Prediction of Thermal Fatigue in Tooling for Die-casting Copper via Finite Element Analysis

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Abstract. Recent research by the Copper Development Association (CDA) has demonstrated the feasibility of die-casting electric motor rotors using copper [1]. Electric motors using copper rotors are significantly more energy efficient relative to motors using aluminum rotors. However, one of the challenges in copper rotor die-casting is low tool life. Experiments have shown that the higher molten metal temperature of copper (1085 °C), as compared to aluminum (660 °C) accelerates the onset of thermal fatigue or heat checking in traditional H-13 tool steel. This happens primarily because the mechanical properties of H-13 tool steel decrease significantly above 650 °C. Potential approaches to mitigate the heat checking problem include: 1) identification of potential tool materials having better high temperature mechanical properties than H-13, and 2) reduction of the magnitude of cyclic thermal excursions experienced by the tooling by increasing the bulk die temperature. A preliminary assessment of alternative tool materials has led to the selection of nickel-based alloys Haynes 230 and Inconel 617 as potential candidates. These alloys were selected based on their elevated temperature physical and mechanical properties. Therefore, the overall objective of this research work was to predict the number of copper rotor die-casting cycles to the onset of heat checking (tool life) as a function of bulk die temperature (up to 650 °C) for Haynes 230 and Inconel 617 alloys. To achieve these goals, a 2D thermo-mechanical FEA was performed to evaluate strain ranges on selected die surfaces. The method of Universal Slopes (Strain Life Method) was then employed for thermal fatigue life predictions.

INTRODUCTION

Major factors affecting the fatigue life of the die surface in high pressure die-casting applications are: 1) the initial bulk die temperature, 2) the temperature, heat of fusion and specific heat of the casting alloy, and 3) the elevated temperature physical and mechanical properties of the die material [2]. Comparing the die-casting of aluminum versus copper, experience shows that the thermally induced problems with die materials are more serious with copper alloys. Aluminum alloys are die-cast at relatively low temperatures (675 °C), compared to copper alloys that are cast at temperatures in the 1200 °C range. The higher temperatures in the copper die-casting process induce high compressive strains at the die cavity surface during molten metal injection. The magnitude of the thermal gradient and strains on the die surface are directly correlated to the temperature of the die surface immediately prior to molten metal injection (initial bulk die temperature). Once the casting begins to cool, it contracts, resulting in a reduction of heat transfer to the cavity surface due to less contact pressure. Subsequent to ejection of the casting from the die cavity, the cooling of the die surface via exposure to cool air or spray lubricants may also result in tensile stresses. Cyclic heating and cooling during the die-casting operation results in alternating compressive and tensile strains (strain range) on die surfaces. The cyclic strains eventually initiate cracks, and as the number of casting cycles accumulates, the cracks may grow deeper into the die. Eventually this results in the castings mechanically adhering to the die, or small areas of the die surface actually breaking out. In either case, thermal fatigue cracking creates an undesirable surface finish on the casting. The formation of cracks on the die surface due to thermal fatigue is commonly called heat checking.

Previous CDA copper die-casting experiments using H13 tool steel dies at an initial bulk die temperature of 200 °C has yielded as few as 20 die-casting cycles to the onset of heat checking in the metal delivery system of the die (Figure 1, areas 3 and 4). Nickel-based alloys Haynes 230 and Inconel 617 may offer improved resistance to heat checking as die materials because of their excellent elevated temperature mechanical properties. Also, increasing the initial bulk die temperature may reduce the thermal gradient and strain range induced on the surface of the die material. However, conducting experimental copper die-casting campaigns to assess the heat checking resistance of various die materials at various initial bulk die temperatures is expensive. A lower cost alternative is computer modeling using the Finite Element Analysis (FEA) technique. Using FEA the strain range on die surfaces can be evaluated, and subsequently the method of universal slopes can be employed to predict cycles to failure. Therefore, the objective of this research was to predict the number of copper die-casting cycles to the onset of heat checking in the metal delivery system of a rotor die using FEA. Haynes 230 and Inconel 617 were evaluated at initial bulk die temperatures of 200 °C, 350 °C, and 650 °C. Initial bulk die temperatures above 650 °C are impractical to maintain in a production environment.

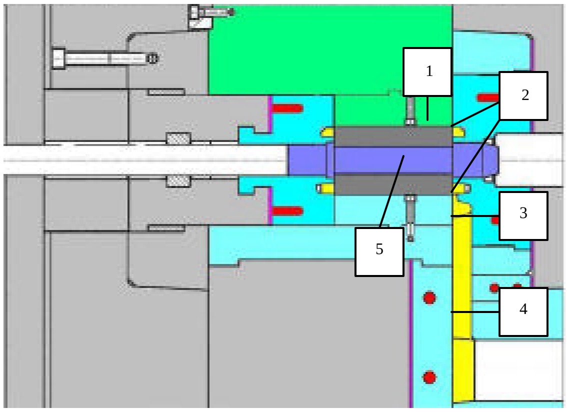

FIGURE 1. 2D cross-section of the copper rotor die: 1. Steel laminations, 2. End ring (Cu), 3. Gate area (Cu), 4. Runner (Cu), and 5. Steel arbor [1].

