Shape Casting: The 3rd International Symposium
Edited by: John Campbell, Paul N. Crepeau, and Murat Tiryakioğlu
TMS (The Minerals, Metals & Materials Society), 2009

PREDICTION OF DEFORMATION AND HOT TEAR FORMATION USING A VISCOPLASTIC MODEL WITH DAMAGE

M.G. Pokorny, C.A. Monroe, C. Beckermann

Dept. Mechanical and Industrial Engineering, University of Iowa, Iowa City, Iowa 52242, USA

Keywords: Casting, Simulation, Stress

Abstract

A viscoplastic deformation model considering material damage is used to predict hot tear formation in a permanent mold magnesium alloy casting. The simulation model calculates the solid deformation and ductile damage. The viscoplastic constitutive theory accounts for temperature dependent properties and includes creep and isotropic hardening. Ductile damage theory is used to find mechanically induced voiding, and hot tears are expected in regions of extensive damage. Previously performed experiments are used to validate the simulation predictions. The test casting consists of a long horizontal bar connected to a vertical sprue on one side and an anchoring flange on the other. Hot tears are observed at the junction between the horizontal bar and the vertical sprue. The hot tearing severity is manipulated by adjusting the initial mold temperature. The simulation results are in good agreement with the experimental observations, both in terms of location and severity of the hot tears.

Introduction

The automotive industry is showing greater interest in magnesium alloys as they have a high strength to weight ratio when compared to steel or aluminum alloys. Because of their low density, incorporating magnesium alloys into the design of new vehicles decreases weight and increases fuel efficiency. This is especially important in helping to reduce carbon emissions that contribute to global climate change. However, some magnesium alloys show a high susceptibility to hot tearing, especially if cast in a permanent mold.

Hot tears are irreversible cracks that form in the semi-solid stage, called the mushy zone, during casting [1]. Hot tears develop as a result of thermal and mechanical strains due to the contraction of the casting and geometric constraints of the mold. In the mushy zone, porosity can form during late stages of solidification due to shrinkage. With sufficient deformation, this porosity may act as a nucleation site for hot tears. Hot tears can also form in the absence of porosity, but the lack of feeding flow is a necessary condition for a tear to remain open. As reviewed by Monroe and Beckermann [2], numerous attempts have been made in the past to understand the effect of various casting variables on hot tear formation and to develop criteria for predicting hot tears in castings. However, a truly predictive and reliable hot tear model is not yet available.

In the present study, a newly developed viscoplastic model that calculates deformation and damage is used to predict hot tears in a AZ91D magnesium alloy steel mold casting. The model is implemented in a general purpose casting simulation code. The model predictions are compared with the experimental results of Bichler *et al.* [1].

Description of Experiments by Bichler *et al.* [1]

The experiments by Bichler *et al.* [1] explored the hot tearing susceptibility of an AZ91D magnesium alloy test casting in a permanent steel mold. The composition of the AZ91D magnesium alloy used in the experiments was 8.61% aluminum, 0.6% zinc, 0.23% manganese, 0.017% silicon, 0.003% copper, 0.0038% iron, 0.0014% nickel, 0.0012% beryllium, and balance magnesium. The 20 mm thick casting consisted of a 260 mm (10.2 in) long horizontal bar connected to a vertical sprue and a flange, as shown in Figure 1. The figure also indicates thermocouple locations (TC1 to TC3), which recorded temperatures during casting at a rate of 7 readings/second. Temperatures of five separate castings poured at 720°C (1,328°F) were recorded using these thermocouples.

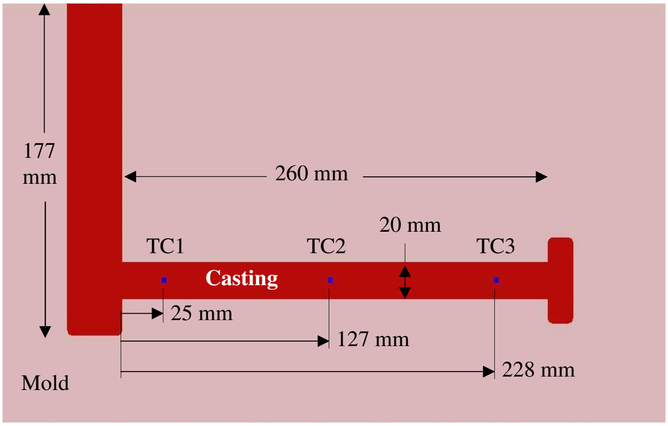

Figure 1. Casting and mold geometry with thermocouple locations [1].

