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INFLUENCE OF MOLD PROPERTIES ON THE QUALITY OF INJECTION MOLDED PARTS

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Abstract

Around one third of all plastics are processed by injection molding, therefore its economy and manufacturing technology have fundamental importance. The major issues in the development of injection molding tools include the progress in material technology and the developments in tool design methodology, such as developing rapid tool inserts. It is essential to develop fast methods to manufacture tools for injection-molded-like prototype parts or mass-produced parts. Due to these high requirements, it is more and more significant to use simulation methods to optimize the part before manufacturing. This paper shows the advantages of tool inserts in injection molding. The main difference between the conventional injection molding tools and rapid tool insert is also described in this paper. Beyond all questions, the rapid tool inserts cause different properties such as different warpage of the polymeric part.

Keywords: injection molding, warpage, shrinkage, injection molding simulation, rapid tooling, epoxy molding.

1. Introduction

Simultaneous engineering requires prototypes, so the design errors can be detected in the earliest possible stage of product design, cutting back the cost and time involved in the modifications.

Injection molding produces highly accurate products in a very short cycle time. It is one of the most important polymer-processing operations in plastics industry. Even in modelling of injection-molded parts one should be careful to fulfill the highly accurate product requirements. The rapid prototyping technologies usually produce inadequate models to fulfil these requirements. Rapid Tooling processes complement the Rapid Prototyping options by being able to provide higher quantities of parts in a wider variety of materials, even short-run injection molded parts in the intended production material.

2. Theoretical Background

2.1. Injection Molding Tools and Prototype Molds

Injection molding is a process by which hot polymer melt is forced into an empty, cold cavity of the desired shape and is allowed to solidify under high pressure and controlled cooling.

The conventional mold material for injection molding is usually tool steel. The mold basically consists of two parts: the stationary part called cavity plate, and the moving part called core plate. Both halves are equipped with straight cooling channels in which cooled fluid is circulated to absorb the heat delivered to the mold by the hot thermoplastic melt [1].

Rapid tooling is the term for either indirectly utilizing a rapid prototype as a tooling pattern for the purposes of molding production materials, or directly producing a tool with a rapid prototyping system [2].

Manufacturing of epoxy or aluminum-epoxy molds are reasonably quicker in comparison with machined molds. It is a relatively inexpensive way to create prototype and production tools. New epoxy resins offer much higher compression strength and heat resistance. If the molds are designed properly, they can withstand the injection or the compression pressures with the use of aluminum standoffs or mold boxes. However, the cycle time is between 5 to 15 minutes because of the poor thermal conductivity. Lifetime of the tool is a function of the thermoplastic material, fillers and part complexity. Some molds can create as few as 50 parts, while others can exceed 5.000 [2], [3], and [4].

The selective laser sintering (known as SLS) technique enables even highly complicated molds, dies and inserts to be built directly in metal from CAD data. In this case there is no geometrical restriction associated with the manufacturing tools. The laser-sintered parts can be post-processed, for example, polished to produce tools suitable for injection molding. As with all layer-manufacturing techniques, even complex shapes can be built easily, including geometries which are impossible to cut with conventional tools. One of the most important applications of this technique is to manufacture curved internal cooling channels. Depending on the type of plastic and the force and temperature of injection molding, core and cavity sets created through the SLS process can produce up to 50,000 parts [5].

2.2. Shrinkage and Warpage

Shrinkage is inherent in injection molding process. It comes from the density difference between melt and the final product, see *Fig. 1*.

Warpage is a distortion where the surfaces of the molded part do not follow the intended shape of the design. If the shrinkage throughout the part is uniform, the product will not deform or warp, it simply becomes smaller. However, achieving low and uniform shrinkage is a complicated task due to the presence and interaction

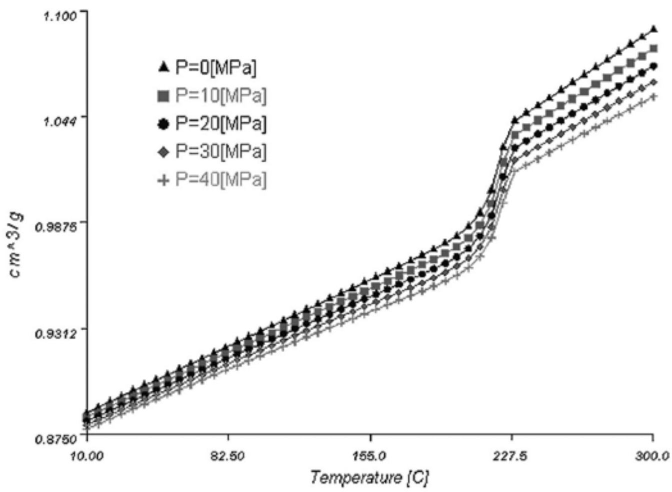

Fig. 1. The specific volume vs. temperature (pvT) curves for PA6 (Bayer Durethan B 30 S)

of many factors such as molecular and/or fiber orientations, mold cooling, part and mold designs, and process conditions.

