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# Thermal transfer in laminated injection moulds and comparison of the mould assembly techniques

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**ABSTRACT:** Recent studies have shown the possibilities to apply rapid prototyping methods for tool making. An advantage of these processes is the ability to obtain complex shapes (that would be impossible to obtain using machining). This aspect is particularly interesting to create cooling circuit in injection moulds. In this paper, conception of cooling circuit in laminated moulds is considered. After a description of steady state and transient heat transfer models in an injection mould, the influence of the cooling circuit geometry, the mould making technique (massive machined mould or laminated mould) and the bonding technique for laminated moulds (glued or brazed) is studied. Results show the advantage of a thermal barrier (which could easily be obtained in laminated tools) on mould thermal regulation. Discontinuities of mould material introduced by the lamination lead to a loss of thermal performance of the mould. However, a brazed mould shows performance almost equal to massive moulds.

**Key words:** laminate tooling, polymer injection, mould cooling, numerical simulation.

## 1 INTRODUCTION

Rapid prototyping processes are now applied to the tool making process to reduce development time, fabrication costs and delays. Among them, the Stratoconception<sup>TM</sup> process consists in building pieces by assembling previously machined sheet laminates. In the case of steel, sheets can be assembled by glue or brazing [1]. This procedure has been successfully applied to the fabrication of the tools of several processes such as injection, SPF, RTM...[1,2,3] In the case of injection moulds, this process allows free and complex forms, especially for cooling channels following the piece surface [3]. Conception methods used today for the cooling or heating of injection moulds [4,5] need to be adapted to this new material and its behaviour.

The objectives of the present paper are, using numerical simulations on a disc-shaped mould, to show :

- the advantage of changing the cooling circuit geometry,
- the influence of the mould making process

(massive mould machining or lamination),

- the influence of the bonding technique (glue or brazing) on the heat transfer within a simple disc-shaped mould.

## 2 INFLUENCE OF THE MOULD GEOMETRY

### 2.1 Constitutive equations

Steady state computation in the mould is used to compare the mould capacity to evacuate heat provided by the polymer to the cooling fluid.

Steady state heat transfer in the mould yields equation (1).

$$\forall M \in \Omega_M \quad \nabla^2 T = 0 \quad (1)$$

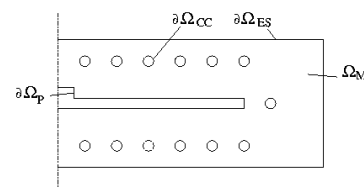


Fig. 1. Massive mould geometry and domain definition

The boundary conditions associated with the problem are (see fig. 1):

- A heat flux density representing heat provided by the polymer piece during the injection cycle is imposed on the mould cavity surface according to equation (2).

$$\forall M \in \partial\Omega_P \quad -\lambda_M \vec{\nabla}T \cdot \vec{n} = \Phi \quad (2)$$

where  $\lambda_M$  is the mould material thermal conductivity.

Heat provided by the polymer is due to cooling and crystallization according to equations (3) and (4) where  $\rho_P$  is the polymer density,  $V_P$  is the polymer volume,  $C_P$  is the polymer specific heat,  $\Delta T$  is the difference between the polymer injection temperature and the mean ejection temperature,  $\chi$  is the crystalline rate and  $H$  the massive latent heat of crystallization.

$$Q_{cooling} = \rho_P V_P C_P \Delta T \quad (3)$$

$$Q_{crystal} = \rho_P \chi V_P H \quad (4)$$

As the objective is to compare mould geometries, only a rough estimation of the heat flux is necessary and therefore, heat provided by crystallization is neglected. The heat flux density  $\Phi$  is supposed to be uniform on the mould cavity surface and is then estimated by dividing heat provided  $Q_{cooling}$  by the mould cavity surface  $A$  and the estimated cooling time  $t$  [4].