During solidification, the contraction of the horizontal bar is restrained by both the sprue and the flange. This restraint can cause hot tears to form. The hot tears always occurred at the junction of the sprue and the horizontal bar [1]. The induced hot tearing was varied by changing the initial temperature of the steel mold. For a pouring temperature of 700°C (1,292°F), test castings were made at seven different initial mold temperatures ranging from 140°C (284°F) to 380°C (716°F). A semi-quantitative method was adopted to represent the severity of the hot tears observed in the test castings. This measure was called the hot tearing susceptibility index (HSI) [1]. The HSI was found to increase with decreasing initial mold temperature. In this paper, the thermocouple results and the hot tearing tendencies are compared to simulations.

Model

The filling, solidification and stress simulations were performed using a modified version of MAGMAsoft [3]. The simulations require inputs such as the three-dimensional geometry, mold temperature, pour temperature, thermo-physical properties, mechanical properties, mold-metal interfacial heat transfer coefficient, and others. Using these conditions and material properties, the temperature variations in both the casting and mold are predicted. The temperatures are then used in subsequent deformation calculations. Material deformation depends on the temperature results, since deformation is driven by density changes during casting solidification and further cooling within a rigid mold.

As part of the current study, a newly developed temperature-dependent viscoplastic deformation model was implemented in a module of MAGMAsoft called MAGMAstress. The details of this model are rather complex, and only a brief overview is presented here. The model considers the solid and liquid phases in the mushy zone along with damage induced porosity. The deformation of the mushy zone is a function of the solid fraction, which is a unique feature of the present model. Conventional models, such as the von Mises plasticity model, do not account for plastic volume change and no damage can be predicted. The model used in the current research includes the effect of plastic volume changes due to tensile (or compressive) strains. Assuming small strain theory, the total solid strain is decomposed into the elastic, thermal, and viscoplastic components. The elastic strain is governed by Hooke's law. The thermal strain is given by the linear thermal expansion coefficient, which is calculated from the density. In the mushy zone, thermal strains are assumed to be present only for temperatures below the eutectic start temperature. The viscoplastic or creep strains are determined by the flow condition. The flow condition limits the maximum stress the material can hold by keeping the equivalent stress below the yield stress. The equivalent stress depends on the solid fraction according to Cocks model [4]. In the limit where the solid fraction is unity, Cocks model returns to the von Mises solution. The yield stress function is a power law model including both isotropic hardening and creep.

Damage due to solid deformation is porosity created by volumetric plastic strain. The volume fraction damage (porosity) is found by integrating over time the volumetric part of the viscoplastic strain rate. The integration is started when the shrinkage porosity calculations indicate that the feeding flow is cut off. It should be noted, that the predicted damage is only an indicator of where hot tears may form in a casting; it does not predict the exact shape or size of the final hot tear. The potential for hot tearing increases with an increase in magnitude of this damage indicator. Damage provides an estimate of the volume that the crack occupies.

Additional details of the model, including the governing equations, can be found in reference [5]. The thermo-physical properties and the solidification path for the AZ91D magnesium alloy were calculated using the software JMatPro [6]. Reference [5] also contains a description of the method used to estimate the mechanical properties of the AZ91D magnesium alloy as a function of temperature.

Results

Temperature Predictions

The temperature measurements were used to determine the mold-metal interfacial heat transfer coefficient and to confirm the accuracy of the solidification and heat transfer simulations. The heat transfer coefficient was obtained using a trial-and-error procedure in which the predicted temperatures were matched with the experimental thermocouple data. The resulting heat transfer coefficient variation with temperature is shown in Figure 2(a). Above the liquidus temperature, a heat transfer coefficient of 6000 W/m^2K was found to result in good agreement between measured and predicted temperatures. Through the solidification range, the heat transfer coefficient was varied with the solid fraction to a final value of 1000 W/m^2K at 100% solid. From 100% solid to room temperature, the heat transfer coefficient was decreased cubically to 100 W/m^2K. The decrease in the heat transfer coefficient with temperature reflects the formation of an air gap between the casting and the mold during cooling.

