Coupled Thermal Stress Analysis in Die Casting: A Contact Problem

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Abstract

A 3D coupled thermal stress analysis of a problem devised to idealize some aspects of the die casting process is presented. The thermal contact conductance between casting and die is computed as a function of gap width and normal traction. The analysis shows that the contact conductance plays a critical role in determining the cyclic steady state temperature, displacement and stress fields.

Keywords: Die casting, thermal stress analysis, contact conductance, cyclic steady state

1 Introduction

Die casting is a manufacturing process in which liquid metal is injected into a steel die at high speeds and high pressures. The metal freezes in the die and when sufficiently cool, the casting is ejected. It is a cyclic process. For larger castings, such as an automotive transmission housings that can weigh up to 20 Kg, the total cycle time is of the order of 80 seconds. The metal is injected in roughly 40 milliseconds. Dies are usually cooled with water lines. During steady state production, the die reaches a cyclic steady state. When the liquid metal first fills the die, assuming no cold shut occurs that prevents the liquid metal from filling the die, the liquid metal directly contacts the die and the contact conductance from liquid metal to die is very high ≈ 3000 W/m^2 K. As the metal solidifies, it shrinks, roughly 6% for aluminum alloys. On those parts of the casting that pull away from the die, the contact thermal conductance drops rapidly and the thermal flux drops rapidly. On those parts of the casting that are pulled tightly against the die by the shrinkage process, the contact thermal conductance increases or stays high and the thermal flux also stays high. Thus the distribution of contact conductance is critical in a thermal stress analysis of the die casting process.

2 Thermal Contact Conductance

The scalar thermal flux, q in units of W/m^2, across an interface is:

$$q = h_i \left(T^+ - T^- \right) \equiv h_i [T] \tag{1}$$

where h_i is thermal interface or contact conductance and T^+ and T^- are the temperatures on either side of the interface and $[T]$ is the jump in temperature across the interface. Following Dhatt et al [2], we assume that the thermal contact conductance is the sum of the conductances due to four mechanisms

$$h_i = h_a + h_{gas} + h_{rad} + h_{conv}. \tag{2}$$

The conductance due to contact of asperities

$$h_a = \beta p^{\alpha} \tag{3}$$

is a function of the normal component of the normal traction $p = \sigma \cdot n$ where σ is the stress tensor, n is the outward normal vector, and β and α are functions of temperature and the interface properties [3] [4] [5]. If there is a gap, then the asperities do not touch, the normal traction is zero and $h_a = 0$.

The conductance due to radiation between the interfaces is

$$h_{rad} = s\epsilon \left(T_{cast}^2 + T_{mold}^2\right)(T_{cast} + T_{mold}) \tag{4}$$

where

$s =$ Boltzmann's constant;

ϵ is the relative emissivity function of the gap surfaces;

In aluminum castings, the gas is likely to be hydrogen. For a gap width of W and thermal conductivity of the gas κ_{gas}, the conductance due to conduction through the gas in the gap is h_{gas}.

$$h_{gas} = \frac{\kappa_{gas}}{W} \tag{5}$$

In die casting problems, the thickness of the air gap is very small, so the gas conduction term is relatively important but we neglect conductance due to gas convection.

3 Methodology

This paper presents results of a coupled FEM thermal stress analysis of an idealized test problem. The stress analysis determines the gap width and normal traction on the casting-die cavity interface. The contact thermal conductance used in the energy equation is computed as a function of gap width and normal contact traction. The temperature field computed by solving the energy equation drives the thermal expansion in the stress analysis.

The governing equations are the standard equations for FEM for quasi-static stress analysis with thermal expansion and the transient energy equation [1]. The die material is H13 tool steel. The casting material is Al380 aluminum alloy. Both are treated as elastic-visco-plastic materials. The transient thermal analysis uses an enthalpy formulation with a solidification model and uses backward Euler time integration.

