THE EFFECT OF MULTIPLE MATERIAL MOULDS ON THE THERMAL BEHAVIOUR AND MOULD DESIGN STRATEGY

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Abstract

Mould cooling is one of the most important characteristics affecting the cycle time and final product quality during the moulding process. Forecast of the thermal behaviour of hybrid moulds (these are moulds where conventional manufacturing techniques like milling are combined with Rapid Tooling techniques like Selective Laser Sintering) is not common as different materials are used like standard 1730 steel and sintering alloys.

Where it concerns optimizing the "time to market" and the related quality of the moulded products, it is essential to modify the mould design, manufacturing and final applied mould materials.

The thermal characteristics of several conventional, high-tech and RT mould materials have been analysed. These results are implemented in the final mould design strategy for both injection and blow moulding, having in mind the effect on the final cooling time and related part quality. The results are also used to solve thermal and related final part quality difficulties of actual developed moulds.

Having in mind this important issue, a fast exchange mould principle for both injection and blow moulding of hybrid moulds is developed at Hogeschool Gent. Originally designed for use within hybrid moulds, the fast exchange mould can be used with any type of injection or blow mould insert.

Introduction

Due to the increasing complexity of plastic products, moulds become more complex. Also the lead time of the mould production process is very important, related to the concurrence with for instance low remunerations countries. By use of rapid tooling production technologies, complex mould cores and cavities can be produced rather fast. Hybrid moulds are produced combining conventional and SLS technologies.

Rapid Tooling (RT) is known to be a fast and rather inexpensive method for the production of short and medium run injection moulds. Some currently existing RT techniques are Aluminium-epoxy casting resins, ProtoTool [1], DMLS, LaserForm and even high speed milling. As for medium run injection moulds, currently selective laser sintered RT mould inserts are used regularly.

Compared with conventional mould materials such as steel 1730 and Aluminium, RT sintered materials have the disadvantage that important cooling parameters are little understood.

Due to the combination of conventional injection mould materials and the integration with RT core and cavity mould inserts produced as with selective laser sintering technology, the thermal behaviour (the cooling time) of the hybrid injection moulds mostly can not be optimised.

This leads to difficulties in estimating cycle time and tool life as well as problems relating to the behaviour of mould material and heat transfer characteristics of rapid tooling alloys.

To analyse and predict these problems, FEM techniques have been integrated into mould design procedures.

The past

The available mould simulation software can predict the cooling time of conventional injection moulds on a rather acceptable way. This means that plastic and mould material characteristics can be involved based on the available possibilities of the related simulation software. Currently available flow simulation software such as MoldFlow and Moldex3D does not accept temperature dependant heat characteristics [2].

Recently, Moldex3D software will be updated so that it will be possible to implement temperature dependant heat characteristics.

Applications such as CalcMaster are used for forecasting cycle time, number of cores and cavities and mould costs in conventional tooling. They are not suited for use in hybrid mould analysis as the material used for rapid tooling is not solid steel, but a combination of a steel mould housing and a rapid tooling alloy; these added complications cannot, as yet, be incorporated in application specific programmes.

To analyse the effect of the added boundary conditions and the temperature dependant heat characteristics, a more general-purpose FEM thermal analysis package has been used [2].

The heat balance of injection moulds

During the analysis on the heat balance of materials, especially for plastic injection moulds, aspects as *heat capacity* $\mathbf{C_p}$, specific density ρ and *thermal conduction* λ are very important.

The relation between these characteristics is the *thermal diffusivity* α of a material.

The thermal characteristics of mould materials

Heat capacity C_p

The heat capacity below the phase change temperature of a substance is defined as the amount of energy or heat required per unit mass to raise a unit mass of substance by one degree of temperature. The equation defines the heat capacity of a substance.

$$C_P = \frac{\Delta Q}{m \times \Delta T}$$

Where:

- C_p denotes the heat capacity [J/kgK]
- ΔQ denotes the heat flow [J]
- m denotes the mass of the substance [kg]
- ΔT denotes the temperature change during heating or cooling process [°C]

Within the scope of this research work, the heat capacity of the hybrid mould materials is very important. Within the heating and cooling range during the injection moulding process, the density and conductivity is assumed to be constant. When extracting the available heat capacity from material data sheets, none or only one fixed value is normally indicated. As the heat capacity of materials is temperature and phase change related, a detailed analysis is needed. This was done via Differential Scanning Calorimetry (DSC).

