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[1]. Miroslav KOŠÍK, [2]. Jozef BÍLIK, [3]. Roland ŠUBA

DESIGN OF INJECTION MOULD WITH CONFORMAL COOLING USING NUMERICAL MODELLING

[1, 2, 3] Slovak University of Technology - Faculty of Materials Science and Technology; Institute of Production Technologies; Department of Machining, Forming and Assembly, Trnava, SLOVAKIA

Abstract: Paper presents a case study focused on design of the cooling system of injection mould for thermoplastic processing, demonstrated on a model example from engineering industry. At first, the whole mathematical approach how to compute suitable cooling system was described in paper. Subsequently, the advantages of the conformal cooling system compared to conventional were investigated with utilization of the numerical modelling. For this purpose a free-form shaped thin-walled part from automotive industry was selected - component of the rear view mirror. In order to achieve shortest cooling time during this part moulding and its minimal warpage, the several conventional and conformal cooling systems were proposed and were evaluated based on results of the numerical modelling. Finally, the best cooling solution was integrated into shape cavity of the 2+2 family mould

Keywords: design of injection mould, conformal cooling, plastic part warpage, numerical modelling

INTRODUCTION

Injection moulding of the thermoplastics is dynamically process where temperature fields are changing very fast and periodically. In order to stabilize such temperature variation, tempering/cooling system is integrated in every injection mould. The function of the tempering system is to retain a constant mould temperature so the optimal moulding conditions were attained for the proper mould cavity filling, minimal warpages of the produced parts and minimal production times. The phase of the cavity filling requires the higher mould temperatures so the molten plastic can smoothly fill up whole cavity without underfills. On the opposite side, the low mould temperatures are required in order to cool down produced parts in minimal production times. Moreover, the third aspect must be taken to account: uniform cooling of the whole part, because its warping is caused mainly by temperature differences inside the mould during cooling. To meet these requirements, all the heat which is supplied into mould during filling phase must be removed by cooling system uniformly and as soon as possible, however, only to the sufficient mould temperature for next cavity filling. In general, the effectiveness of the used cooling system is given by cooling channels geometry, their size and shape, distance from mould cavity, temperature and volumetric flow of the coolant and mould material. The whole procedure how to design cooling system is described in this case study. In first, thermokinematics of the injection moulding process and principles for the cooling system creation are described. Next, the design of the appropriate cooling system is demonstrated on a part from automotive industry. Since the free-form shaped part was used, several variants of the conventional and conformal cooling systems were investigated by numerical modelling. Finally, the best solution was applied to injection mould.

THERMOKINETICS OF MOULDING PROCESS

In order to design optimal cooling system of the injection mould there is a need to know all the thermal processes occurring during moulding cycle.

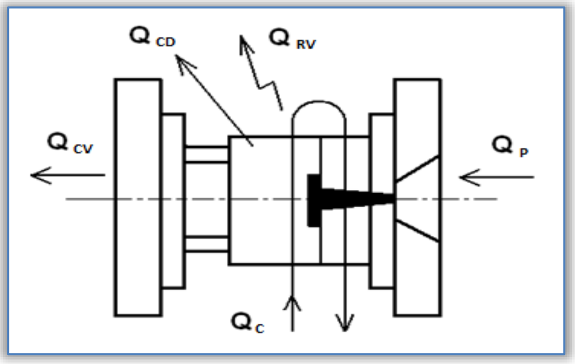

Figure 1. Thermal balance of injection mould

These can be derived from the basic condition of the heat transfer in moulding process:

$$Q_P = Q_C + Q_L \quad [J]$$

where: Q_P - heat supplied by molten plastic [J], Q_C - heat removed by coolant [J], Q_L - heat loss to ambient environment [J], according to Figure 1.

In the case of the heat loss, all kinds of the heat transfer are observed as following:

Q_{CD} - heat conduction to clamping plates of injection machine [J], Q_{CV} - heat convection to environment [J], Q_{RD} - heat transfer by radiation to ambient environment [J],

The source of the heat supplied to mould is molten plastic. In the specific case, it can be also heat generated in injected melt due very high shear rates during cavity filling. The overall heat brought to the mould is determined as:

$$Q_P = m \cdot c_T \cdot (T_M - T_E) = C_T \cdot (T_M - T_E) \quad [J]$$

or:

$$Q_P = m \cdot \Delta H \ [J]$$

where:

m - weight of moulded part including runners [kg],

c_T - specific heat capacity of melt [J/K·kg],

C_T - heat capacity of melt [J/K],

T_M - temperature of melt [K],

T_E - temperature of ejected part [K],

ΔH - enthalpy difference of plastic during melt injection and part ejecting [J/kg]

According to heat supplied to the mould, the required cooling time can be computed. Cooling time is defined as a time needed for the part to be cooled down to recommended ejection temperature, starting at the end of filling phase. The following relations are valid.

