Utilizing of inner porous structure in injection moulds for application of special cooling method

M Seidl¹, J Bobek¹, J Šafka², J Havránek³, I Nováková³ and L Běhálek¹
¹Department of engineering technology, Technical University of Liberec, Czech Rep.
²Laboratory of prototype technologies and processes, Technical University of Liberec, Czech Rep.

E-mail: martin.seidl1@tul.cz

Abstract. The article is focused on impact evaluation of controlled inner structure of production tools and new cooling method on regulation of thermal processes for injection moulding technology. The mould inserts with porous structure were cooled by means of liquid CO₂ which is very progressive cooling method and enables very fast and intensive heat transfer among the plastic product, the production tool and cooling medium. The inserts were created using rapid prototype technology (DLSM) and they had a bi-component structure consisting of thin compact surface layer and defined porous inner structure of open cell character where liquid CO₂ was flowing through. This analyse includes the evaluation of cooling efficiency for different inner structures and different time profiles for dosing of liquid CO₂ into the porous structure. The thermal processes were monitored using thermocouples and IR thermal analyse of product surface and experimental device. Intensive heat removal influenced also the final structure and the shape and dimensional accuracy of the moulded parts that were made of semi-crystalline polymer. The range of final impacts of using intensive cooling method on the plastic parts was defined by DSC and dimensional analyses.

1. Introduction
The injection moulds belong among the main aspects that affect the quality of the production technology (injection moulding). The production tools include tempering systems that control the thermal processes in the mould and thereby directly influence the final properties and dimensional stability of the products. Conventional cooling methods may not be able to provide homogeneous heat transfer from the entire volume of the geometrically complex part. To increase the efficiency of the cooling process many unconventional ways of cooling were developed (vortex tube, heat pipe, Contura system etc.). These cooling systems include cooling by liquid technical gases as well. In this study liquid carbon dioxide was used for cooling of modified shape inserts in injection mould. The shape inserts were adapted for this purpose. Liquid CO₂ was spread in open-cell structure that surrounded shape cavity of injection mould. The core of the bi-component core / shell structure was created by pore elements that increased the surface area available for heat transfer between the solid part and coolant (air, water, oil etc.). [1, 2]
2. Materials and methods

2.1 Cooling method employing liquid CO₂
Carbon dioxide is an inert, non-flammable, colourless gas and it is delivered in a liquid state for technician applications and must be compressed above 5,185 bars (45-65 bars in pressure bottles / bundles or 12-35 bars in isolated cylinders). Pressure drop of compressed CO₂ causes its rapid adiabatic expansion when leaving the bottle or cylinder and the Joule-Thomson effect generates reduction of temperature up to value of -78,9 °C at the ambient pressure. [3]
System assembled from tubes, capillary tubes, solenoid valves and control unit was completed to deliver “liquid” carbon dioxide to critical places inside manufacturing tools. This intensive cooling method was developed in the 90th as an output of cooperation between companies Linde Gas and IKS (Iserlohner Kunststoff Technologie GmbH) and this system was introduced under the trademark “Spot cooling”. [4]

2.2 Bi-component injection mould insert
This article deals with high potential of porous metal materials in the field of intensive heat removal in combination with liquid carbon dioxide and their employing in the injection mould. The insert with bi-component core / shell structure was created with using of the DMLS (Direct metal laser sintering) technology.

2.3 Temperature fields analysis
The temperature field distribution on the part surface was observed after part removal from the mould in IR spectrum with using Flir ThermaCAM SC 660 and acquired images were further evaluated with using the software instruments of Flir company. Temperatures on the part surfaces allowed evaluating the efficiency of individual cooling variants.

2.4 Shape analysis
The progress of heat transfer from the product to the cooling system has direct impact on the shape and dimensional stability of the part. The shape stability analysis consisted of two steps. In the first stage the parts were digitized using a 3D optical measuring device Atos II and the data were then compared to the CAD model.