DSC (Differential Scanning Calorimetry)

The Diffential Scanning Calorimetry (DSC) measures the heat flow from or to the sample as a function of temperature or time. Almost all processes occurring in and between substances generate some kind of thermal effect. Some examples of such processes are melting, chemical reaction and decomposition. Therefore DSC is used to characterise many processes in a wide variety of materials. The technique provides qualitative and quantitative information about physical and chemical changes that involve endothermic or exothermic processes or changes in heat capacity using minimal amounts of sample. It has many advantages including fast analysis time, typically 30 minutes, easy sample preparation, applicability to both liquids and solids, a wide range of temperature applicability and excellent quantitative capability. In a standard DSC apparatus, two pans sit on a pair of identically positioned platforms connected to a furnace by a common heat flow path (Figure 1). The substance sample is placed in one pan. The other one is an empty reference pan. Within the apparatus, a furnace heats the two pans at a specific rate, usually 10 or 20 °C per minute. The control unit ensures that the heating rate remains exactly the same throughout the experiment. But more importantly, it ensures that the two separate pans heat at the same rate of temperature.

The extra material in the sample pan means that it will need more heat to keep the temperature of the sample pan at the same rate as the reference pan. The DSC apparatus measures the needed heat difference between both pans.

The measurements can be plotted to show the heat difference between the first and second pan. One axis of the graph is the heat flow (i.e. the heat per time); the other axis is the temperature change per time. This means that the graph illustrates the heat capacity of the material for a certain temperature, as given by the next equations:

$$\frac{heat}{time} = \frac{q}{t} = heat\ \ flow$$

$$\frac{Temperature\ increase}{time} = \frac{\Delta T}{t} = heating\ rate$$

$$\frac{\frac{q}{t}}{\frac{\Delta T}{t}} = \frac{q}{\Delta T} = C_p = heat\ capacity$$

The DSC analysis methodology

The DSC analysis methodology consists of three analysing steps to be taken before testing.

The first step is used for calibrating the machine. The calibration of the DSC apparatus is obtained by analysing Indium.

The second step determines the base line of the machine.

The third step analyses the heat capacity of a known material. The heat capacity of this material (sapphire) is well known. After those three steps, the testing of unknown materials can start.

The heat capacity Cp is given by the following equation:

$$C_p = \frac{60 \times E_s \times (\text{heat flow metal - heat flow empty pan})}{H_r \times m}$$

Where:

- C_p: the heat capacity at a certain temperature [J/kgK]
- E_s: the cell calibration coefficient [dimensionless]
- H_r: the heating rate [°C/min]
- Q: the difference in y-axis between sample and base line curves [mW]
- m: sample mass [mg]

Thermal diffusivity

The conduction of a material illustrates the heat transport during the “steady state heat flow”. This is the moment at which a part or construction is at a fixed heat balance, time independent. The “transient heat flow” is illustrated by the thermal diffusivity. This is the time varying heat distribution within a part or construction.

$$a = \frac{\lambda}{C_P \times \rho}$$

Where:

- λ denotes thermal conductivity [W/mK]
- C_p denotes heat capacity [J/KgK]
- ρ denotes the material density at injection temperature [Kg/m³]

During the start up of an injection mould, some injection cycles will be needed to obtain a constant “steady state” situation. Once a mould is at steady state, one can assume that the heat balance of the mould will be the same during every cycle. During every cycle, the mould will be at ”transient solution heat flow”, as temperature will change due to the heating and cooling down of the plastic within the mould.

Results

When analysing the heat characteristics of different mould materials, some very important results are obtained.

Figure 2 and 3 illustrate the heat capacity $\mathbf{C_p}$ [J/kgK] of some sintering and conventional mould materials. Figure 4 and 5 illustrate the temperature dependant thermal diffusivity $\boldsymbol{a}$ of hybrid mould materials.