Cooling time for thin-walled part:

$$t_{THIN} = \frac{s^2}{\pi^2 \cdot a} \cdot \ln\left(\frac{8}{\pi^2} \cdot \frac{T_M - T_{IM}}{T_E - T_{IM}}\right) \ [s]$$

where: s - maximal thickness of part wall [m],

a - thermal conductivity of plastic [m²/s],

T_{IM} - initial mould temperature [K] [1].

- Cooling time for thick-walled part, if L >> s:

$$t_{THICK} = \frac{s^2}{23{,}14 \cdot a} \cdot \ln\left(0{,}692 \cdot \frac{T_M - T_{IM}}{T_E - T_{IM}}\right),$$

or if L ≈ s:

$$t_{THICK} = \frac{1}{\left(\frac{23{,}14}{s^2} + \frac{\pi^2}{L}\right) \cdot a} \cdot \ln\left(0{,}561 \cdot \frac{T_M - T_{IM}}{T_E - T_{IM}}\right) [s]$$

where: L - length of part [m] [1].

Subsequently, the needed cooling capacity can by computed. Cooling capacity is defined as a quantity of heat removed from mould for time unit according to following relation:

$$\dot{Q}_{CL} = Q_P / t_{THIN} = Q_P / t_{THICK} \quad [J/s]$$

or:

$$\dot{Q}_{CL} = h_{MM} \cdot S_C \cdot (T_{CW} - T_C) \ [J/s]$$

where: $h_{MM} = \frac{\lambda_C}{D} \cdot Pr^{0,42} \cdot (Re^{0,42} - 180)$ [W/m²·K]

$$Pr = \frac{\eta \cdot c_C}{\lambda_C} \ [-], \ Re = (v \cdot \rho \cdot D) \ / \ \eta \ [-],$$

and individual variables are:

h_{MM} - heat transfer coefficient between mould / cooling channel wall and coolant [W/m²·K],

S_C - size of cooling channel surface [m²],

T_{CW} - temperature at cooling channel surface [K],

T_C - temperature of coolant [K],

λ_C - thermal conductivity of coolant [W/m·K],

D - cooling channel diameter [m],

Pr - Prandtl number [-],

Re - Reynolds number [-],

η - dynamic viscosity of coolant [Pa·s],

c_C - specific heat capacity of coolant [J/kg·K],

v - velocity of coolant flow [m/s⁻¹],

ρ - coolant density [kg/m³]

or in specific case, the thermal loss can be considered in cooling capacity calculation:

$$\dot{Q}_{CL} = \frac{Q_P}{t_{CY}} - \frac{(Q_{CV} + Q_{CD} + Q_{RD})}{t_{CY}} \ [J/s]$$

where the loss by heat convection is:

$$Q_{CV} = h_{CP} \cdot S_{CP} \cdot t_{CY} \cdot (T_{MT} - T_{IP})$$

$$\dot{Q}_{CV} = h_{CP} \cdot S_{CP} \cdot (T_{MT} - T_{IP})$$

with: h_{CP} - heat transfer coefficient between mould clamping plates, $h_{CP} = \lambda_P / l$. If thermo-insulating plate is used:

$$h_{CP} = \frac{1}{\frac{l}{\lambda_P} + \frac{l_{IP}}{\lambda_{IP}}} \ [W/m^2 \cdot K],$$

λ_P - thermal conductivity of clamping plates material [W/m¹·K],

λ_{IP} - thermal conductivity of clamping plates material [W/m¹·K],

l - distance of mould cavity from clamping plates [m],

l_{IP} - thickness of insulating plate [m],

S_{CP} - contact surface between mould clamping plates [m²],

T_{MT} - mould temperature [K],

T_{IP} - clamping plate temperature [K],

t_{CY} - time of one moulding cycle [s],

the loss by heat conduction is:

$$Q_{CD} = h_{MA} \cdot t_{CY} \cdot t_O \cdot (S_A + 2 \cdot S_P) \cdot (T_{MT} - T_A)$$

$$\dot{Q}_{CD} = h_{MA} \cdot (S_A + 2 \cdot S_P) \cdot (T_{MT} - T_A)$$

with:

t_O - mould opening time [s],

h_{MA} - heat transfer coefficient between mould and ambient flowing air [approximately 6 - 10 $W/m^2 \cdot K$],

S_A- external mould surface in contact with ambient air [m^2],

S_P - external mould surface in contact with ambient air [m^2],

T_A - ambient air temperature [K],

and the loss by heat radiation is:

$$Q_{RD} = \sigma \cdot C_0 \cdot t_{CY} \cdot S_A \cdot (T_{MT}^4 - T_A^4)$$

$$\dot{Q}_{RD} = \sigma \cdot C_0 \cdot S_A \cdot (T_{MT}^4 - T_A^4)$$

with: σ - emissivity of mould material [-],

C_0 - Stefan-Boltzmann constant

$$C_0 = 5{,}67 \cdot 10^{-8}\ [W/m^2 \cdot K^4].$$

Required cooling capacity can be also determined in relation to individual cooling circuit:

$$\dot{Q}_{CCi} = \dot{Q}_{CL} / i \qquad [J/s]$$

where i - number cooling circuits.

