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Bi-metallic dies for rapid die casting

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Almost all casting processes involve placing the melt in a mould of lower thermal conductivity. As a result, high rates of energy extraction are effectively prevented. The reasons for this are all too apparent with materials of high thermal conductivity not having the necessary mechanical and thermal properties to withstand the rigours of the casting process. Moreover, slower solidification rates allow for minimal control and relatively simple design processes. The challenge is to design dies that allow for phenomenally higher rates of heat transfer. Dies are usually manufactured from hardened steel and incorporate cooling channels in order to increase the rate of energy extraction. Dies could plausibly be made from copper which has a thermal conductivity some 16 times greater than conventional steels. However, copper cannot withstand the rigours of the casting process and in particular the abrasive action of the liquid melt albeit zinc or aluminium. This paper is concerned with the establishment of thermal models for copper-alloyed dies suitably protected with a thermally sprayed steel layer. Both steady state and transient thermal models are developed that are capable of predicting the time-averaged and transient cyclic thermal behaviour of the new die designs. The models are based on the boundary element method. A perturbation approach is adopted for the prediction of transient die temperatures. Numerical experiments are performed and predicted temperatures are compared with thermocouple readings obtained from a copper-steel die on a commercial die casting machine.

1. INTRODUCTION

Pressure die casting is an important industrial process used for the mass production of intricate components. The cost effectiveness of the process is dictated by the rate at which components can be produced and the working life of the dies. The extraction of energy from a solidifying casting is resisted by the casting itself, the thermal barrier at the casting-die interface, the die and the coolant boundary layer. The high thermal conductivity of copper makes it a plausible candidate as a replacement for the conventional tool steel in the manufacture of the die tool. However, a means of ensuring sufficient strength and resistance to the abrasive action of the liquid melt must be employed. This problem can possibly be overcome by depositing a layer of hardened steel onto a copper die block so as to establish a die with the correct mechanical and thermal properties. In order to investigate the thermal balance of the copper-steel alloy die tool and the solidification pattern of the component a numerical model based on the boundary and finite element methods has been developed. This model is capable of predicting both steady state and transient temperatures in the alloy dies and casting. The boundary element model used for the dies is based on that developed by Davey et al. [1]. This model was extended to incorporate the solidification of the casting using a FE based method by Bounds et al. [2]. To incorporate the copper-steel layer the authors have extended the boundary and finite element models and this is the focus of this paper. The copper-steel composite is modelled by considering the copper-alloy block and the steel layer as two separate domains linked by suitable boundary conditions. In practice, a high heat transfer coefficient h_{sc} is applied on the interfaces between the steel layer and the copper-alloy to reflect the physical situation.

2. STEADY STATE THERMAL BOUNDARY ELEMENT MODEL

Figure 1 shows a typical two-slide die and component from the pressure die casting process. The die naturally subdivides into zones with the copper blocks, steel layer and component each defined as separate zones. The cyclic nature of the process enables die temperature (Ψ_i) to be considered to be made up of two components as follows, $\Psi_i(\vec{x},t)=\overline{T}_i(\vec{x})+T_i(\vec{x},t)$ where $\overline{T}_i(\vec{x})$ is the steady state or time averaged temperature for the cycle and where $T_i(\vec{x},t)$ is the transient perturbation of temperature (over the cycle) about the steady state value. The steady state die model comprises a boundary integral representation of Poisson's equation [1] for the component coupled with a boundary integral representation of Laplace's equation [1] for the die blocks. These formulations can be represented by the equation below, where the domain Ω_i, is assumed to be homogeneous and to have isotropic and temperature independent thermal properties

$$k_i \overline{T}_{im} C_{im} + k_i \sum_{j=1}^{E_{it}} \sum_{\ell=1}^{3} \overline{T}_{i\ell} \int_{\Delta_j} \phi_\ell \frac{\partial \overline{T}^*}{\partial n} d\Gamma = \sum_{j=1}^{E_{it}} \sum_{\ell=1}^{3} \overline{q}_{i\ell} \int_{\Delta_j} \phi_\ell \overline{T}^* d\Gamma + Q_i \sum_{j=1}^{E_i} \int_{\Delta_j} \frac{\partial U}{\partial n} d\Gamma \qquad (1)$$

where $\vec{x}_m$ is the source point position, Δ_j is the domain for element j, $\overline{T}_{i\ell}$ are nodal values of temperatures; $\overline{q}_{i\ell}$ are nodal fluxes; ϕ_ℓ are shape (interpolation) functions; E_{it} is the number of linear triangular elements employed, $\overline{T}^* = (4\pi r)^{-1}$ for the three-dimensional case, $\partial U/\partial n = \vec{r}.\vec{n}/8\pi r$ and where the heat source Q_i is zero when the domain considered is a die domain.