- A heat convection conditions is imposed on the cooling channel boundary (5).  $h$  is the convective heat transfer coefficient and  $T_\infty$  is the fluid temperature.

$$\forall M \in \partial\Omega_{CC} \quad -\lambda_M \vec{\nabla}T \cdot \vec{n} = h(T - T_\infty) \quad (5)$$

$h$  is estimated from fluid flow properties :

$$h = \frac{Nu \lambda_F}{D} \quad (6)$$

where  $D$  is the channel diameter,  $\lambda_F$  is the fluid conductivity and  $Nu$  is the Nusselt number.

The flow rate is chosen to get a turbulent flow ( $Re > 2300$ ). In this case,  $Nu$  can be estimated using equations (7) and (8).

$$Nu = 0.023 Re^{0.8} Pr^{1/3} \quad (7)$$

$$\text{with } Re = \frac{4\rho_F Q}{\pi\mu D} \text{ and } Pr = \frac{C_F \mu}{\lambda_F} \quad (8)$$

where  $Re$  is the Reynolds number,  $Pr$  is the Prandtl number,  $Q$  is the fluid flow rate,  $C_F$  is the fluid specific heat,  $\rho_F$  is the fluid density,  $\mu$  is the fluid viscosity and  $\lambda_F$  is the fluid thermal conductivity.

- The outer surface of the mould is isolated as heat exchange with the ambient air and the press is neglected (less than 5% of the mould heat loss [8]).

$$\forall M \in \partial\Omega_{ES} \quad -\lambda_M \vec{\nabla}T \cdot \vec{n} = 0 \quad (9)$$

## 2.2 Numerical computation

Equation (1) is solved by a finite element method using ABAQUS<sup>TM</sup>. Different configurations of the cooling circuit are tested to evaluate the influence of the number, size and position of the channels. Injection of a polypropylene disc in a steel mould cooled with water is considered (Tables 1 and 2).

Table 1. Mould and polymer thermal properties

	Mould (Steel)	Polymer (PP)
$\lambda$ (W.m <sup>-1</sup> .K <sup>-1</sup> )	36.5	0.15
$\rho$ (kg.m <sup>-3</sup> )	7820	980
$C$ (J.kg <sup>-1</sup> .K <sup>-1</sup> )	460	1700

Table 2. Fluid properties and processing conditions

$\lambda_F$	0.6 W.m <sup>-1</sup> .K <sup>-1</sup>	$T_\infty$	20 °C
$C_F$	4.18 J.kg <sup>-1</sup> .K <sup>-1</sup>	$\mu$	10 <sup>-2</sup> P
$\rho_F$	1000 kg.m <sup>-3</sup>	$\Delta T$	250-100=150 °C

## 2.3 Results

Temperature distribution is shown inside the mould in fig. 2 and on the mould cavity surface in fig. 3.

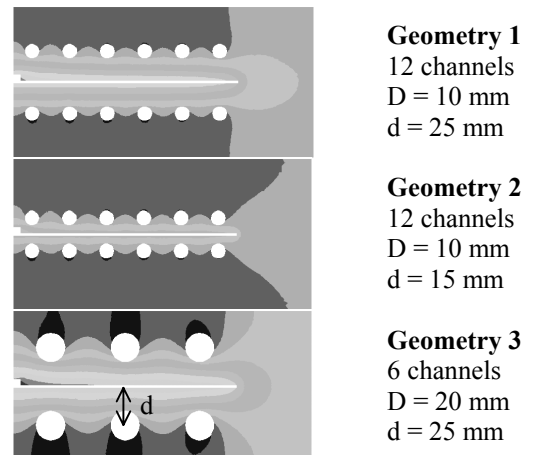


Fig. 2. Steady-state temperature distribution in the mould

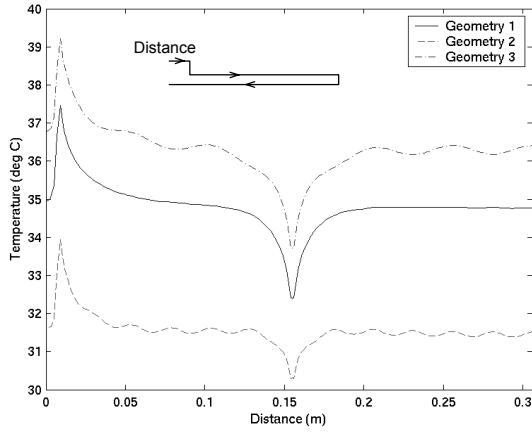


Fig. 3. Temperature distribution on the mould cavity surface according to cooling system geometry