Generally, the amount of removed heat is dependent mainly on the volume of coolant overflowed through mould and its temperature drop at inlet and outlet. The necessary volumetric flow of the coolant (volume of the coolant which must flow through the one cooling circuit for time unit) can be determined as:

$$\dot{V}_i = \frac{\dot{Q}_{CCi}}{c_C \cdot \square \cdot (T_{C2} - T_{C1})}\ [m^3/s]$$

where:

T_{C1} - temperature of coolant at the inlet,

T_{C2} - temperature of coolant at the outlet.

The recommended maximal temperature difference at the coolant inlet and outlet is 3 °K. Effectiveness of the heat removal is more significant in case of the higher Reynolds number, thus in case of the turbulent coolant flow. Consequently, the parameters of the cooling channels can be determined as [2]:

- Maximal diameter of the cooling channel:

$$D_{MAX} = \frac{4 \cdot \rho \cdot \dot{V}}{\pi \cdot \eta \cdot Re} = \frac{4 \cdot \dot{V}}{\pi \cdot \nu \cdot Re}\ [m]$$

where:

ν - kinematic viscosity of coolant[m^2/s]

- Minimal diameter of the cooling channel:

$$D_{MIN} = \sqrt[5]{\frac{\rho \cdot L_C \cdot \dot{V}}{10 \cdot \pi \cdot \Delta p}}\ [m]$$

where:

L_C - estimated cooling channel length [m]

Δp- difference of coolant pressure at the coolant inlet and outlet [Pa]

The recommended maximal pressure drop is 0,1 MPA. The signature of the individual variables is the same in whole computation procedure. However, the design of the optimal cooling channel dimensions is dependent on other influences and should consider designer experience. The recommended distance between mould cavity and cooling channel H is in range of 2D < H < 5D of the cooling channel diameter. Exact value is influenced by coolant pressure and mould material strength, as well as in the case of spacing between channels W, which should be set in the range of H < W < 2H [2].

COOLING SYSTEM DESIGN

However, according to requirements of the engineering industry, more and more shape-complicated parts are produced nowadays. Computation of the appropriate cooling system for such a free-form shaped parts by analytical approach can be very difficult and inaccurate, therefore, numerical modelling is widely used for its investigation [3, 4]. In addition, the more complicated the part geometry is, the more complicated cooling system is usually required. In order to achieve uniform and adequate cooling of these parts, the cooling channels must copy the pattern of the part geometry, but this cannot be attained by straight, conventional drilled channels. Therefore, engineers are forced to use advanced cooling technologies increasingly. There are many non-conventional cooling methods, for example as Spot Cooling, Tool-Vac Cooling, cooling by Ranque - Hilsch vortex tubes, and others. In this case study, effectiveness of the conformal cooling was studied in comparison to conventional drilled. Conformal cooling channel is a cooling passageway which follows the shape or profile of the mould cavity to perform rapid uniform cooling process for injection moulding, as it is demonstrated in studies [5, 6, 7, 8]. Its principle is shown in Figure 2.

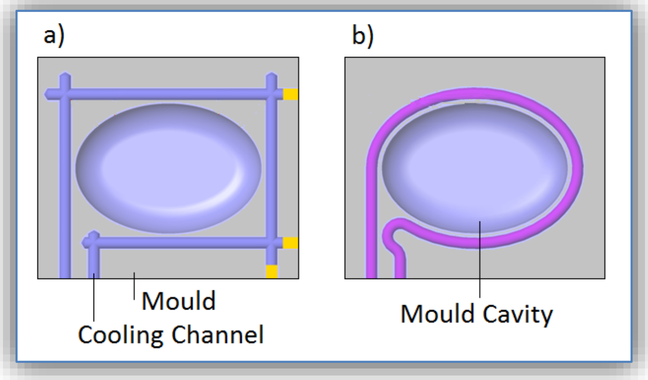

Figure 2. Comparison of the: a) conventional, and b) conformal cooling channels

For investigation, a free-form shaped thin-walled part from automotive industry was selected - cover of the rear view mirror. Cover is lacquered to high gloss and its surfaces must be smoothly aligned to surfaces of the adjacent mirror covers. Therefore, the high dimensional accuracy must be achieved during moulding.

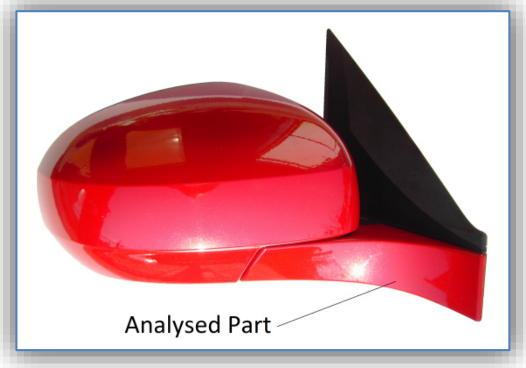

Figure 3. The rear-view mirror and analysed part

Analysed cover as a component of the complete mirror set is shown in Figure 3. Detail of the cover showed from both sides, created as CAD model, is in Figure 4.

