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Friction modeling and analysis of injection process in squeeze casting

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ABSTRACT

An analytic model is presented for quantitatively investigating the impact of friction between the punch and the shot sleeve on dynamic match status during the injection process of squeeze casting, with the ultimate purpose of optimizing machine design and controlling injection process more accurately. By combining lubrication model and friction experiment, the friction characteristics between the punch and the shot sleeve are investigated in four cases of different clearance values. The lubrication model is validated by comparing the calculated and experimental values of the friction coefficient. The friction model of injection process is then established by means of updating incremental boundary conditions iteratively. The temperature and deformation data are collected from laboratory testing and used to compare with the simulation data obtained from both the general model and the proposed friction model. The simulation data from the friction model is approximately in agreement with the experimental data, better than the general model, implying that the proposed analytics model provides more accurate simulation of the friction coefficients.

1. Introduction

Injection mechanism plays a significant role in squeeze casting and die casting (Ghomashchi and Vikhrov, 2000). Under cyclic thermal and mechanical loading, the defects such as plastic deformation, fatigue fracture and abrasion intend to occur on two key components of injection mechanism, i.e., the shot sleeve and the plunger (Shi, 2002). Recently the use of new materials, e.g., the silicon nitride ceramic, for the shot sleeve has received the attention of researchers (e.g., Okayasu et al., 2009). Moreover, the varying fitting clearance between the shot sleeve and the plunger caused by their deformation may reduce the precision and stability of the process control (Shi, 2002). Robbins (2002) believes that it is essential to maintain the reasonable clearance during the casting cycle. As such, it is of paramount importance to maintain appropriate components temperature, deformation and clearance for process control and failure prevention.

Numerical simulation has been widely used to analyze the influence of heat transfer and mechanical loads on the deformation and clearance of shot sleeve and plunger. Penhollow et al. (1992) developed a finite element model using ABAQUS software to investigate the effects of the processing parameters on the shot sleeve deformation. Paliani and Brevick (1993) improved the simulation accuracy by calibrating model parameters with experimental measurements. Brevick et al. (2002) built a three-dimensional (3D) model to predict the distortion in large diameter shot sleeves. Shi (2002) established two-dimensional plane strain computer models and thereafter extended to 3D application to study the radial distortions of the large shot sleeve with thin/thick wall thickness. In Shi's study, controlling the "out of roundness" is treated as the key factor for large Inner Diameter (ID) shot sleeve clearance design between its ID and plunger tip. The experiments were conducted on the lab testing device by Jain (1999). Mao (2004) developed an athermal shot sleeve model to estimate the externally solidified products formation during the shot sleeve pouring and shot delay time period. Its distribution in the shot sleeve is also estimated from the model. Ahmad et al. (2012) presented the design element concept of squeeze casting process. Direct Differentiation Method (DDM) and Adjoint Variable Method (AVM) were employed in calculating the design element sensitivities. Various numerical models have also been developed to simulate the flow, velocity and heat transfer in shot sleeve. Helenius et al. (2005) modeled the thermal field in the shot sleeve of High Pressure Die Casting (HPDC) using the MAGMASOFT software and investigated the temperature history. Nikroo et al. (2009) developed a 3D numerical model by using the finite difference method and the volume fluid method. The model is used to analyze the mechanism of the liquid metal flow and the possibility of air entrapment in the injection cham-

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ber of die casting machine. Korti and Abboudi (2011) simulated the interface molten metal air in the shot sleeve and the mold cavity of the HPDC machine to eliminate the creation of pores in the finished casting. However, few researchers have taken into account the friction in these aforementioned numerical models. In addition, only the horizontal injection mechanism in die casting has been considered, rather than vertical in squeeze casting.

Over the past decade, many researches have been found on quantification of friction characteristics between the shot sleeve and punch. For example, Lu et al. (1996) investigated the friction characteristics in different loading, temperature and lubricant conditions by using a friction measurement device. Huang et al. (2001) described the wear and corrosion process between the shot sleeve and punch under interference fitting in a magnesium alloy hot chamber die casting machine. Kimura et al. (2002) developed high insulating powder lubricant of shot sleeve to control the formation of the abnormal structure in aluminum alloy squeeze castings and then improve the castings strength and fracture elongation. Wang et al. (2013) proposed an approach to measure the transient friction force in a continuous-casting process. Furthermore, a few researchers have investigated the friction loading and coefficients in material process by Finite Element Analysis (FEA). For instance, Sun et al. (2012) established FEA models of the rubber forming process of Ti-15-3 alloy to analyze the effects of various friction coefficients on the strain distributions. Jin et al. (2015) designed an indirect rheo-casting die for thin plates considering two friction conditions for the cavity by a filling simulation. Ma et al. (2015) analyzed the effect of friction coefficients on the deep drawing of aluminum alloy AA6111. Nevertheless, there is a need to quantitatively investigate the interaction between the thermal deformation and friction of injection mechanism.