Tendencies known by mould makers are similar to computations: a high number of cooling channels should be preferred to get a low homogenised temperature. Channels close to the mould cavity should be preferred for a low temperature but with a loss of the temperature homogeneity at the mould cavity surface. These results show the advantage of creating a cooling system surrounding the polymer piece.

### 3 EFFECT OF THE MOULD LAMINATION

#### 3.1 Introduction of the lamination in the computation model

Stratification introduces discontinuities and material changes influencing the heat transfer in the mould. Among the different possibilities, it is taken here into account in the computation by introducing a thermal contact resistance on the interface between laminates.

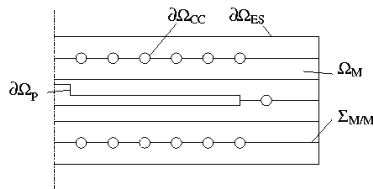


Fig. 4. Laminated mould geometry and domain definition

This resistance is evaluated by dividing the thickness  $e$  of the joint by its thermal conductivity  $\lambda$ .

Table 2. Interface properties according to assembly technique (RTG, Loctite, CEA)

	Glue	Brazing
$e$ (mm)	0.3	0.03
$\lambda$ ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ )	1.8	410
$R_{MM}$ ( $\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$ )	$1.6 \cdot 10^{-4}$	$7.3 \cdot 10^{-8}$

### 3.2 Results

The effect of the stratification is different according to the bonding method (fig. 5 and 6). When brazing is used, no differences are found compared with the original mould. Thermal contact resistance is too low to influence the heat transfer between the mould cavity surface and the cooling channel.

When glue is used, the contact thermal resistance becomes high enough compared to the mould conductivity to influence heat transfer leading to a higher temperature on the mould cavity surface.

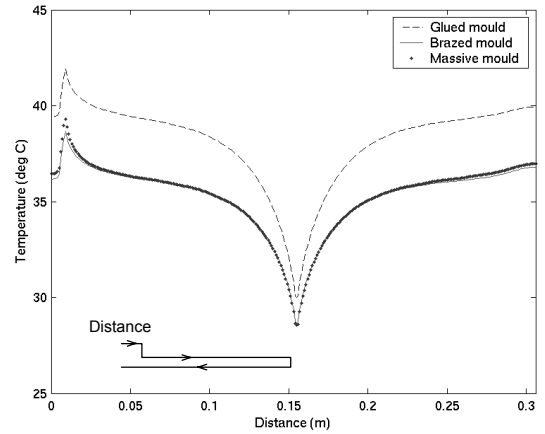


Fig. 5. Temperature distribution on the mould cavity surface according to laminate assembly technique

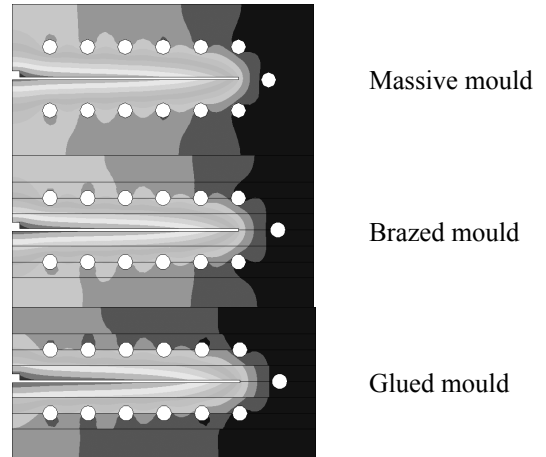


Fig. 6. Temperature distribution in massive and laminated moulds

## 4 POLYMER COOLING MODELISATION

### 4.1 Constitutive equations

The transient heat transfer equation (10) is applied to the mould and the polymer simultaneously.