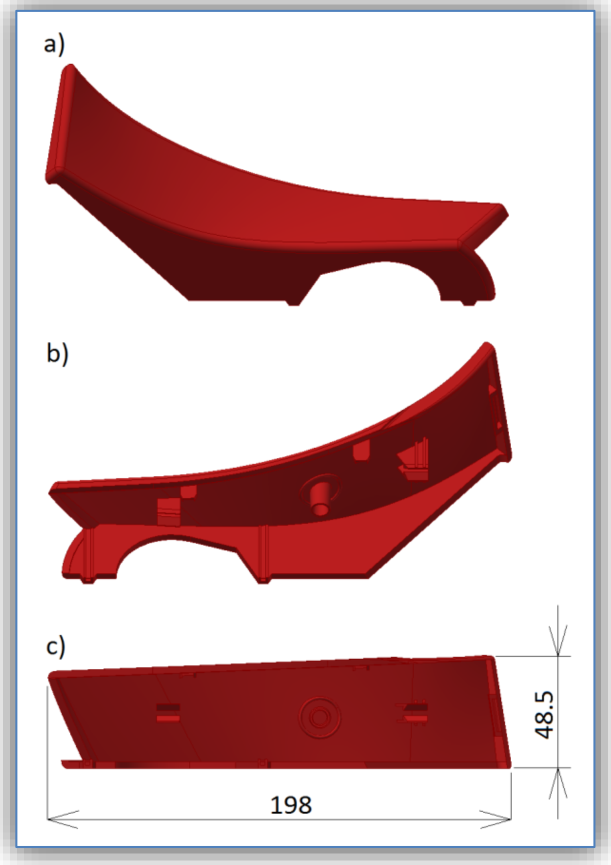

Figure 4. CAD model of the cover from:
a) front side, b) back side, c) dimensioned view

Cover is made from ABS Novodur P2H-AT with wall thickness in range of the 1 - 3 mm. Injection shot volume is around 44580 mm^3 and part weight is 0,03 kg.

Cover includes the fixing and guiding features, which require using of the cores and lifters in mould, limiting the space for channels drilling and thus the coolant cannot be applied to important places of the heat concentration. Cover is product of the mass-production and designed as left and right. Any shortening of the production time can have significant influence on production cost saving and final product price. Therefore, creating of the conformal cooling in this case would have positive effect.

In the first step, the heat conduction in mould during cover moulding was studied in order to determine where cooling channels should be localized. Hence, the fast computation model of the mould with runner and without cooling system was prepared in Moldex3D/Solid and preliminary analysis of the cavity filling/ packing was carried, mainly in order to identify the distribution of the temperature fields in mould. Also an effort to optimization of the injection parameters. In Figure 5, the areas of the heat concentration inside the solidifying cover, which require more intensive cooling, is showed as a result of the preliminary analysis. Typically, these are the areas of the thicker walls, corners and region of the runner gate, which solidifies last. They are characterized by molten core at the end of the packing phase.

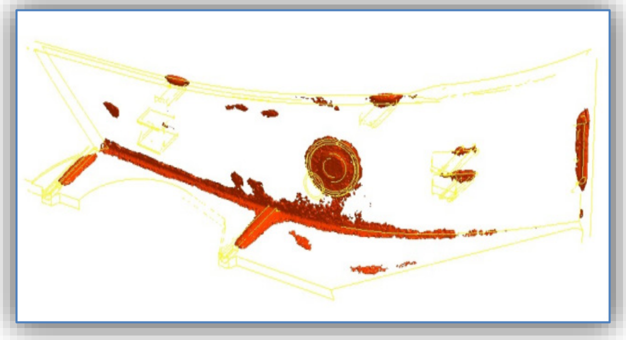

Figure 5. The areas of the potential heat concentration inside the cover

Consequently, the several types of the conventional and conformal cooling channels were designed. In following Figures 6 and 7, some models of these designs are illustrated.

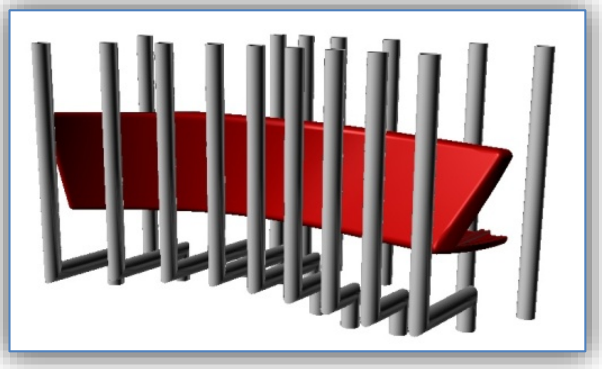

Figure 6. Design of the conventional cooling channels

For all of these designs, full computation model of the complete injection mould was generated from solid meshes of the mould cavities, runner systems, cooling systems and mould bases. In order to achieve maximal accuracy of the analysis results, the mould cavities were meshed by BLM hybrid meshes from tetrahedrons elements for cavity cores and two refined layers of the hexahedron elements for cavity surfaces. The example of such full computation model is shown in Figure 8.