Some important results can be derived from these analyses. Copper is an ideal material for heat transfer within injection moulds as this is also noticed during conventional mould design. Copper and copper beryllium alloys have a heat transfer 5 till 10 times better than conventional mould steel.

Furthermore, it can be considered that Alumec and Protherm (Uddeholm^{TM} materials) are very good heat conductors, although their heat capacity are far apart: Alumec has a heat capacity more than double of Protherm.

Compared with conventional mould steel, LaserForm100 contains a lot of Bronze so that the heat balance increases with around 30%. At room and cooling temperature all DMLS metals have two times less heat transfer possibility compared with standard mould steel. At injection temperature, the difference is acceptable.

These analyses of the thermal characteristics of conventional and RT mould steels have proven that it is important to involve temperature dependant values for heat capacity, conductivity and thermal diffusivity. This is one of the main reasons why commonly used flow simulation software is not accurate enough[2].

The conventional available software predicts the general heat balance within injection moulds by use of the surface temperature of the plastic material. When identifying the heat characteristics, only fixed values for density, conductivity and heat capacity can be involved. This includes that internal heat analysis of the injection moulds cannot be evaluated in detail, resulting in a misunderstanding of hot and cold spots within the mould. In this way, optimisation of the heat balance and/or cycle time, is not always possible. Based on recent available information, Moldex3D will be upgraded so that it will be possible to implement temperature dependant heat characteristics.

Implementing the thermal results in the mould design strategy

Based on the experience and results of the material analyses, some directives for hybrid mould design strategy are suggested:

When one notices sink marks affecting the final part quality, they can partially be reduced implementing a mould insert with different thermal characteristics. By this way, the part will cool down slower or faster, resulting in a better part quality. The Belgian TETRA ongoing research project on multi material moulds [3] tries to implement and prove this via industrial case studies.

The need for a fast exchange mould system

During the design of hybrid moulds one must take into account that the inserts easily can be assembled and disassembled (fast inter-exchange mould system), so that it is possible for the operator to place another insert in a very short time. Therefore, reducing the assembling time is as important as reducing the cycle time. At Hogeschool Gent, a fast exchange mould system for both injection an blow moulding applications have been developed (Figure 6 and 7).

Integration of conformal cooling

Not only the use of hybrid moulds, but also the integration of conformal cooling techniques (Figure 8) in hybrid moulds will improve the cycle time and final product quality such as reduction of warpage. For RT mould inserts such as SLS and SLM, conformal cooling is easily to produce, even for complex parts. Those metal inserts are produced by Layer Additive Manufacturing. Implementing this technology, more uniform cooling will be achieved.

Conclusions

The effect of the integration of multi material moulds, LAM technologies and the fast exchange mould systems may not be underestimated for both injection and blow moulding applications. The actual results of several ongoing research projects at Hogeschool Gent, some of them in collaboration with research institutes such as De Nayer Instituut – Belgium and Universidade do Minho – Portugal, are promising for future results. It has proven that integration of all knowledge in a new mould design strategy is of great influence on the thermal behaviour, cycle time and final part quality of plastic parts. More detailed research results will be presented during the 2nd International Conference on Polymers and Moulds Innovations PMI2007 – www.polymoulds.org, Ghent – Belgium.

Acknowledgments

The research has been partially supported by the Belgian – Flemish IWT-TETRA research fund, under the project "*Optimizing the product quality and cycle time by improving the thermal behaviour of hybrid moulds – TETRA 050080*" and the European Leonardo da Vinci project "*E-Learning Hybrid moulds – N° 2003-B/03/B/F/PP-144.336"* www.hybridmoulds.org

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Keywords

Thermal behaviour, Thermal diffusivity, Heat capacity, Rapid Tooling, Hybrid Moulds, Layer Additive Manufacturing.