2.5 DSC analysis
The impact of different technological conditions on the morphology and mechanical properties of the product made of semicrystalline thermoplastic PE HD LITEN BB 29 (produced by Unipetrol) was monitored by differential scanning calorimetry. During solidification the macromolecules are formed into the structure that reflects the progress and intensity of heat removal. Each semicrystalline thermoplastic reacts characteristically to the heat removal and the cooling process should provide maximum level of macromolecule ordering and thus possibly the best mechanical properties. The test sample was subjected to a linear heating rate of 10 °C/min from a temperature of 25 °C to 150 °C. Tests were carried out according to the standard EN ISO 11357-1 with using of DSC 1 unit Stare System Mettler Toledo.

3. Results
In the first step of this study the dosing of liquid carbon dioxide into various structures was evaluated. For this purpose test samples were produced both either with the compact inner structure or bi-component (core / shell) test samples with the core created by fractal elements with size of 1 mm in the first variant and with size of 2,5 mm in the second variant. Total amount of injected cooling medium was 52,5 grams per one cycle and the batching of CO₂ followed adjusted profiles (three cooling modes). The first cooling mode denoted continuous injection of carbon dioxide for the duration of 5 seconds. In the second and third cooling mode the batching of CO₂ was divided into five
(solenoid valve was open 1 second and 1 second closed) respectively ten (solenoid valve was open 0.5 second and 0.5 second closed) pulses and the cooling cycle time had a duration of 10 seconds. Temperature distribution on the sample surfaces was monitored with using of two K thermocouples placed at locations situated geometrically to outfall of capillary tubes. The most effective cooling was observed when injecting the liquid CO$_2$ in the pulse mode with pulse duration of 0.5 s. The most uniform spread of liquid coolant was monitored inside the structure formed by fractal elements with size of 2.5 mm. Results from the first phase of the study were transferred to the production stage, where the evaluation of cooling efficiency for both cooling systems was performed. One shape insert was modified for the cooling by water that circulates in drilled tempering channels. Into this shape insert the expansion chambers were also drilled. The presence of expansion chambers allowed monitoring of the combined effect of simultaneous cooling in the conventional way and cooling with CO$_2$. The second shape insert had a bi-component structure (core / shell) with a core consisting of the fractal elements with size of 2.5 mm. Tempering water had a temperature of 40°C. Liquid CO$_2$ was injected into the shape insert in pulses with length 0.5 seconds. Distribution of temperature fields on the part surface was monitored at different cooling time (namely after 5, 10 and 25 seconds of cooling). The cooling time was set only on 5 and 10 seconds when using the liquid CO$_2$, see figure 1(left) and table 1. The produced parts were subjected to shape analyse and the results are shown in figure 1 (right). The influence investigation of the unconventional method of cooling on the morphology of produced parts was the last step of this analysis. For this purpose the DSC analysis was performed that revealed a level of macromolecular structure depending on the heat transfer progression, see table 2.

![Figure 1](image1.png)

**Figure 1.** Graphical comparison of mean values of part surface temperatures (left) and comparison of part dimensional stability (right).

### 4. Discussion

In the first part of this analysis the effective dosage of liquid CO$_2$ into a production tool was determined. The most intensive heat removal was observed when injecting the liquid carbon dioxide in the pulse way into the porous structure created by the biggest analysed fractal elements. Based on these results mould insert was designed. During injection moulding of test samples the distribution of temperature fields on the surface of the products was monitored after their demoulding from the mould. The results summarized in table 1 imply that very uniform temperatures on the product surface were achieved when cooling in conventional way. The longer the product was cooled, the lower the temperatures on the part surface were. Cooling with using of liquid CO$_2$ was assumed to be more
Table 1. Maximum and minimum temperatures on the part surface.

| Cooling time | 5 s  | 10 s  | 25 s  |
|--------------|------|-------|-------|
| Conventional cooling | max. 93 °C | 85 °C | 72 °C  |
|               | min. 91 °C | 83 °C | 69 °C  |
| CO\textsubscript{2} cooling | max. 79 °C | 66 °C  |
|               | min. 84 °C | 60 °C  |
| Combined cooling | max. 93 °C | 81 °C | 54 °C  |
|                | min. 87 °C | 77 °C | 51 °C  |