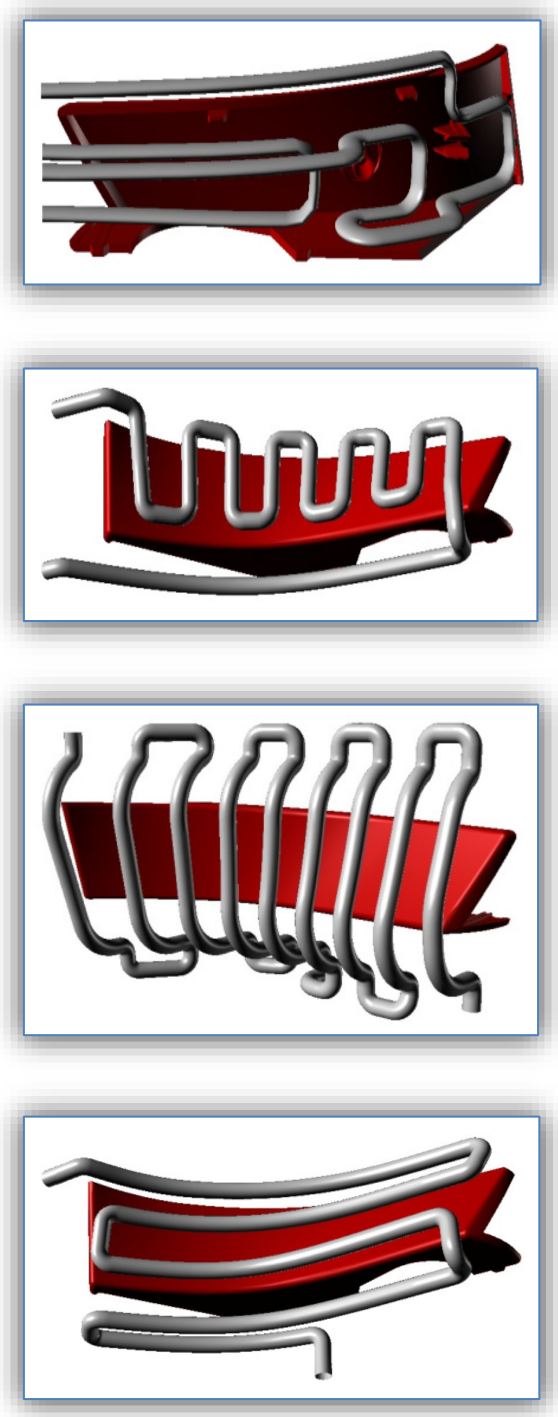

Figure 7. Several designs of the conformal cooling channels

In the next step, the detailed analyses of the cavity filling, packing, cooling phase and part warpage were performed in Moldex3D/Solid solver for all cooling system designs.

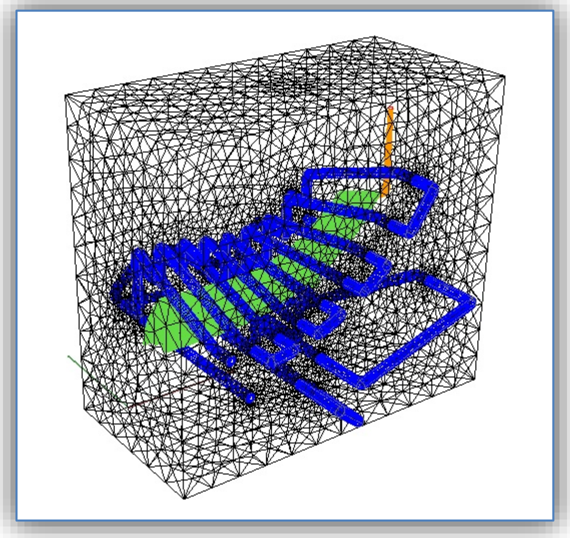

Figure 8. Full computation model of the injection mould with conformal cooling.

RESULTS

The freeze temperature of used plastic was approximately 115°C and recommended temperature for part ejection from mould was 85°C. For all of the cooling designs, estimated cooling time of the 20 sec. was preliminary determined at first and temperatures fields inside the moulds and parts were simulated in this time step. The results of these analyses are shown in Figures 9 - 12 in cross-sections of the moulds with the best conventional and conformal cooling solution.

