MPa
- Tensile modulus: 2800MPa
- Heat deflection temperature at 0.45 MPa: 173°C

The cooling time (i.e., the time of the cycle) has to be higher for the insert made from the plastic material. It is caused by the lower thermal resistivity and conductivity with respect to the insert made from the aluminium.

The temperature of the plastic cavity cannot exceed the heat deflection temperature. [14] There was used the shaped cavity only at one side of the mold. The other side (static part of the mold) was flat and produced from aluminium plate for both variants. The molded part was cooled down primary via this stationary half of mold. The aluminum has much better heat transfer properties. [15] It is obvious that this solution cannot be used for all shapes of products. There was produced 30 parts from the plastic mold without significant destruction of the plastic mold.

5. Thermal analysis performed with measurement and simulation

The temperature of the produced part was analyzed during the time of the mold opening. Two different approaches were used in this research. First approach is usage of the thermal simulation in the system Siemens NX with the thermal solver Simcenter Thermal/Flow. This task was solved as a time-dependent solution within the time 0 to 65s.

The initial conditions were: temperature of the specimen 240°C, ideal cooling before the molding on the ambient temperature, both materials were defined with properties from the material library of the Siemens NX software and between all parts was considered perfect contact. The thermal transfer coefficients were calculated by the software with respect to the temperatures. [16,17]

Second approach is usage of the thermal measurement. The Flir thermocamera E6 was used during the measurement. It is a point-and-shoot infrared camera that is fully automatic with and thermal sensitivity less than 0.06°C and with an IR resolution 160x120 pixels. It is possible to notice the reflectivity of the shiny aluminium surfaces. Therefore, the pictures from thermocamera looks like blurred.

5.1. Aluminium cavity- measurement and simulation

![Figure 2. FEM simulation model (left) and Flir thermocamera E6 (right)](image-url)
Maximal measured temperature of the part after the mold opening was 75°C. The virtual simulation shows the temperature 78°C. The temperature of the mold was 42°C within the virtual simulation. It was not possible to find out the correct temperature of the mold (for both materials) from the thermocamera because of reflections of shiny surfaces. The cavity made from the aluminium is shown in the following figure. The difference between simulation and the measurement is caused by the inaccuracy of thermal coefficient.

**Figure 3.** Removable cavity made from the Aluminium

Results from the Flir camera are shown in the following figure after the postprocessing of the measurement.

**Figure 4.** Results from the thermocamera

Results from the Simcenter Thermal/Flow simulation are shown in the following figure.

**Figure 5.** Results from the virtual simulation
5.2. Plastic cavity- measurement and simulation

Maximal temperature of the part after the mold opening was 87°C. The virtual simulation shows the temperature 84°C. The temperature of the mold was 40°C within the virtual simulation.

![Figure 6. Removable cavity made from the PA12GB](image)

Results from the Flir camera are shown in the following figure after the postprocessing of the measurement.

![Figure 7. Results from the thermocamera](image)

Results from the Simcenter Thermal/Flow simulation are shown in the following figure.

![Figure 8. Results from the virtual simulation](image)
6. Comparison of both designs

The comparison of both designs was performed with respect to the temperatures and quality of the part. The production cost (time and money) and durability of both designs were described in previous paragraphs. It can be simply said, that the quality of the final part is better using the aluminium mould and the costs are lower for the plastic mould.

6.1. Thermal comparison of both designs

The following table shows results (in terms of temperatures) from the measurement and from the virtual simulation. There are small differences between these two approaches caused by the hard determination of the thermal coefficient.

| Mould design  | Part temperature after mold opening – simulation [°C] | Mold insert temperature after opening – simulation [°C] | Part temperature after mold opening – measurement [°C] | Mold insert temperature after opening – measurement [°C] |
|---------------|------------------------------------------------------|------------------------------------------------------|------------------------------------------------------|------------------------------------------------------|
| Aluminium cavity | 78                                                   | 42                                                   | 75                                                   | -                                                    |
| Plastic cavity | 84                                                   | 40                                                   | 87                                                   | -                                                    |

6.2. Comparison of surface quality of both designs

Both cavities (plastic and aluminium) had the same geometry. There was only one difference in the surface quality. The aluminium mould has the surface roughness about Ra 0.4. The plastic mould has the roughness about Ra 3.2. It is obvious that the quality of the final part from the plastic mould will be worse. There are some chemical methods used to the improvement of the surface quality after the 3D prints. These methods will be tested in the future research.

Following figures shows the macroscopic view on the surface of the final part. There are obvious differences of the surfaces, not only in the structure (for example on the part from the aluminium mould is obvious the milling process of the mould) but also is there a difference in the light refraction. The views are 50 times zoomed and composed from 12 separate fields.