UNIVERSAL SLOPE METHOD

Thermal fatigue failure in a die is caused by the strains generated by the combination of thermal and mechanical stresses in the die. When cyclic strains cause failure in metals in less than 10^4 cycles, the phenomenon is called low-cycle fatigue. When more than 10^5 cycles are required for failure to occur, the phenomenon is called high-cycle fatigue. The equation to predict the number of cycles to failure was derived by Manson [2] and is given as,

$$\frac{\Delta e}{2} = \frac{\Delta e_p}{2} + \frac{\Delta e_e}{2} = D^{0.6}(N_f)^z + 3.5\frac{s_u}{E}(N_f)^g \qquad (1)$$

where D = -ln(1-R_A) is the logarithmic ductility
R_A is the percentage reduction in area
σ_u is the ultimate tensile strength

Manson further stated that z and γ in the above equation are material independent constants and can be assumed to have values –0.6 and –0.12, respectively. When equation (1) is plotted on a log-log scale, the constants z and γ are said to be the slopes of the curves in this relation and hence the method is called universal slopes. The first term in equation (1) is the plastic strain range, whereas the second term is the elastic strain range. In low-cycle fatigue, plastic strains dominate, while in high-cycle fatigue elastic strains dominate [3]. To evaluate the number of cycles to failure for a given situation, the appropriate strain component(s) should be utilized.

For example, Shi et al. [4] developed a 3D FEA model for a shot sleeve to predict the number of cycles to failure by heat checking. In their work, the method of Universal slopes was used after obtaining the strain range from computer modeling of the shot sleeve. The elastic component of the Manson equation was used for modeling, as it was a high cycle fatigue situation. The maximum principal strain range from the analysis obtained was 0.004683 and the number of cycles to failure corresponding to the strain range was 34,294 cycles. This calculation was obtained by considering the principal strain range, which represents a uniaxial model. But in reality, the strain range is multiaxial. Hence, the authors considered the maximum effective or Von Mises strain range for fatigue life evaluation and calculated the cycles to failure as 42,967 from an effective strain range of 0.004558.

COMPUTER MODEL

A 2D model was constructed using ANSYS™. Since the focus of this study was the metal delivery system of the die, only the runner, gate and biscuit areas (as shown in Figure 2) were included in the model [5]. The runner and the gate sections were the regions of the die where heat checking occurred during experiments at only 20 casting cycles using H-13 tool steel. These regions were modeled as planar elements.

In reality, the biscuit section is circular, but it was assumed to be planar for modeling purposes. It was important to model the biscuit section for analysis, as it is a major source of heat during the casting cycle and is the last part to solidify during casting. However, the strains in the biscuit section were not evaluated for fatigue life prediction as the circumference of the biscuit is in contact with a shot sleeve and the biscuit end is in contact with a plunger tip. These are separate tooling components and outside the focus of this study.

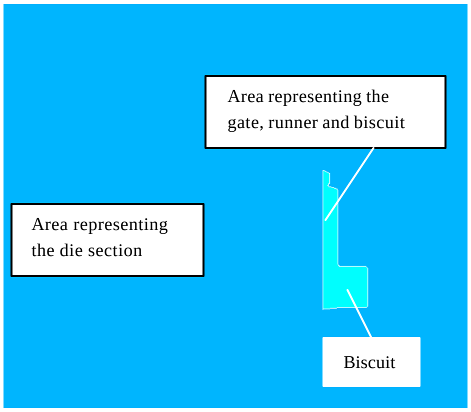

FIGURE 2. Final model for simulation for strain range evaluation [5]

Preliminary modeling efforts suggested that the influence of internal heating or cooling lines in the tooling was negligible with respect to the strain ranges experienced at the die surfaces. Therefore, they were not included in the final model. Also, since the research focus is thermally induced strains, any externally superimposed mechanical strains from die clamping have not been considered in the model.

An uncoupled thermo-mechanical FEA was performed to evaluate the strain range in the die during a cycle. The points with maximum strains at different surfaces of the die cavity were considered as points of interest and strains at those points were considered in modeling the onset of heat checking.

Hence, the sections considered for thermal fatigue analysis were the plane sections of the gate and runner, which experience a high thermal load for a relatively long period of time during the casting process. Based on the aforementioned experimental results, it was anticipated that the resulting high strain ranges in those sections would initiate heat checking before any other section of the die. Therefore, this FEA analysis was focused on determining the "worst case" thermal fatigue situation in the entire rotor die tooling.