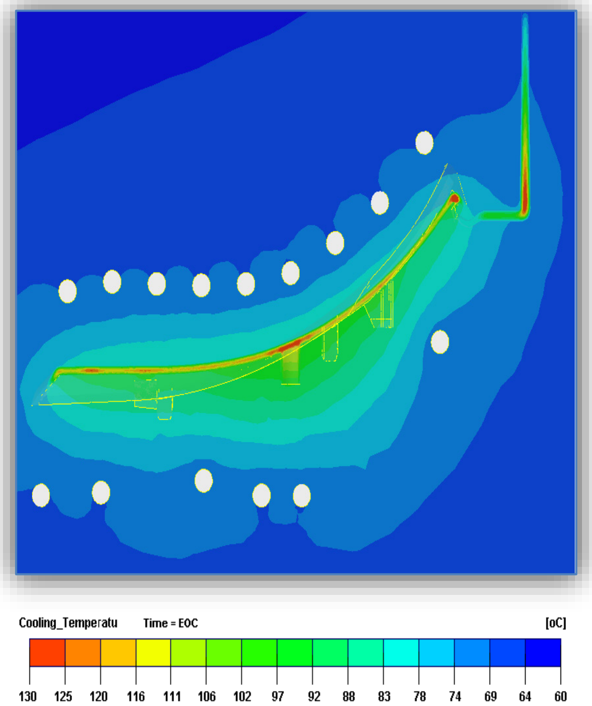

Figure 9. Temperature fields in conventional channels cooled mould after 20 sec. of cooling time (perpendicular cross-section)

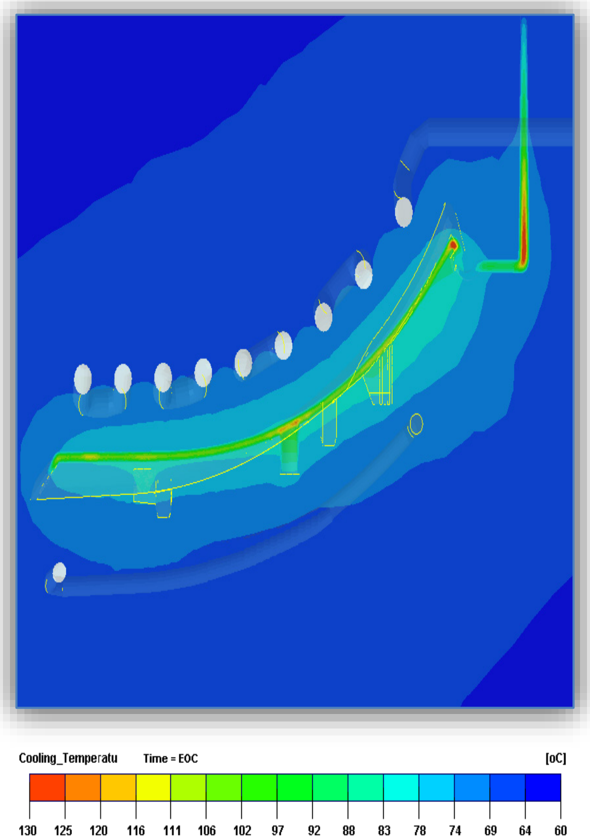

Figure 10. Temperature fields in conformal channels cooled mould after 20 sec. of cooling time (perpendicular cross-section)

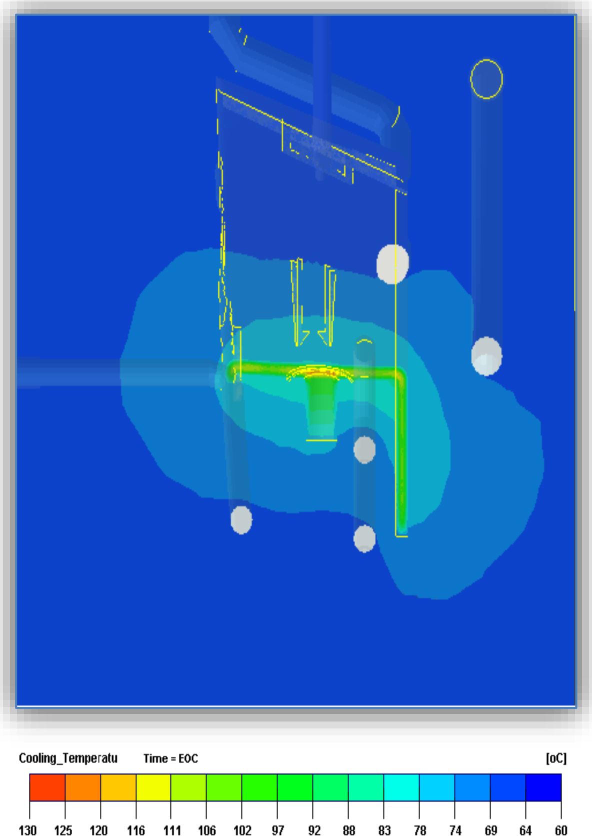

Figure 12. Temperature fields in conventional channels cooled mould after 20 sec. of cooling time (longitudinal cross-section)