**Figure 9.** Photography from the microscope of the surface (only part of it) of the final part from the plastic mould (left) and from the aluminium mould (right)

7. Conclusion

An analysis of the usage of additive technologies in the production of prototype injection molds was performed as part of the research. This procedure is used in industry only in a very limited number of
cases. An indisputable advantage of plastic injection molds is significantly lower price compared to metal molds. The main disadvantage of the plastic mold is a lower surface quality and much shorter lifetime of the mold. It is necessary to adjust the injection cycle properly in order to ensure the sufficient cooling of the mold. This problem with cooling is caused mainly by the difference in the thermal conductivity coefficient, which is for aluminium at 25 °C on value \( \lambda = 237 \text{[W·m}^{-1}·\text{K}^{-1}] \). This value is \( \lambda = 0.2 \text{[W·m}^{-1}·\text{K}^{-1}] \) for a plastic mold made from polyamide (for the temperature 25 °C). It is necessary to set the cooling cycle and cooling level very carefully, because the usability temperature (long-term) for polyamide should not exceed 100 °C. As part of the research, the principle of a single-sided insert was used. The plastic insert is only on the moving part of the mold. The solid side is flat and made of aluminium. For this reason, there is primary heat transfer through the solid plate of the mold. This research will continue with creating of the mold with two cavities from plastic material. There is expected a problem with lower heat transfer, longer cycle times and thermal degradation of the mold.

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References

[1] Gorguluarslan, Recep & Gandhi, Umesh & Mandapati, Raghuram & Choi, Seung-Kyum. (2015). Design and fabrication of periodic lattice-based cellular structures. Computer-Aided Design and Applications. 13. 10.1080/16864360.2015.1059194.
[2] K. Raz, Z. Chval, F. Sedlacek, 2019. Compressive Strength Prediction of Quad-Diametral Lattice Structures. 69-74 pp., Key Engineering Materials
[3] Wikipedia contributors, "Young's modulus" Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/w/index.php?title=Young%27s_modulus&oldid=940567807 (Accessed February 26, 2020).
[4] Egan, Paul & Gonella, Veronica & Engensperger, Max & Ferguson, Stephen & Shea, Kristina. (2017). Computationally designed lattices with tuned properties for tissue engineering using 3D printing. PLOS ONE. 12. e0182902. 10.1371/journal.pone.0182902.
[5] J. Bozzelli. Injection Molding: How to Set Second-Stage (Pack and Hold) Pressure, Plastic Technology, February 2011
[6] M. Miller. Avoiding and Solving Injection Molding Problems Using Shear Rate Calculations-Part 1, Plastics Today, February 2007
[7] J. Bozzelli. Injection Molding: Develop Guidelines-Not Strict Procedures-For a Robust Molding Process, Plastics Technology, December 2015
[8] A. Ausperger. Simulation of Deformation and Compression of Fabric During the Back Injection Moulding Process, Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium, 2011, Austria, Volume 22, No. 1, pp. 1261-1262, ISSN 1726-9679, ISBN 978-3-901509-83-4
[9] M. Stanek, M. Manas, D. Manas, K. Kyas, J. Navratil. Injection Molding Process and its Optimization, Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium, 2011, pp. 0155-0156, Vienna, ISSN 1726-9679, ISBN 978-3-901509-83-4
[10] Alketan, Oraib & Rowshan, Reza & Abu Al-Rub, Rashid. (2018). Topology-Mechanical Property Relationship of 3D Printed Strut, Skeletal, and Sheet Based Periodic Metallic Cellular Materials. Additive Manufacturing. 19. 167–183. 10.1016/j.addma.2017.12.006.
[11] O’Connor, Heather & Dickson, Andrew & Dowling, Denis. (2018). Evaluation of the mechanical
performance of polymer parts fabricated using a production scale multi jet fusion printing process. Additive Manufacturing. 22. 10.1016/j.addma.2018.05.035.

[12] K. Omer, A. Abolhasani, S. Kim, T. Nikdejad, C. Butcher, M. Wells, S. Esmaeili and M. Worswick, "Process parameters for hot stamping of AA7075 and D-7xxx to achieve high performance aged products," Journal of Materials Processing Technology, vol. 257, pp. 170-179, 2018.

[13] Voyiadjis GZ, Woelke PB, 2005 “General non-linear finite element analysis of thick plates and shells”. Int. J. Solids Struct, 43 (7–8, 1):2209–42

[14] N. Arcuri, F. Reda, M. De Simone, Energy and thermo-fluid-dynamics evaluations of photovoltaic panels cooled by water and air, Solar Energy 105 (2014) 147–156

[15] Z. Chval, K. Raz, Effect of heat load on a mechanical forging press. In Proceedings of the 27th DAAAM International Symposium, 2016, Vienna: DAAAM International, pp. 344-348. ISBN: 978-3-902734-08-2, ISSN: 1726-9679

[16] V. Marek, Basic Research of Thermal Transfer Simulations, Proceedings of the 27th DAAAM International Symposium, pp.0578-0585, B. Katalinic (Ed.), Published by DAAAM International, 2016, ISBN 978-3-902734-08-2, ISSN 1726-9679, Vienna, Austria, DOI: 10.2507/27th.daaam.proceedings.085

[17] V. Marek, Z. Hajicek, Thermal Simulations Based on Macro-Models, Proceedings of the 28th DAAAM International Symposium, pp.0627-0634, B. Katalinic (Ed.), Published by DAAAM International, 2017, ISBN 978-3-902734-11-2, ISSN 1726-9679, Vienna, Austria, DOI: 10.2507/28th.daaam.proceedings.089