$$\forall M \in \Omega_{i(i=M,P)} \quad \rho_i C_i \frac{\partial T}{\partial t} = \lambda_i \nabla^2 T \quad (10)$$

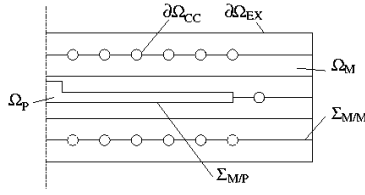


Fig. 7. Transient model domain definition

Boundary conditions on the mould channels and mould surface are the same as the steady-state model (5, 9).

For points located on the polymer surface or on the mould cavity surface, a new contact condition is introduced (11) where  $\Delta T$  is the temperature difference between the polymer surface and the mould surface,  $R_{M/P}$  is the thermal contact resistance at the mould/polymer interface and  $\Phi$  is the heat flux crossing the interface.

$$\forall M \in \Sigma_{M/P} \quad \Delta T = R_{M/P} \Phi \quad (11)$$

Several studies have been carried out to determine the value of the thermal contact resistance [6,7]. This resistance is dependant on polymer pressure and shrinkage during the injection cycle. In order to avoid a coupled thermo-mechanical computation, the resistance is supposed to be constant in the model and equal to  $10^{-3} \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$ .

In our case, the initial temperature in the polymer is uniform and equal to the injection temperature  $T_{inj} = 250^\circ\text{C}$ .

$$\forall M \in \Omega_p \quad T(t=0) = T_{inj} \quad (12)$$

The initial temperature in the mould is homogenous and equal to the coolant temperature at the beginning of the first cycle. At the beginning of the following cycle, the initial temperature is equal to the final temperature of the previous cycle (13).

$$\forall M \in \Omega_M \quad \begin{cases} T(t=0) = T_\infty & 1^{st} \text{ cycle} \\ T(t=0) = T_{N-1} & N^{th} \text{ cycle} \end{cases} \quad (13)$$

#### 4.2 Results

The results obtained here confirm the previous obtained using the steady-state model. At the cooling channel surface and at the cavity surface (fig. 8), the temperature obtained using the brazed mould is equal to the temperature obtained using the massive mould whereas the glued mould leads to a higher temperature.

In the polymer, the temperature obtained at the end of the cycle (for the same cooling time) is higher

with a glued mould. It confirms that heat transfer in the mould is less efficient with the glued assembly.

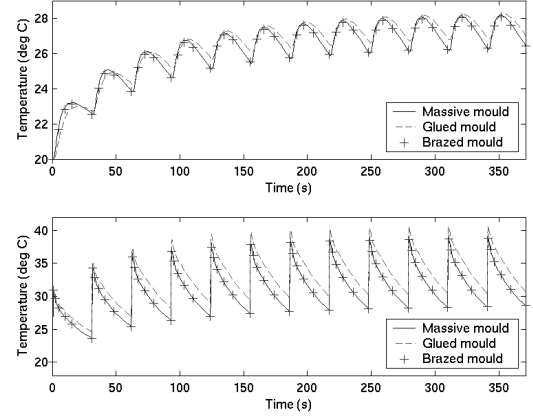


Fig. 8. Evolution of the mould temperature at the cooling channel surface and at the cavity mould surface

## 5 CONCLUSIONS

Steady state and transient models of the mould thermal regulation are detailed here and used to compare cooling channels geometry, mould making technique and bonding method. Results show the advantage of the brazed laminates making method that allow the realisation of complex shapes for the cooling system, without a modification of the heat conduction performance of the mould.

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