Illustrations

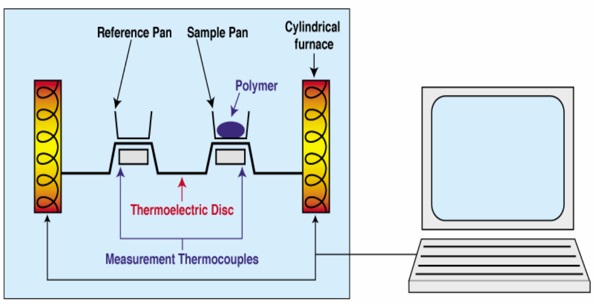

Fig. 1. DSC instrument

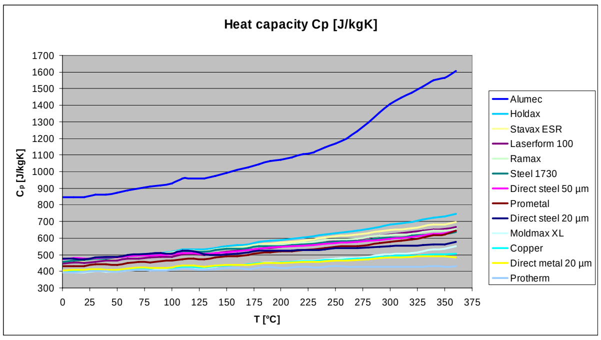

Fig. 2. Heat capacity of mould materials

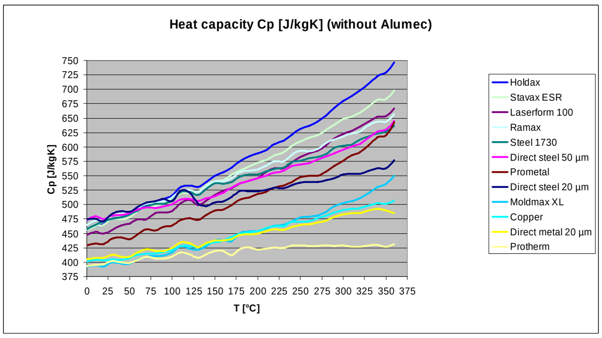

Fig. 3. Heat capacity of mould materials without alumec

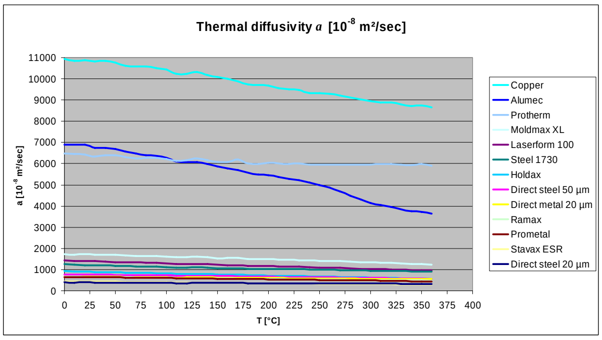

Fig. 4. Thermal diffusivity of hybrid mould materials

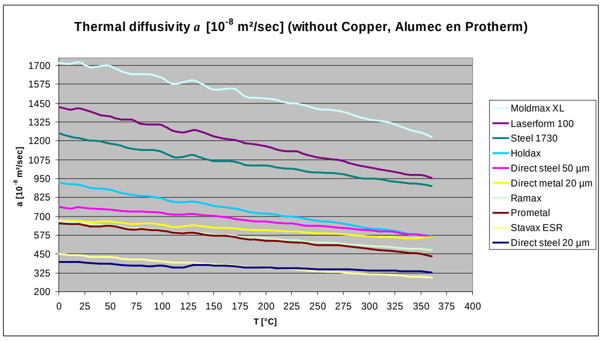

Fig. 5. Thermal diffusivity of hybrid mould materials without Copper, alumec and protherm