This paper presents a friction modeling methodology to investigate the friction characteristics between the punch and shot sleeve, heat transfer, deformation and fit clearance as well as their interaction, thus facilitating the optimal design of injection mechanism and the improvement of injection process controlling in squeeze casting. The established friction model is then validated by comparing the simulation and experimental results.

2. Friction modeling

2.1. General model

The injection mechanism of squeeze casting machine is shown in Fig. 1. After pouring the high-temperature molten aluminum alloy into the chamber, the punch moves upward at a preset rate to push the molten metal from the shot sleeve to the mold cavity. After then the punch pressure increases and maintains in the solidification. The initial clearance between the punch and shot sleeve is determined by the manufacturing tolerance. In this study, the following assumptions are made:

1 The convection in the melt is ignored;
2 The mass transfer in the liquid and solid materials is ignored;
3 During the pouring, the temperature distribution of the melt is uniform, and
4 The thermos-radiant boundary with the air is neglected.

In general model, ignoring the effect of friction between punch and shot sleeve, the transient heat transfer equation in the injection process is expressed as follows (You et al., 2007):

$$\rho c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+Q \quad (1)$$

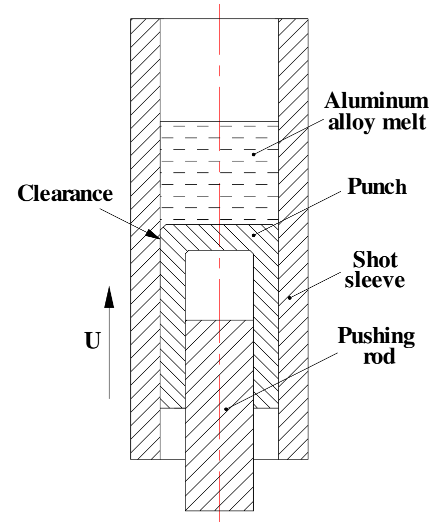

Fig. 1. Injection mechanism.

where λ is the thermal conductivity; T is the transient temperature; Q is the heat source or latent heat; ρ is the material density; c is the specific heat capacity, and t is the time. The enthalpy method is used to compute the latent heat in this study.

The boundary condition for Eq. (1) is

$$-\lambda\left(\frac{\partial T}{\partial n}\right)_{\Gamma}=h\left(T_f-T_w\right) \quad (2)$$

where n is the normal direction of the heat exchange surface; h is the surface heat transfer coefficient; The symbol Γ is objects' interface; T_w is the temperature of the punch or shot sleeve, and T_f is the temperature of the melt.

In the heat transfer process, the change of temperature and phase may cause the deformation of the injection mechanism and casting. Thus the stress-strain field is calculated as follows (Cho and Lee, 2014):

$$d\{\sigma\}=\left[D_{ep}\right](d\{\varepsilon\}-d\{\varepsilon_T\}-d\{\varepsilon_0\})+d\{\sigma_0\} \quad (3)$$

where $[D_{ep}]$ is the elastic-plastic matrix; $d\{\varepsilon_T\}$ is the thermal strain; $d\{\varepsilon_O\}$ is the additional strain, and $d\{\sigma_0\}$ is the additional stress. The stress-strain relationship can be obtained from the generalized Hooker's law. Therefore, the derived thermal-mechanical coupling formula of finite element method is given by Heckel et al. (2012):

$$[M]\left\{\frac{\partial^2\delta}{\partial t^2}\right\}+[N]\left\{\delta\right\}=\left\{F\right\} \quad (4)$$

where $[M]$ is the structural mass matrix; $[N]$ is the stiffness matrix; $\{\delta\}$ is the unknown structural displacement of shot sleeve and punch, and $\{F\}$ is the sum of the thermal load vector, body force, surface force and concentrated force.

2.2. Friction modeling

During the injection process, the temperature of the injection mechanism increases due to the heat transfer between the melt and the shot sleeve or the punch, leading to the thermal expansion of components. Different thermal expansion coefficients result in various deformations and various fit clearance values. Consequently, the change of the oil film thickness will result in the variation of the friction coefficient.

In this section, the lubrication numerical model is established to calculate the loads of friction with different gaps under oil lubrication conditions. Then friction tests are carried out on an abrasion