Each casting cycle is broken down into three stages. In the die open stage, the die is opened, the casting is ejected, the die is blown clean and a liquid coating is sprayed on the die cavity surface. During the filling stage the liquid metal is injected into the die very quickly, typically 50 ms, the heat from the casting can only diffuse a very short distance into the die, roughly $\sqrt{D\Delta t}$, where $D \approx 1$ e-6 m^2/s is the thermal diffusivity of the die and Δt is the cycle time. This transient temperature field in the die wall is computed with an analytic equation. The temperature of liquid aluminum metal does drop as it flows into the die. If the die is too cold, the liquid could freeze before it filled the die. This would be called a cold shut. In this paper, we assume that the liquid metal does fill the die. (Although when analyzing a real casting we do simulate the filling process by solving the Navier-Stokes equations for viscous incompressible flow together with the equation for the advection of liquid metal into the die and the energy equation, the filling simulation is not discussed here. Then the specific enthalpy state, temperature and fraction filled, of the liquid metal at the end of the filling stage is the initial condition for the die closed stage.)

The test problem is a smooth dumbbell discretized with 2000 8-node elements. The die is discretized with 2000 8-node elements. See Figure 1. The initial conditions in the die at time zero are zero displacement, zero stress and an initial temperature of 300 K. In the die open stage of the first casting cycle, there is no change. In the die closed stage, the casting is placed in the die at a temperature of 910 K in the liquid state. (In analyzing a real casting, the initial state of the casting is taken from the end of the filling stage. This will be shown at the conference.) At the end of the die closed stage, the casting is ejected and the next die open stage of the next cycle begins. For each die open stage, the initial conditions of temperature, stress and displacement of the die change until a cyclic steady state is reached. The die open stage is solved in four equal time steps. The die closed stage is solved in ten equal time steps. In each time step, the energy equation is solved first and then the stress is solved. In each time step in the die closed stage, the energy equation is solved with the contact conductance computed at the end of the previous time step. Then the stress analysis is solved. Thus the computed contact conductance lags the stress analysis. In each of these stage, the domain changes and the boundary conditions change.

4 Discussion and Conclusions

Figure 1 shows that the gap width goes to zero where the dumbbell surfaces are pulled against the die wall. The gap width is greatest at the ends of the dumbbell where it pulls away from the die. Thus the contact conductance as a function of gap width and normal traction varies dramatically over the surface of the dumbbell (and with time). Figures 2a and 2b compare transient temperature solutions in a cross-section of the casting and die for the cases of constant contact conductance and contact conductance computed as a function of gap width and normal traction. The temperature distributions are entirely different. Also the effective stress in the die is entirely different for the two cases. Figure 3 shows that the effective stress for the case of non-constant contact conductance is very high adjacent to points on the die cavity surface that have high contact conductance, high thermal flux and high temperature gradients (See Figure 3).

The results have significant implications for the design of dies for die casting. The die is cooled by cooling lines. If the die is run too cold, the risk of cold shuts increases. If the die is run too hot, the cycle time has to be increased in order to cool the casting sufficiently before ejecting. An increase in cycle time reduces productivity. Thus the positioning of cooling lines is critical to optimizing die design and this positioning should be based on a realistic estimate of the transient temperature field. Dies tend to fail by heat checking caused by low cycle thermal fatigue, typically in the range of 70,000 casting cycles. Minimizing regions of high effective stress will extend die life.

The cooling effects of blowing compressed air on the die cavity surface and spraying a lubricant has been neglected because of lack of data on the spray patterns. Some studies have estimated that not more than 5% of the heat is lost to the sprays. In the future, we hope to characterize the spray processes and include the cooling effect of sprays as a thermal flux or convection boundary condition.

We conclude that in the thermal analysis of the die casting process, it is essential to compute the contact conductance as a function of gap width and normal traction.