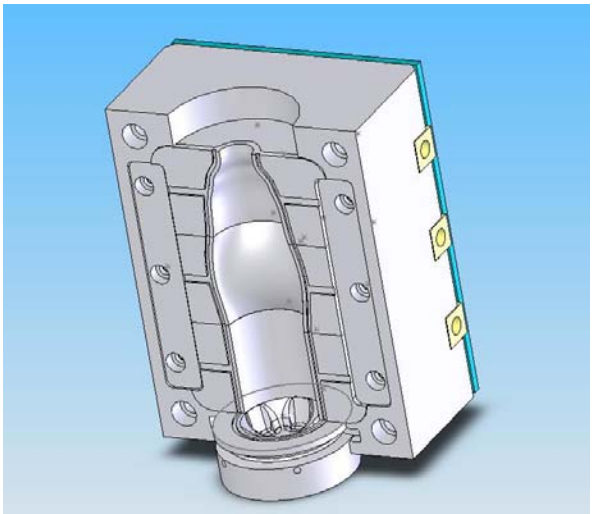

Fig. 6. Hybrid blow mould design

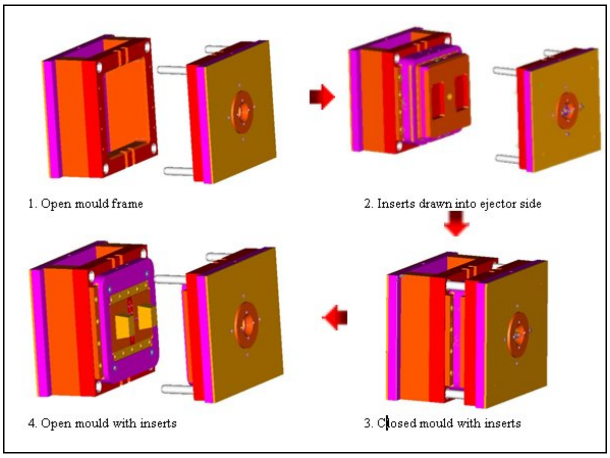

Fig. 7. Sequence of the setup of a fast exchange mould system for injection moulding

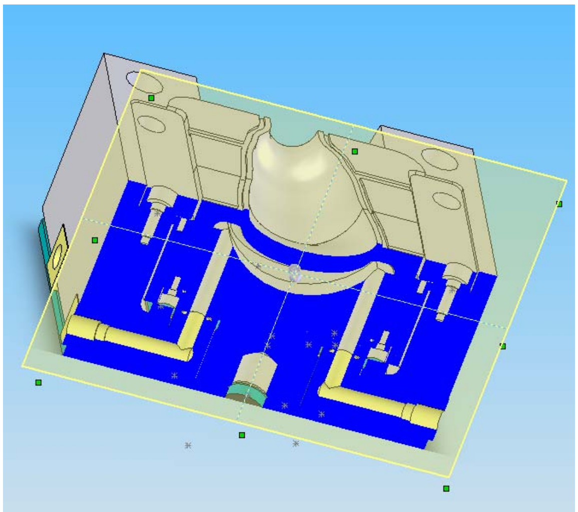

Fig. 8. A section of the blow mould with integrated conformal cooling

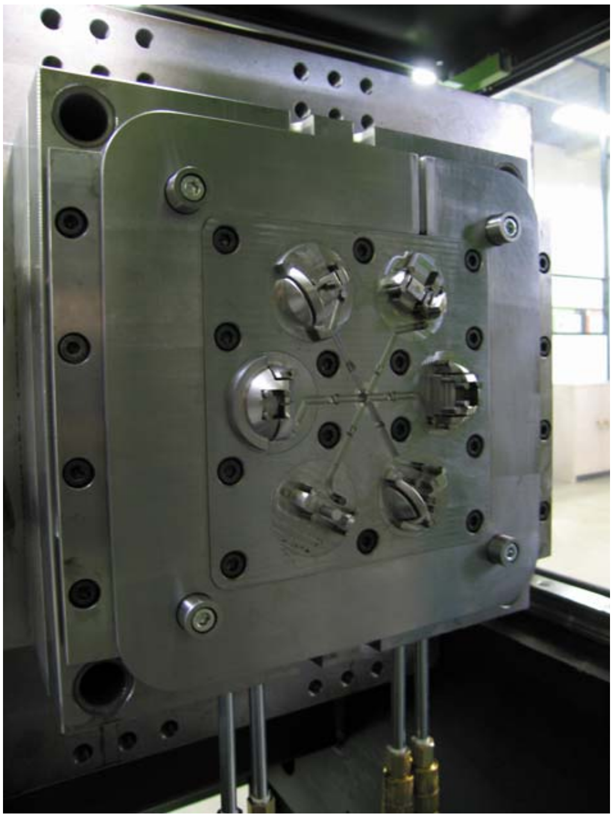

Fig. 9. The Leonardo da Vinci “knappe bollen” E-learning hybrid mould – a “family” mould