Using the rapid tool inserts may cause warpage of the part because of the different thermal conductivity and other properties compared with conventional injection molds. Nonuniform cooling in the part, i.e. asymmetric cooling across the part thickness from the skin to the core, can also induce different shrinkage [6], [7] and [8].

2.3. *Injection Molding Simulation*

For analysing the injection molding the programmes use the equations of continuity, momentum and energy. The shear viscosity is the most important material property in numerical simulation of the filling stage (*Fig. 2*). It depends on the shear rate and the polymer temperature. The shear thinning behaviour of the viscosity is characterized either by the Power-law polymer viscosity equation or Cross-WLF equation [9]. The Power-law polymer viscosity model characterizes the flow behaviour of the material but it only works when shear rates are relatively high. This model does not account the effect of pressure and it might lead to inaccuracies. The Power-law equation, utilized by the Moldflow programmes, is the following [9]:

$$\eta(T, \dot{\gamma}) = A \cdot \exp\left(\frac{T_a}{T}\right) \cdot \dot{\gamma}^{(n-1)}, \tag{1}$$

where T is the actual temperature, T_a is the ambient temperature, $\dot{\gamma}$ is the shear rate, n and A are constants.

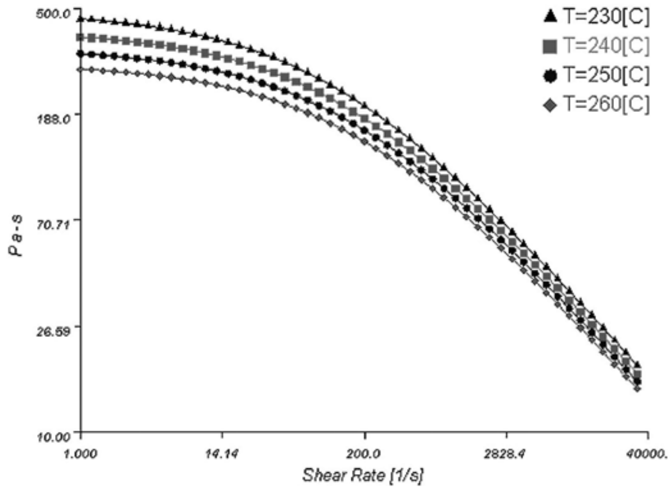

Fig. 2. Viscosity – shear rate function for PA6 (Bayer Durethan B 30 S)

The Cross-WLF model is more appropriate for injection molding simulations as temperature and pressure sensitivities of the zero-shear viscosity are better represented. The shear thinning behaviour of the viscosity is characterized by the Cross-WLF equation [9]:

$$\eta(T, \dot{\gamma}, p) = \frac{\eta_0 (T, p)}{1 + \left[\frac{\eta_0(T) \cdot \dot{\gamma}}{\tau^*}\right]^{(1-n)}}, \tag{2}$$

where $\dot{\gamma}$ is the shear rate, p is the pressure, T is the temperature, τ^* is constant and η_0 is the zero-shear viscosity which can be represented by the WLF form as follows:

$$\begin{aligned} &T > T_{\text{trans}} \rightarrow \eta_0(T, p) = B \cdot \exp\left(\frac{T_b}{T}\right) \cdot \exp(\beta \cdot p) \\ &T < T_{\text{trans}} \rightarrow \eta_0(T, p) = \infty, \end{aligned} \tag{3}$$

where T_{trans} is a reference temperature and is typically taken as the glass transition temperature of the material, B, T_b and β are constants.

The pvT data reflect the transitions as the material undergoes a phase change from a physical state to another (from melt to solid). The kink of the curve of pvT data of crystalline thermoplastics (*Fig. 1*) at atmospheric pressure is the crystallization temperature of the material (T_g). It depends on pressure. The slopes of the specific volume vs. temperature curves in the melt and solid states represent the bulk thermal expansion coefficients in the given states.

Modified Tait polymer density equation describes the variation of density (specific volume) with temperature and pressure in the melt and the solid states, between room and processing temperature over a wide pressure range:

$$\rho(T,p) = \left[\nu_0(T) \times \left(1 - C \times \ln\left(1 + \frac{p}{B(T)}\right)\right) + \nu_1(T,p)\right]^{-1}, \qquad (4)$$

where ρ is the polymer density, C is a universal constant which is equal to 0.0894, $\nu_0(T)$ is a temperature dependant specific volume, $\nu_1(T,p)$ is a temperature and pressure dependant specific volume. Above the transition temperature $\nu_1(T,p)$ is equal to zero.

Finite element methods are used to solve the coupled equations of continuity, momentum and energy. Three-noded triangular elements are used to describe the cavity and two-noded tube elements for the runners, connectors and channels. The melt front advancements are calculated by the control volume method. The pressure, temperature and velocity field can be obtained in each time step. These results constitute the basis of the stress and deformation analysis [8], [9], [10].

3. Experimental

A number of simulation packages are commercially available for the simulation of the injection molding process such as the Moldflow Plastics Insight. The basic idea is to create a model of the geometry or mold to be analysed as *Fig.3* shows.