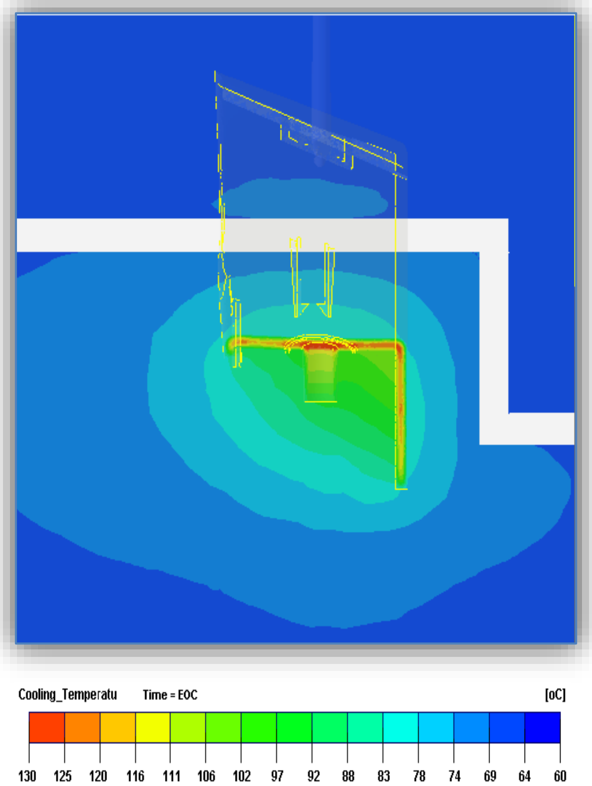

Figure 11. Temperature fields in conventional channels cooled mould after 20 sec. of cooling time (longitudinal cross-section)

According to results, the most of the conventional cooled part achieved temperatures higher than 115°C at the end of 20 seconds cooling time, thus the most of plastic was in molten state in this time. Although conformal cooled part contained molten core also, this were only minimal and acceptable for part ejection due to most of this part was cooled down to temperature about 85°C, thus to sufficient temperature for part ejection. The estimated cooling time for the conformal cooled cover of 20 seconds was identical as computed required cooling time of 23 seconds, according to mathematical relation for cooling time of the thin-walled parts. As following analyses showed, the necessary cooling time in case of the conventional cooling cover was 34 second. The obtained time saving was 41 %. If mass-production of the 50 000 cycle (for one mould life cycle) is considered, time saving of 194.4 hours would be obtained.

In the next step, the results of the warp analyses were evaluated. During cooling, the cover had tendency to bend and flexure to itself. The warping behaviour of the solidifying cover is shown in Figure 13.

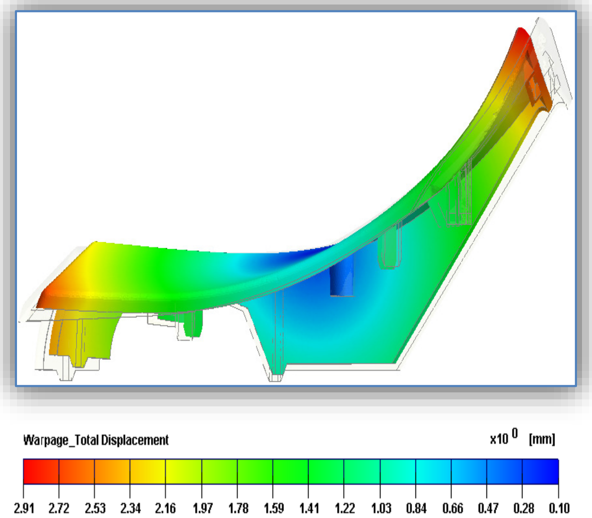

Figure 13. Warp behaviour of conventional cooled cover in scale 2

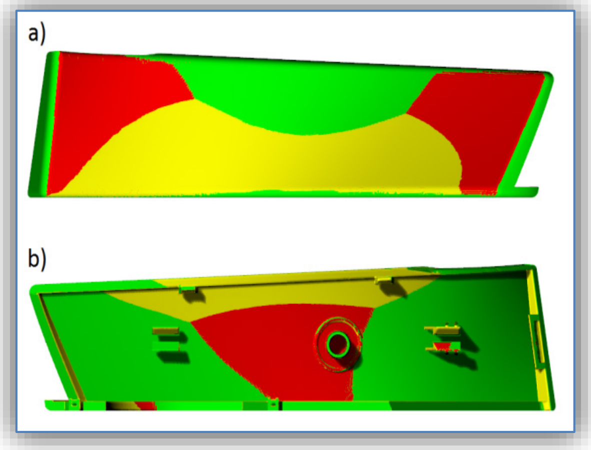

Figure 14. The comparison of the non-deformed (green), conventional cooled (red) and conformal cooled (yellow) cover

The maximal total displacements were observed on the opposite outer corners. In the case of the conventional cooling, the maximal displacement achieved almost 3 mm. On the other side, it was only 1.4 mm in the case of the conformal. However, the warp behaviour of the covers cooled by both cooling systems was partially different mainly due to conformal channels located in area around the mould inserts, where conventional channels cannot be introduced. The comparison of the non-deformed, deformed conventional and deformed conformal cooled cover is shown in Figure 14. In case of the fixing and guiding features, the attained total displacement were in lower range of less than 1 mm between both cooling variants.