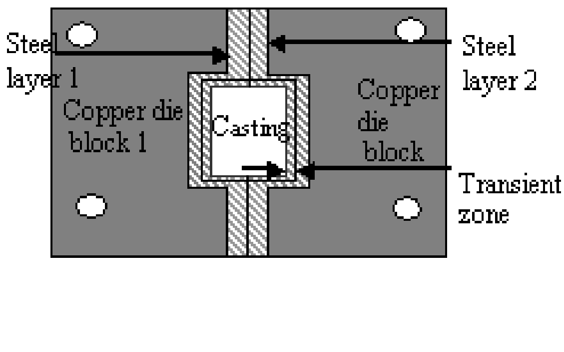

Figure 1. Two slide die and component.

2.1. Steady State Boundary Conditions

Steady state boundary conditions are obtained by integrating the actual transient boundary conditions over a typical casting cycle, for example flux boundary conditions are required to satisfy $\bar{q}_i(\vec{x}) = t_\chi^{-1}\int_\tau^{\tau+t_\chi} q_i(\vec{x},t)dt$, where $q_i(\vec{x},t)$ is the actual (transient) boundary condition, and $\bar{q}_i(\vec{x})$ is the corresponding steady state boundary condition. Convective and pseudo-convective boundary conditions are used extensively in the die boundary element models. These boundary conditions take the form $q_i(\vec{x},t) = h(\vec{x},t)(\Psi_s(\vec{x},t) - \Psi_i(\vec{x},t))$ where h is the heat transfer coefficient, Ψ_j is the temperature of the surface and Ψ_s is the temperature of the surrounding medium or opposing domain. The specification of heat transfer coefficients on each identifiable surface of the model is therefore required. A detailed description of the formulation of the steady state boundary conditions and the determination of corresponding heat transfer coefficients on the die outer surfaces, cooling channel surfaces, die block (steel to steel) contact surfaces and die cavity-casting interface surfaces can be found in reference [1]. The modelling approach of considering the copper block and steel layer as distinct domains introduces the need for the application of boundary conditions on the interface between the steel layer and the copper block. The steady state boundary condition applicable here is of the form $\bar{q}_i(\vec{x}) = h_{sc}(\bar{T}_j(\vec{x}) - \bar{T}_i(\vec{x}))$ on Γ_i^{sc}, where h_{sc} is the heat transfer coefficient between the copper block and the steel layer, $\bar{T}_j(\vec{x})$ and $\bar{T}_i(\vec{x})$ are the temperatures on opposing interface surfaces. In practice, a high heat transfer coefficient is applied on the interfaces between the steel layer and the copper-alloy in order to unify temperatures at corresponding nodes on opposing interfaces.

3. TRANSIENT (PERTURBATION) BOUNDARY ELEMENT EQUATIONS

The transient perturbation model of the dies consists of a boundary element formulation of the parabolic heat equation [1]. The transient surfaces of the model are discretised with isoparametric linear triangular elements. An efficient domain integral approximation technique is employed to advance the solution in time. The method [2] bounds the number of time intervals integrated over to a predefined value M. Defining v to be the time step number; for $v > M$ application of the truncation technique to the integral representation of the parabolic heat equation yields the following equation

$$C_i(\vec{x})T_{iv}(\vec{x},t) - \int_{\Omega_i} T_{iv-M}T_M^* d\Omega(\vec{x}') + \alpha_i \sum_{j=1}^{E_i}\sum_{n=0}^{M-1}\sum_{\ell=1}^{3}\sum_{m=1}^{2} T_{im\ell}\int_{\Delta_j}\int_{t_{v-M+n}}^{t_{v-M+n+1}} \eta_m\phi_\ell \frac{\partial T^*}{\partial n} dt' d\Gamma(\vec{x}')$$
$$+\frac{\alpha_i}{k_i}\sum_{j=1}^{E_i}\sum_{n=0}^{M-1}\sum_{\ell=1}^{3}\sum_{m=1}^{2} q_{im\ell}^p \int_{\Delta_j}\int_{t_{v-M+n}}^{t_{v-M+n+1}} \eta_m\phi_\ell T^* dt' d\Gamma(\vec{x}') \tag{2}$$

where $T_i(\vec{x}',t')$ is the transient perturbation temperature, T^* is the fundamental solution , T_{i0} is the perturbation temperature at time t_0 and T_0^* the fundamental solution at time t_0, Δ_j is the domain of element j, $T_M^* = [\pi M\kappa]^{-3/2} \exp[-r^2 / M\kappa]$, η_m are temporal interpolation (shape) functions, ϕ_ℓ are spacial interpolation (shape) functions; other symbols take their usual meaning This equation forms the basis for the transient thermal model of the copper-steel layer alloy die. It is coupled to a capacitance based FE formulation [2] that models the phase change in the casting. The coupling is via the boundary condition on the die cavity-casting interface. Coupling the BE and FE models ensures that accurate values for the energy and the distribution of energy leaving the casting and entering the die are obtained.