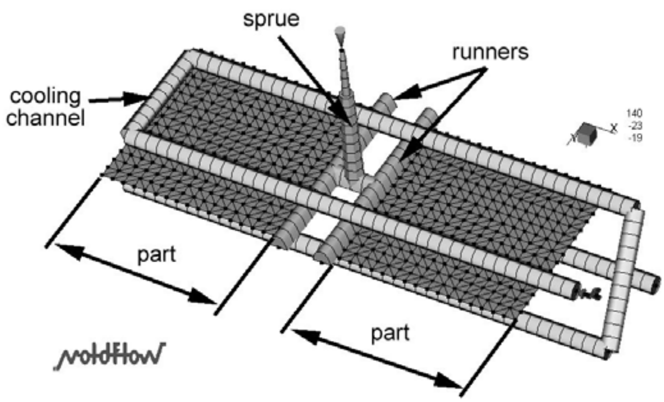

Fig. 3. FEM model of the examined part

In the present work the conventional injection mold was compared to the rapid tooling. There are significant differences between these two techniques such as the mold materials, which cause different cycle times, and warpages.

Naturally, the durability and abrasion of the rapid tool inserts are worse compared to the conventional molds, but it is worth to use to produce a couple of thousand parts.

In practice, rapid tooling mold material can be added to the simulation programme (material database).

As a mold material we investigated an epoxy resin filled with metal powder to increase stiffness and heat conductivity. The epoxy resin has a heat conductivity of 0.2 W/mK, the metal has 75–90 W/mK, while the metal powder has 6–10 W/mK depending on the porosity. The heat conduction is dramatically grooving up above the limit of 90% metal filler, but in practice the possible ratio is around 60% to the metal powder, so heat conductivity is usually less than 0.5 W/mK as *Fig.* 4 shows.

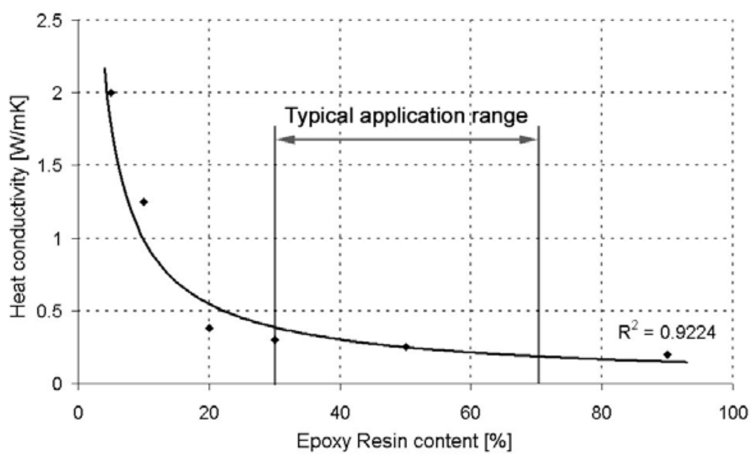

Fig. 4. Heat conductivity of metal powder filled epoxy

The influence of the mold thermal conductivity on the warpage of the mold was examined. *Fig.* 5 shows that the part warpage – which is caused by the differential cooling – is function of the mold thermal conductivity.

The typical mold thermal conductivity is between 25 and 80 [W/mC] using conventional tool steel. The deformation dependence between these values is near constant, but using rapid tool inserts it could vary much more. The selective laser sintered tool insert's thermal conductivity is less than 15 [W/mC] and the unfilled epoxy resins' thermal conductivity is around 0.5 [W/mC], which causes increased warpage of the part.

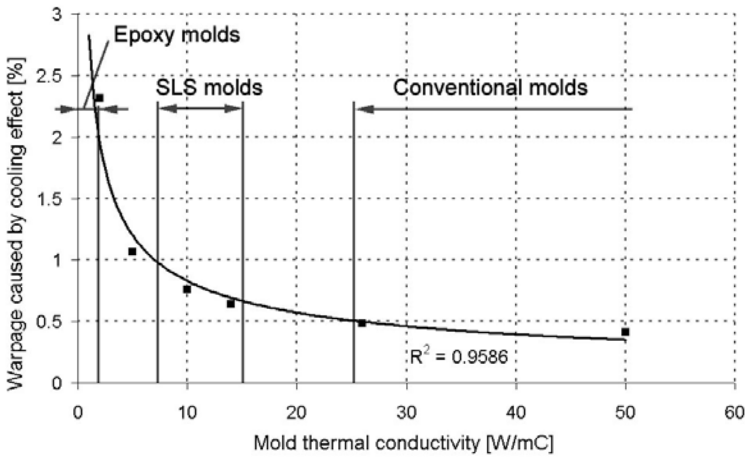

Fig. 5. The influence of the mold thermal conductivity on warpage

4. Summary

It has been demonstrated that the rapid tool inserts are useful in the injection molding technology although the warpage of the part could be more significant. Injection molding simulation programmes can analyse the cooling, and can optimize or minimize the warpage using special cooling channel forms.

The mass-production with these rapid tooling technologies is already available, but the prototyping methods could be improved to produce more accurate tools with better surface finish.

Acknowledgements

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