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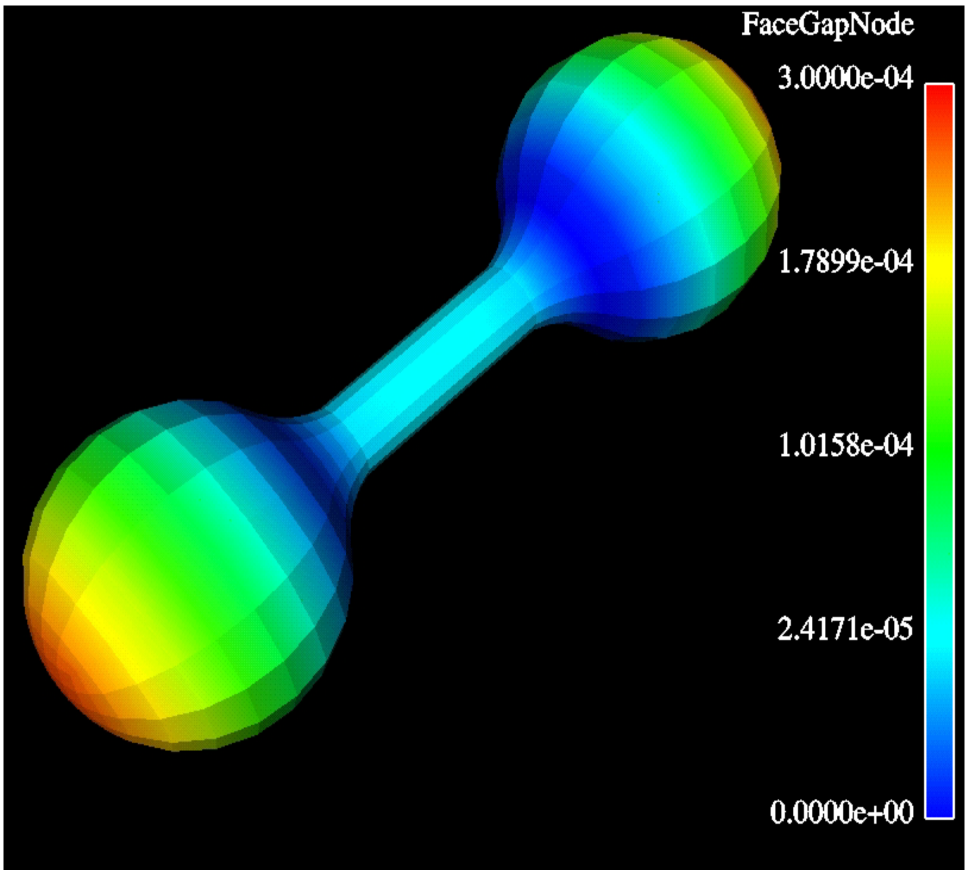

Figure 1: The distribution of the computed gap width is shown. This gap width is used to compute contact conductance when a die closed cycle is 75% complete.