3.1. Perturbation Boundary Conditions

Due to the fact that a perturbation approach has been taken then only the surfaces over which a transient variation of temperature occurs need be considered in the transient model. The perturbation boundary condition q_i^p is related to the actual q_i and the steady state $\bar{q}_i$ boundary conditions by the following equation

$$q_i^p(\vec{x},t) = q_i(\vec{x},t) - \bar{q}_i(\vec{x}) = h(\vec{x},t)\left(\Psi_j(\vec{x},t) - \Psi_i(\vec{x},t)\right) - \bar{q}_i(\vec{x}) \qquad (\vec{x},t) \in \Gamma_i \ X\left[\tau,\ \tau + t_\chi\right] \tag{3}$$

where h is the heat transfer coefficient between the surface and the surrounding medium or opposing domain (surface), Ψ_j is the temperature of the surrounding medium or opposing domain (surface), $\bar{q}_i(\vec{x})$ is the corresponding steady state boundary condition. The applied perturbation boundary condition on the interface between the steel layer and the copper block is $q_i^p(\vec{x},t) = h_{sc}(\Psi_s(\vec{x},t) - \Psi_c(\vec{x},t)) - \bar{q}_i(\vec{x})$, where Ψ_s is the temperature of the steel and Ψ_c is the temperature of the copper.

4. EXPERIMENTAL WORK AND MODEL VALIDATION

The die depicted in Figure 2 was utilised in tests on an experimental rig used to simulate the die casting process. The rig was designed to reproduce the transient heat transfer mechanisms and induced stresses due to the transient thermal loads involved in die casting whilst avoiding the hazardous features of the real process. Heat is applied to the die cavity surface in a cyclic manner simulating the period when the melt is contained within the die following injection and the period following ejection of the casting when the dies are open

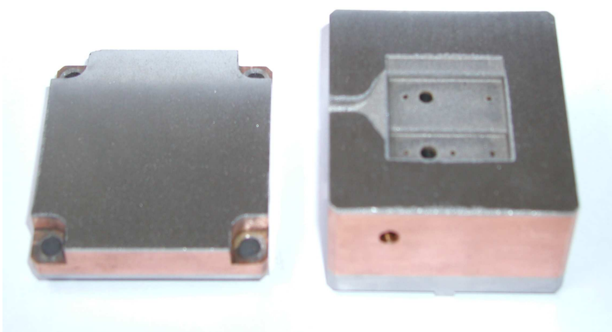

Figure 2. Copper steel alloy die

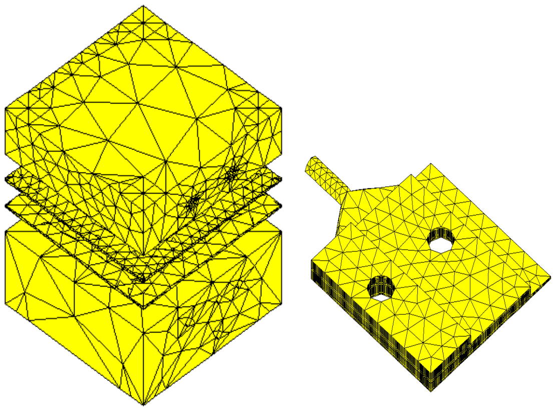

Figure 3. Model used in numerical test

to air. Stress results were recovered from strain measurements obtained from three strain gauges attached at various locations on the experimental die as shown in Figure 3 (a). Fibre reinforced plastic type strain gauges were employed. Ideally a temperature compensation of zero is required in order to measure thermal stress. Therefore gauges with a thermal expansion of 1.0 ppm/C were chosen. Gauges 1 and 3 measured strain in the x-direction, whilst gauge 2 measured strain in the y-direction. The thermoelastic BE model described in this paper was employed to predict deformations and stresses in the experimental die. Four casting cycles were analysed with twenty time steps being employed per cycle. The predictions obtained from the model were compared against the experimental results. Figure 3 (b) shows a comparison between predicted and measured stresses at the three locations on the die surfaces over a typical casting cycle. The shape of the plots is generally the same for all three positions. There is a sharp increase in stress close to the start of the cycle corresponding to injection when die temperatures increase rapidly. The stress continues to rise until the point at which the ejection of the casting from the dies is simulated, 0.5 seconds in the plots, after which stress falls during the period that represents the portion of the cycle for which the dies are open to air. Further inspection of Figure 3(b) reveals that in general reasonable agreement is obtained between predicted and measured stress. The main objective in modelling the thermoelastic behaviour of the copper-steel alloy dies is to obtain a tool that enables the structural integrity of the dies to be investigated prior to the manufacture and deployment of a die into production. Of particular interest are the stresses on the interface between the copper die block and the sprayed steel layer as this can affect the bonding of the two metals. It was found that static stress at the interface is predominantly compressive, which is an aid to maintaining the attachment of the steel layer to the copper die block.

5. CONCLUSIONS

This paper is concerned with the establishment of a thermal computational model for copper-alloyed sprayed dies utilised in the pressure die casting process. The following conclusion can be made: the superposition of steady state and transient perturbation temperatures is feasible for the prediction of die temperature in this application.

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