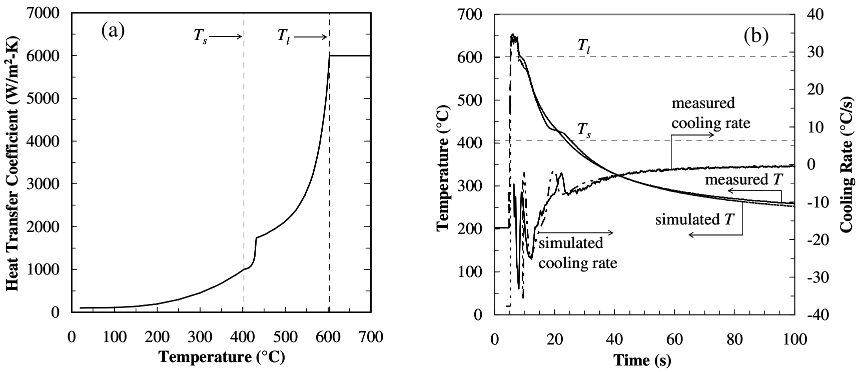

Figure 2. Interfacial heat transfer coefficient as a function of temperature (a); measured [1] and simulated thermocouple results for TC1 and an initial mold temperature of 202°C (b).

Figure 2(b) shows an example of a measured and predicted temperature comparison. Temperature versus time curves are shown for a thermocouple indicated as TC1 in Figure 1. The measured and predicted temperatures can be seen to be in generally good agreement. Similar agreement was obtained for all experiments in which temperatures were measured. More insight can be obtained by examining the measured and predicted cooling rate curves that are also shown in Figure 2(b). The cooling rate curves were obtained using a five point moving average of the time derivative of the temperature data. The first major peak in the measured cooling rate curve indicates nucleation of the primary Mg-rich solid. The peak corresponds to a temperature of 598°C (1,108°F) (average value from all temperature measurements). This nucleation temperature is 5°C (9°F) below the liquidus temperature of 603°C (1,117°F) predicted by JMatPro. The difference may be attributed to the presence of some nucleation undercooling; in fact, a temperature recalescence can be observed in the measurements. Nucleation is not modeled by JMatPro. A second major peak in the cooling rate curve indicates the start of eutectic solidification. The measured eutectic start temperature is equal to 421°C (790°F) (average value from all temperature measurements). This value is 10°C (18°F) lower than the eutectic start temperature predicted by JMatPro. The difference may be attributed to inaccuracies in JMatPro, in particular the Scheil analysis used to model solidification and the neglect of eutectic undercooling. The final 100% solid temperature cannot be inferred from the measured and predicted cooling rate curves due to the absence of any discernible peak. Despite the inaccuracies in the JMatPro data, the agreement between the measured and predicted temperatures was still deemed satisfactory for the present purposes.

Deformation and Hot Tear Predictions

Model predictions are compared to experimental results for three mold temperatures, 140°C (284°F), 260°C (500°F) and 380°C (716°F), and a pouring temperature of 700°C (1,292°F). Figure 3 shows the calculated final damage field and distortion of the casting magnified by 20 times for the three different initial mold temperatures. The simulations were terminated at 350 s after pouring; at this time the casting was fully solid and at a temperature close to the initial mold temperature. In Figure 3, the solid black line represents the original non-deformed casting. It can be seen that the sprue undergoes free contraction along its height. The magnitude of the contraction decreases with increasing initial mold temperature, since the thermal strain is less for a smaller temperature interval between the end of solidification and the final casting temperature (which is approximately given by the initial mold temperature). Several contact points can be observed along the mold-metal interface, which provide the necessary restraint for deformation and hot tears to occur. The most important contact points are seen at the junction of the sprue and the bar and at the flange end. Although the entire bar experiences contraction and restraint, the deformation causes the most significant damage on the sprue side of the bar. As expected, more damage (and distortion) is predicted to occur as the initial mold temperature is decreased.