Since the conformal channels offered more effective cooling than conventional ones, these were integrated to design of the family 2+2 injection mould for two right and two left cover. Its final design including cooling channels is shown in Figure 15.

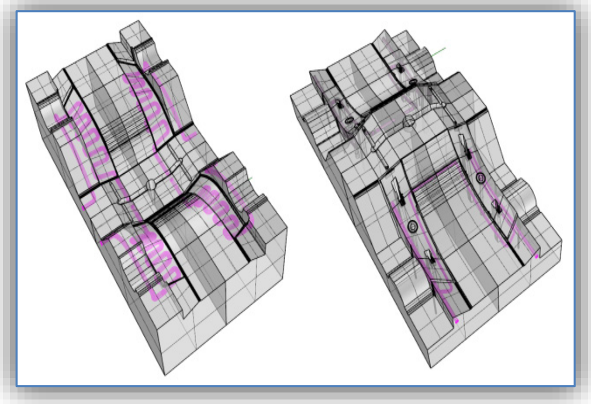

Figure 15. Final design of the injection mould with conformal cooling (A and B blocks)

In an effort to achieved the maximal effectiveness of the cooling, the channels with elliptical cross-section profile was used in areas between mould inserts due to elliptical profile is characterized by the higher perimeter in relation to internal area than it is in a circular, so the heat transfer from mould to coolant can be increased by this way. Cross-section of the mould in area with elliptical channels is shown in Figure 16.

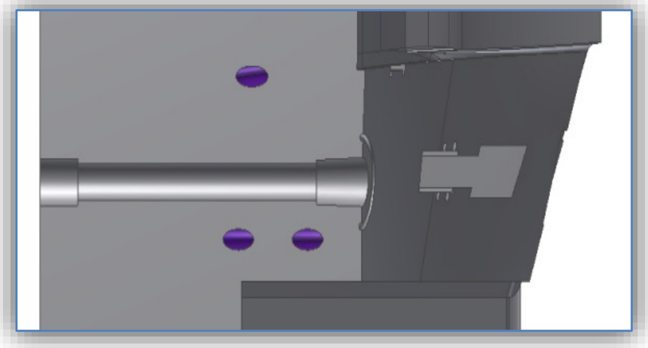

Figure 16. Cooling channels with elliptical cross-section in area of the mould inserts

Generally, the same minimal distance of 8 mm between mould cavity and channel axis was preserved for all channels so the same conditions were retained for correct cooling systems investigation.

Table 1. Moulding Parameters

Parameter	Value	Unit
Melt Temperature	240	°C
Mould Temperature	60	°C
Filling Time	1.6	s
Packing Time	6	s
Coolant Temperature	60	°C
Max Injection/Packing Pressure	12	MPa

Finally, the injection moulding parameters according to Table 1 were determined for cover production.

CONCLUSIONS

In this case study, a cooling effectiveness of the several variants of the conformal cooling system design were investigated in comparison to conventional using a part form automotive industry. As results of the numerical modelling shown, there can be achieved more intense heat removal and more balanced temperature fields inside mould during cooling, which can have the positive effect on cooling time decreasing and reduction of the product warpages. The effectiveness of the conformal cooling channel is given mainly by the possibility of the geometrical freedom for its design. If the application of the conformal cooling channels should be approved, the using of the adequate production technology for mould manufacturing must be considered. However, although the benefits of the conformal cooling system were proven by the numerical analyses, the final confirmation of the obtained results requires another experiment based on the real injection moulding and product warpages measuring.

References

[1.] G. Menges, W. Michaeli, P. Mohren. (2001). How to make injection molds. Cincinnaty: Hanser, Hanser garden, third edition

[2.] D. Kazmer, (2007). Injection mold design engineering. Hanser Verlag, 423

[3.] CoreTech System Co., Ltd., (2011). Moldex3D 3D Cooling Channel Simulation - Functionalities and Features. Moldex3D R11 European Webinar Series

[4.] CoreTech System Co., Ltd., (2012). Conformal Cooling Industrial Application and Design Optimization Technology. Moldex3D R11 European Webinar Series

[5.] H. S. Park, N. H. Pham, (2009). Design of Conformal Cooling Channels for an Automotive Part. International Journal of Automotive Technology, vol. 10, no. 1, pp. 87–93

[6.] D. E. Dimla, M. Camilotto, F. Miani, (2005). Design and optimisation of conformal cooling channels in injection moulding tools. Journal of Materials Processing Technology, vol. 164–165, pp. 1294–1300

[7.] H. S. Park, N. H. Pham, (2009). Design of Conformal Cooling for an Automotive Part, International Journal of Automotive Technology, Vol. 10, No. 1, pp. 87–93

[8.] J. C. Ferreira, A. Mateus, (2003). Studies of rapid soft tooling with conformal cooling channels for plastic injection moulding. Journal of Materials Processing Technology, vol. 142, pp. 508–516

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University POLITEHNICA Timisoara,
Faculty of Engineering Hunedoara,
5, Revolutiei, 331128, Hunedoara, ROMANIA
http://acta.fih.upt.ro