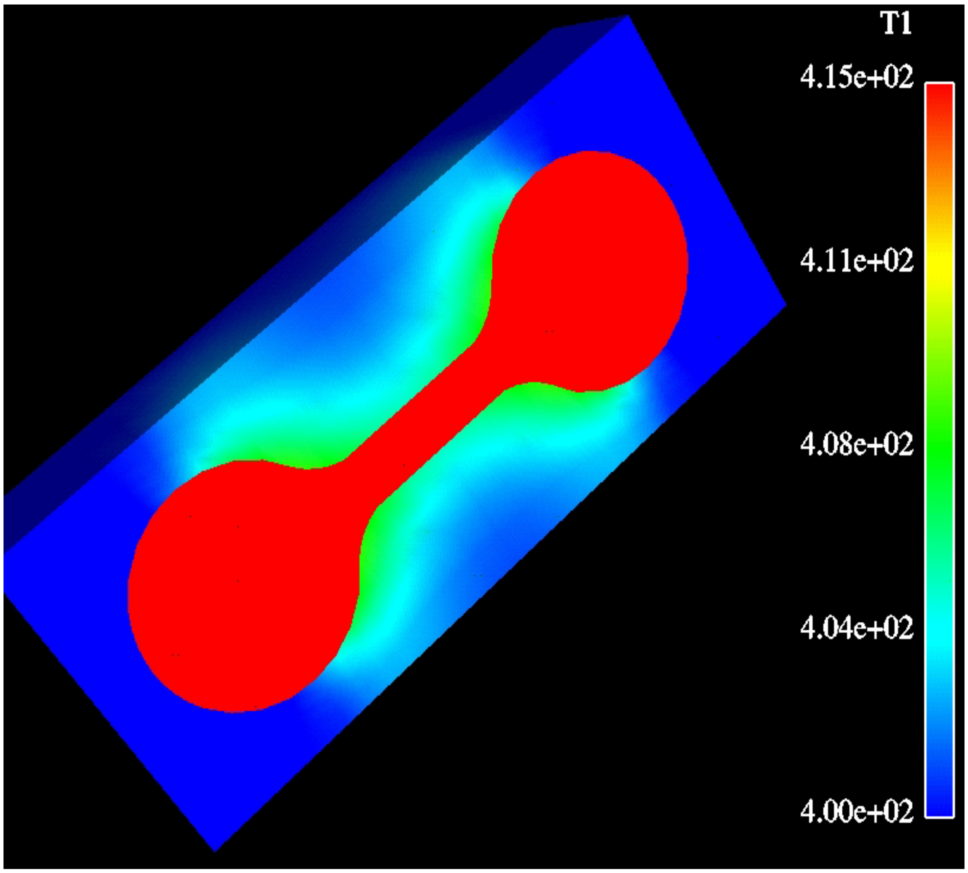

Figure 2: Temperature distribution is shown in a cross-section using contact conductance computed based on computed gap width and normal traction when a die closed cycle is 75% complete.