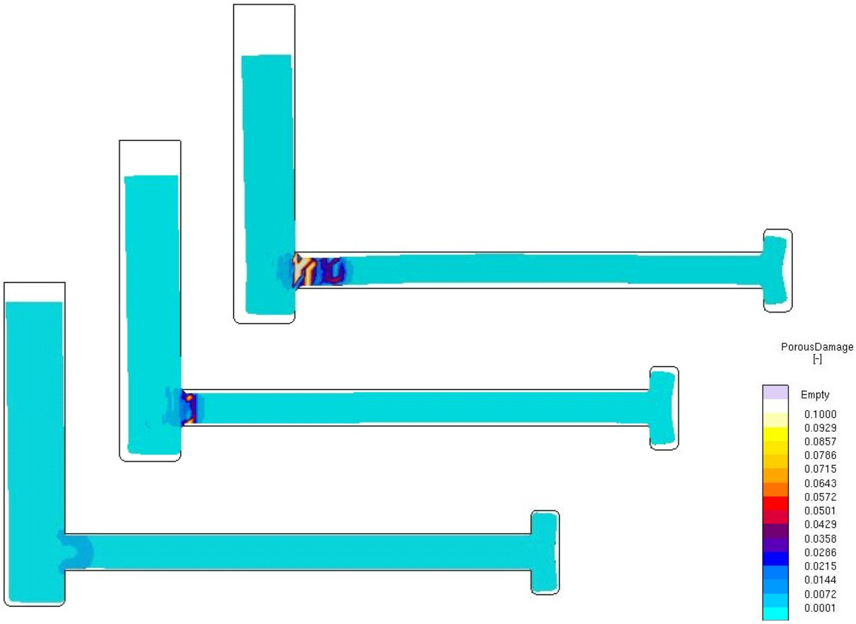

Figure 3. Calculated distortion, magnified 20 times, and damage field for initial mold temperatures of 140°C, 260°C and 380°C (from top to bottom).

Figure 4 shows the calculated von Mises stress and plastic effective strain at the end of the simulation for an initial mold temperature of 260°C (500°F). The von Mises stress is largest in the bar and almost zero in the sprue, as can be seen in Figure 4(a). In Figure 4(b), the plastic effective strain can be seen to be large in the bar with the largest values near the corners at the flange end. Hence, a hot tear criterion based on a von Mises model and effective strain alone would predict hot tear formation at the flange end where the stress and effective plastic strain are highest. However, in the experiments the hot tears did not form at the flange end, but at the junction with the sprue. Therefore, a prediction based on the von Mises stress and effective plastic strains would be inadequate for this casting.

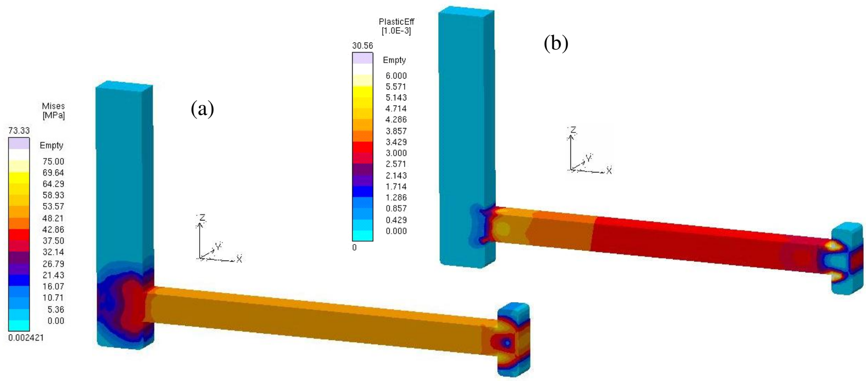

Figure 4. Calculated von Mises stress (a) and plastic effective strain (b) at the end of the simulation, 350s, for an initial mold temperature of 260°C.

Figure 5 shows a comparison between the predicted damage fields and photographs of the hot tears formed in the experiments for the three mold temperatures [1]. In Figure 5, the graphs with the simulation results were rotated by 180° so that the sprue is now to the right of the horizontal bar. This rotation is done in order to match the view in the photographs. It can be seen that the predicted damage is at the same location where the hot tears occurred in the experiments. The strong increase in the calculated damage with decreasing mold temperature corresponds well with the increasing severity of the hot tears seen in the experimental results. Hence, the simulation results confirm the observed decrease in hot tear susceptibility with increasing mold temperature.

