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Simulation of transport processes in squeeze casting

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Abstract

In squeeze casting process, molten metal is cooled and solidified at a very high level of pressure around and over 40 MPa. The time required for solidification is substantially reduced due to enhanced heat transfer at the mould surfaces under high pressure. In the present paper, a fixed grid enthalpy formulation is applied to model solidification for a cylindrical geometry (ϕ 200 mm × 100 mm). The solidification time is estimated at varying heat transfer coefficient with A-356 as the domain material. Higher heat transfer coefficient is interpreted as a consequence of higher applied pressure. The solidification time, as estimated by monitoring liquid fraction, was found to decrease asymptotically with increasing heat transfer coefficient. Segregation pattern in the object was studied by solving the species transport equation. The effect of segregation is found to be negligible for small-volume objects. It is also observed that the contribution of convection can be safely neglected in analysing the solidification process during squeeze casting.

Keywords: Squeeze casting; Simulation; Solidification; Heat transfer; Segregation

1. Introduction

Squeeze casting is an advanced manufacturing process where molten metal is subjected to high applied pressure during cooling and solidification [1,2]. The advantages of the squeeze cast products are mainly near-zero gas porosity or shrinkage porosity, better mechanical properties and reduced metal wastage. It has been reported that the mechanical properties of a squeeze cast item can be as good as wrought products of similar composition [2,3].

In squeeze casting, the applied pressure plays a very important role. The influence of high pressure on the properties of cast product has been a subject of research during last four decades, see e.g. in Refs. [4,5]. The main advantage of the deployment of high pressure is that it enhances the heat transfer coefficients by several orders of magnitude. This enhancement is realized due to the establishment of direct contact between the liquid metal and the die wall. Owing to the high heat flux at the boundaries, the solidification is quickly achieved. A representative table (Table 1) is enclosed from literature [6] to demonstrate the effect of pressure on heat transfer behaviour. The applied pressure has another role in increasing the melting temperature of the alloy. This is given by the Clausius–Clapeyron equation [5] and it may be mentioned here that for Al/Si binary alloys at 150 MPa pressure, the rise in liquidus temperature by about 9 °C is observed.

Solidification and heat transfer is a very important aspect of the squeeze casting process. The quality of the cast product is dependent upon the microstructure, which in turn is an outcome of the solidification rate [7,8]. Due to very fast cooling rates at high pressure, the dendrite cell size and the closer spacing of Si particles lead to improved strength of the resultant product [4]. Thus, the quantification of thermal parameters becomes necessary. From a thermal model, the temperature profiles at a desired location and the occurrence of hot spots could also be predicted.

Among the past works, Lee et al. [6] analysed the 2-D conduction process in the die–mould assembly to predict the temperture histories. They incorporated the latent heat term in the equivalent heat capacity formulation. The work of Zhang and Cantor [9] simulated heat transfer along with phase change for A356 alloy using finite difference technique. This work demonstrated that solidification time decreases asymptotically with increased heat transfer at the walls. Youn et al. [10] studied the solidification process in an automotive disk brake manufactured through squeeze casting route using MAGMASOFT package. They have observed that the mechanical properties of the developed components are related with the temperature distribution.

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Nomenclature

C	concentration
C_p	specific heat at constant pressure
D	diffusivity
h	sensible enthalpy
H	total enthalpy
J	diffusive flux of secondary phase
k	thermal conductivity
k_s	partition coefficient
L	latent heat of fusion
m	gradient of liquidus line
P	pressure
r	radial coordinate
R	source term in diffusion equation
s	source term in momentum equation
t	time
T	temperature
v	velocity

Greek symbols

β	liquid fraction
μ	viscosity

Superscripts

liq	liquid
m	melting point of pure metal
o	overall
sol	solid

The analysis of segregation is another important parameter related to casting process. Segregation determines the quality of the final product and should be avoided as far as possible. However, due to limited solubility of the secondary phase at a particular temperature, segregation is bound to occur. Previous authors [11,12] have related the observed segregation pattern with the thermal transient field. However, these studies did not quantify the segregation numerically as they do not treat the transport of solute separately.

2. Scope of work

The present work attempts to simulate in a systematic manner the heat transfer process during squeeze casting for a cylindrical geometry. The simplified geometry is dimensionally closer to typical automotive components in the order of magnitude of their sizes. Through numerical analysis, time requirement for solidification has been estimated at different levels of heat transfer. The question of whether to incorporate the effect of convection in the simulation is also addressed. Besides the solidification history, it was also attempted to quantitatively study the segregation pattern through numerical simulation.

Table 1
Heat transfer coefficients at different casting conditions [6]

Method	h (W/m^2 K)
Gravity	4,500
Squeeze cast $P = 25$ MPa	100,000
Squeeze cast $P = 50$ MPa	110,000
Squeeze cast $P = 100$ MPa	125,000

3. Simulation strategy

The solidification process in the present system was calculated by solving the Navier–Stokes equation along with the energy equation as given below:

$$\frac{\partial}{\partial t}(\rho H) + \nabla(\rho \vec{v} H) = \nabla(k\,\nabla T) + s \quad (1)$$

The transport of the secondary phase is governed by:

$$\frac{\partial}{\partial t}(\rho C) + \nabla(\rho \beta \vec{v} C) = -\nabla(J) + R \quad (2)$$

where

$$J = -\rho[\beta D_l\,\nabla C_{liq} + (1-\beta) D_{sol}\,\nabla C_{sol}] \quad (3)$$

The solidus and liquidus temperatures are related in the following manner:

$$T_{sol} = T_m + \frac{m_c C_s}{k_s} \quad \text{and} \quad T_{liq} = T_m + m_c C_s$$

Liquid fraction in the mushy region is related to its temperature in the following manner:

$$\beta = \frac{T - T_{sol}}{T_{liq} - T_{sol}} \quad (4)$$

For, $T > T_{liq}$, $\beta = 1$ and when $T < T_{sol}$, $\beta = 0$.

Here, subscripts sol and liq indicate solidus and liquidus, respectively.

It may be mentioned here that relationships other than the linear rule as in Eq. (4) are also possible. However, the linear rule is preferred for its simplicity. The recent work of Bakhtiyarov et al. [13] demonstrated that for Al alloy the results from the linear relation relationship and from Scheil model do not differ significantly.

The above Eqs. (1) and (2) are elliptic partial differentials equations. They can be numerically solved when appropriate boundary conditions are known. The boundary conditions may be of Dirrichlet type or Neumann type or a combination of them.

A very popular approach for modelling solidification is the fixed grid enthalpy approach due to Voller and Prakash [14] in which fluid and solid zones are not treated separately but a common grid is used in the entire region. The solidification front is traced as a part of the solution of the enthalpy equation. The liquid fraction of the mushy zone is obtained from the linear relationship described in Eq. (4).

The domain material used in the simulation was A356. The physical properties are provided in Table 2.

The above formulation was used to build a model using FLUENT commercial CFD code [15]. A cylindrical geometry (ϕ 200 mm × 100 mm) was simulated to study the effect of