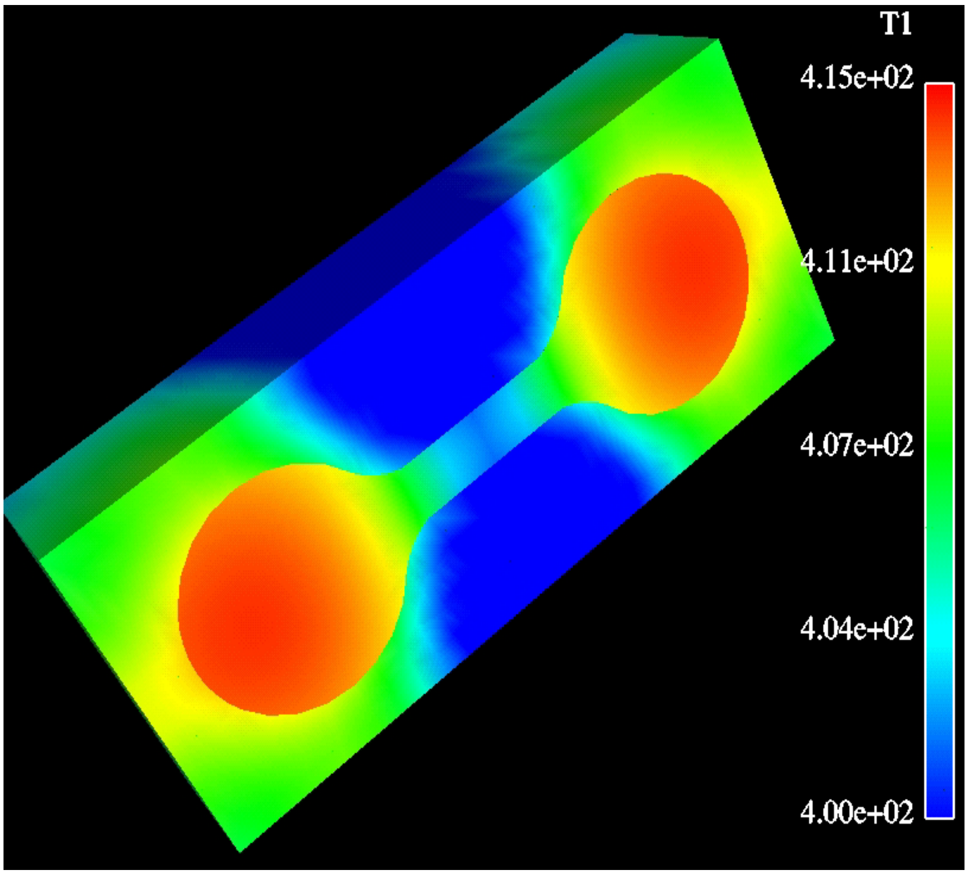

Figure 3: Temperature distribution is shown in a cross-section using constant contact conductance when a die closed cycle is 75% complete.

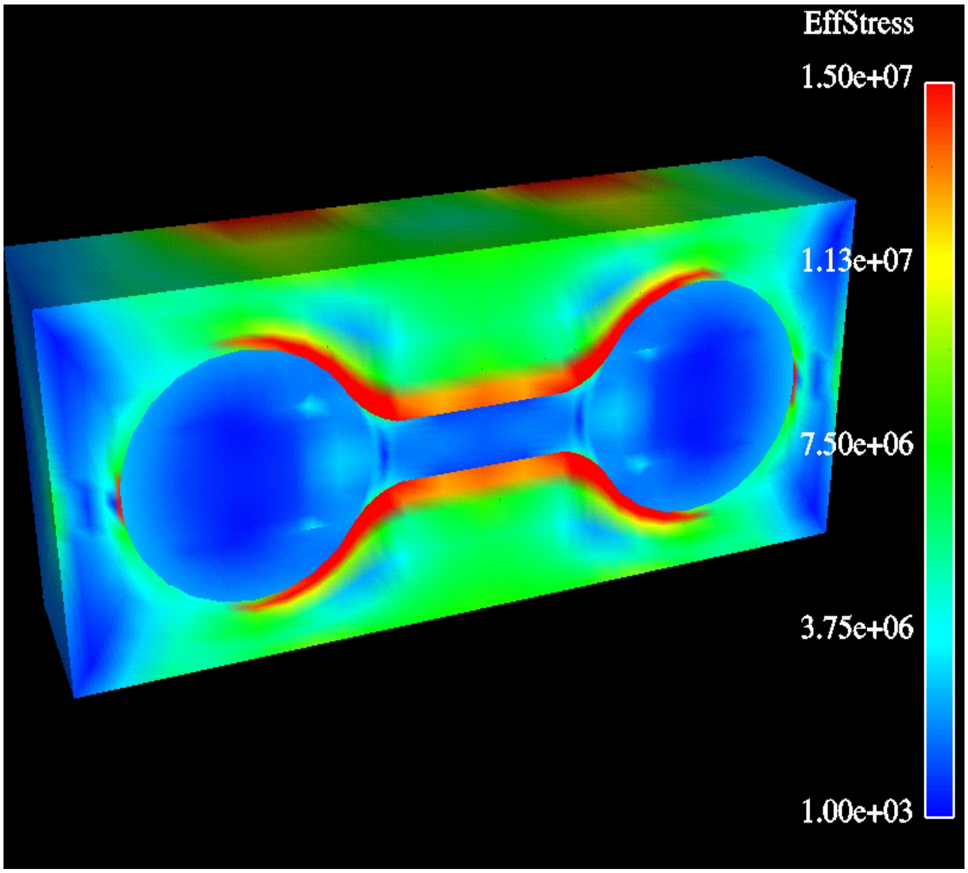

Figure 4: The effective stress computed using contact conductance based on the computed gap width and normal traction is shown when a die closed cycle is 75% complete.