Conclusions

A viscoplastic deformation model was used to predict hot tears in an AZ91D magnesium alloy permanent mold casting. The model calculates deformation and material damage. Preliminary estimates of temperature and strain-rate dependent mechanical properties were

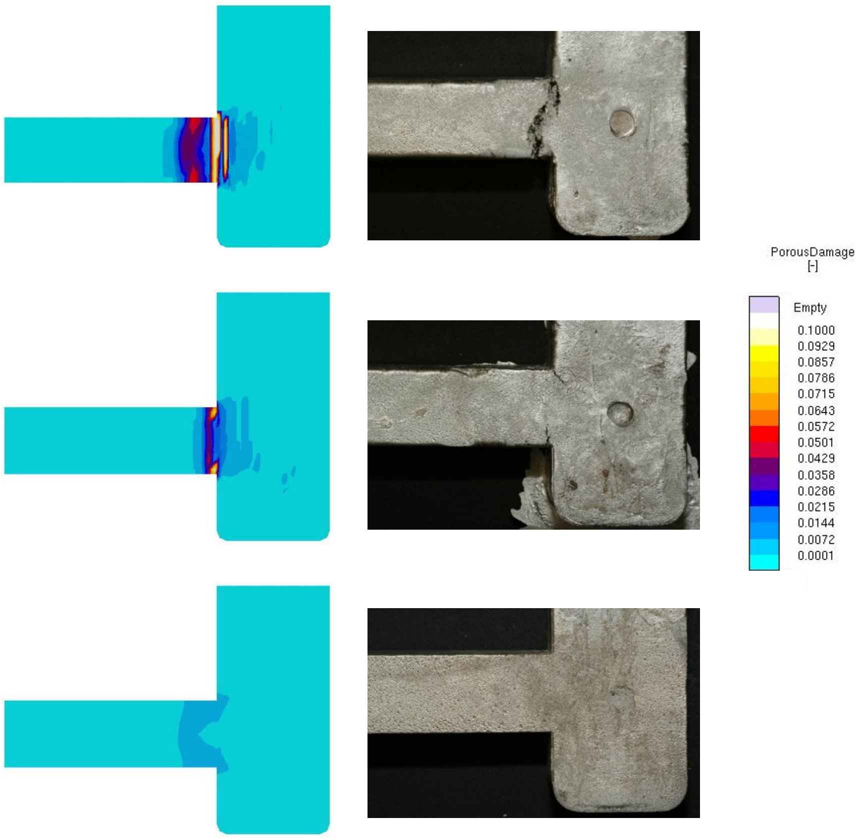

Figure 5. Simulation results showing calculated damage (left side) and the corresponding experimental results (right side) [1] for initial mold temperatures of 140°C, 260°C and 380°C (from top to bottom).

obtained from stress-strain data found in the literature [5]. Simulations were performed of experimental test castings of Bichler *et al*. [1]. The predicted damage from the simulations was found to be in good agreement with the hot tears observed in the experiments, both in terms of location and severity. The simulation results corroborate that the hot tears form most likely at the junction between the horizontal bar and the vertical sprue. The simulation results also confirm that hot tear susceptibility decreases with increasing mold temperature. These results indicate that the damage calculated using the viscoplastic deformation model is a reasonable predictor of hot tearing. Future work will include the measurement of more accurate mechanical properties. In addition, it will be desirable to compare the predicted stresses and strains with direct experimental measurements.

Acknowledgements

This study was performed under the High Integrity Magnesium Cast Components (HIMAC) Project funded by the Department of Energy under Award Number DE-FC26-02OR22910. The authors would like to thank Dr. L. Bichler and Prof. C. Ravindran of the Centre for Near-net-shape Processing of Materials, Ryerson University, Toronto, Ontario, Canada, for making the experimental data available. The authors are also grateful to MAGMA GmbH for their support through the donation of software, time and information.

References

1. L. Bichler, A. Elsayed, K. Lee, and C. Ravindran, "Influence of Mold and Pouring Temperatures on Hot Tearing Susceptibility of AZ91D Magnesium Alloy," *International Journal of Metalcasting*, 2 (1) (2008), 43-56.

2. C.A. Monroe and C. Beckermann, "Development of a Hot Tear Indicator for Steel Castings," *Materials Science and Engineering A*, 413-414 (2005), 30-36.

3. MAGMAsoft, MAGMA GmbH, Kackerstrasse 11, 52072 Aachen, Germany.

4. E.B. Marin and D.L. McDowell, "A Semi-implicit Integration Scheme for Rate-dependent and Rate-independent Plasticity," *Computers and Structures*, 63 (3) (1997), 579-600.

5. M. Pokorny, C.A. Monroe, C. Beckermann, L. Bichler, and C. Ravindran, "Prediction of Hot Tear Formation in a Magnesium Alloy Permanent Mold Casting," *International Journal of Metalcasting*, 2 (4) (2008), 41-53.

6. JMatPro, Sente Software Ltd., Surrey Technology Centre, Surrey GU2 7YG, United Kingdom.