intense. However temperature distribution on the part surface was not so uniform which arose from location of the capillary tubes that fed liquid CO\textsubscript{2} into the mould insert. Combined cooling showed again relatively even distribution of temperature fields on the part surfaces. Increasing cooling time of combined cooling method did not bring a positive effect on the uniformity of temperature distribution on the part surface. Different progress of solidification process had a direct impact on the dimensional stability of the product after its removal from the mould. Even temperature field indicated better dimensional stability of the part, see figure 1 (right). The lowest level of deformations was achieved when cooling in conventional way. The lower temperature was on the part surface after its removal from the mould, the greater dimensional stability of the product. On the contrary relatively large shape deformations appeared when application of liquid CO\textsubscript{2}. With increasing cooling time the dimensional stability was even reduced. For combined cooling similar trends as for cooling with CO\textsubscript{2} were observed. With increasing cooling the part deformation increased as well. Measured values ranged between deformations obtained by individual cooling systems separately. Cooling with using of liquid CO\textsubscript{2} did not affect positively the morphology of the products, see table 2.

Table 2. DSC analyse of test samples.

| Cooling Time | ΔH | Onset of melting | Endpoint of melting |
|--------------|----|-----------------|-------------------|
| Pure PE      | 0 s | 174.8 J/g       | 84 °C             | 142 °C             |
| Conventional cooling | 5 s | 165.6 J/g       | 92 °C             | 146 °C             |
|               | 10 s | 163.1 J/g       | 90 °C             | 143 °C             |
|               | 25 s | 160.9 J/g       | 89 °C             | 142 °C             |
| CO\textsubscript{2} cooling | 5 s | 159.2 J/g       | 86 °C             | 145 °C             |
|               | 10 s | 155.3 J/g       | 83 °C             | 144 °C             |
| Combined cooling | 5 s | 163.6 J/g       | 89 °C             | 145 °C             |
|               | 10 s | 161.3 J/g       | 89 °C             | 143 °C             |
|               | 25 s | 159.8 J/g       | 87 °C             | 142 °C             |

The best arrangement of the macromolecules was achieved when cooling in conventional way in the duration of 5 seconds (the shortest analysed cooling time). Uniform morphological structure was created with regular formations of macromolecules which disintegrated when reaching relatively high temperature. Above this temperature the structure disintegrated relatively quickly. In the case of parts cooled with using of CO\textsubscript{2} less amount of heat was necessary to be supplied to disintegrate their morphological structure. Smaller macromolecular formations were disintegrated already at lower temperatures because the intermolecular forces were not strong. These facts indicated lower
mechanical properties. With longer cooling time by means of liquid CO\textsubscript{2} the uniformity of macromolecular formations was decreasing.

5. Conclusions

Liquid CO\textsubscript{2} ensured very intense heat removal from the injection mould. From the viewpoint of uniformity of part cooling the application of liquid carbon dioxide did not obtain better results than the conventional cooling method. The location of capillary tubes had a significant impact on the progress of heat transfer from the plastic part. Considering high cooling potential of liquid carbon dioxide it is also necessary to accurately specify the amount of injected cooling medium to avoid the overcooling of the production tool. Suitable applications where liquid CO\textsubscript{2} could be employed the combined methods of cooling are where this intensive cooling works together with conventional cooling way. Liquid CO\textsubscript{2} ensures very fast heat removal from hot spot areas in the mould and conventional tempering system enables the maintaining the tool at desired operating temperature.

6. References

[1] Kennedy A 2012 Porous Metals and Metal Foams Made from Powders Powder Metallurgy DOI:10.5772/33060
[2] Qu Z, Xu H, Wang T, Tao W, Lu T 2011 Thermal Transport in Metallic Porous Media Heat Transfer - Engineering Applications DOI: 10.5772/27018
[3] Union engineering 2007 Properties of carbon dioxide
[4] Resgren U, Praller A 2004 Industrial gases in plastics processing Kunststoffe (9) 251-252 Retrieved from: http://www.kunststoffe-international.com/PE102988

Acknowledgment

The published results were obtained through the financial support of the project LO1201 that was created in the framework of the targeted support of the "National Programme for Sustainability I" and the OPR&DI project Centre for Nanomaterials, Advanced Technologies and Innovation CZ.1.05/2.1.00/01.0005.