BOUNDARY CONDITIONS

An uncoupled thermo-mechanical FEA requires the temperature loads from the thermal analysis to be imported for the subsequent structural analysis to obtain the stresses and strains due to temperatures at a particular time. Hence, the boundary conditions for the thermal and structural analyses were applied during their respective stages.

Thermal Analysis

Following are the boundary conditions specified during the thermal analysis:

- Thermal contact conductance or gap conductance of 10,000 W/m^2K taken as constant through all sections of the model.
- Heat transfer coefficient at the external surfaces of the die, h = 40 W/m^2K at a bulk temperature of 30 °C.
- Initial temperatures applied to appropriate nodes of casting and die materials. Three die temperatures were considered for analysis: 200, 350 and 650 °C. The initial molten copper casting temperature was set to 1200 °C.

Structural Analysis

Following are the boundary conditions that were applied during the structural analysis:

- Temperature loads from thermal analysis at appropriate sub-steps for stress and strain analyses.
- Two nodes on each side of the die to restrict its movement in space by spring elements of stiffness, k = 10,000 N/m^2.

MATERIAL PROPERTIES

This section tabulates the material properties of the materials involved in the FEA, i.e. pure copper, Haynes 230 and Inconel 617. The thermal conductivity of copper used in the model is shown in Table 1. Pure metals have the same solidus and liquidus temperature and the enthalpy change occurs at the same temperature. However, it was necessary to incorporate a temperature range for liquidus and solidus so that the enthalpy varied over a temperature range in the finite element model (Table 2). The structural properties of copper are not listed, because mechanical strains in the copper casting section were not considered during the structural analysis.

TABLE 1. Temperature dependent thermal conductivity of copper.

Temperature (°C)	Thermal Conductivity (W/mK)
400	379
500	374
600	366
700	359
900	346
1000	337
1083	160
1093	160
1100	160
1200	158

TABLE 2. Temperature dependent enthalpy (volume basis).

Temperature (°C)	Enthalpy (J/m^3)
0	0
1050	2.742×10^9
1085	4.500×10^9
1200	4.808×10^9

Haynes 230 alloy is a nickel-chromium-tungsten-molybdenum alloy that possesses excellent high temperature strength and outstanding resistance to oxidizing environments up to 1149 °C for very long times and good long-term thermal stability [5]. It possesses a low thermal expansion coefficient along with high elongation and high percentage reduction in area at elevated temperatures. This makes it suitable for high temperature applications where ductility is important. It can be used effectively for very long-term applications at high temperatures, and is capable of outlasting stainless steel and other nickel alloys depending on the operating temperature. This alloy also exhibits excellent low cycle fatigue properties at elevated temperatures. Haynes 230 has a density of 8970 Kg/m^3 at room temperature.

Inconel 617 is a solid solution, nickel-chromium-cobalt-molybdenum alloy having exceptional high-temperature strength and oxidation resistance. This alloy also has very good elevated temperature ductility. The high chromium and nickel contents make it resistant to the extreme reducing and oxidizing conditions. Cobalt and molybdenum impart the solid solution strengthening. Inconel 617 was chosen for analysis as it was concluded as one of the most reliable die materials from test die experiments performed by CDA [1]. This alloy gave very good results after setting the initial bulk die temperature to about 650 °C. Inconel 617 has a density of 8360 Kg/m^3 at room temperature.

Tables 3 and 4 show the pertinent temperature dependent physical and mechanical properties for Haynes 230 and Inconel 617 alloys. The tangent modulus (TM) values were calculated from the yield stress and ultimate tensile stress values for each temperature. A constant value of poisson’s ratio was given for both alloys as 0.3.

PROCESS DWELL TIME

The dwell time for the simulation was taken as 150 seconds. This is the time for which the die remains closed while the casting solidifies. Other times involved during the cycle (e.g. die open) were not considered relevant and were not included in the model.

COMPUTER SIMULATION RESULTS

This section discusses the post-processing results from ANSYS^{TM} and the thermal fatigue life prediction that was made on the basis of the strain values obtained from the analysis [6].

In this simulation the strains from the structural analysis were compressive for the entire dwell time of 150 seconds. Therefore, the strain range was the magnitude of the compressive strain from the simulation based on the Von Mises-Hencky effective strain criteria. The strains observed from the thermo-mechanical analyses with initial bulk die temperature of 200 °C were observed to be the highest; those for an initial bulk temperature of 650 °C were the lowest. All the strain values observed from the structural analyses were in the plastic range. This is due to the high temperature difference between the casting melt and relatively low initial temperature of the die surface.

For the prediction of number of cycles to failure, the plastic strain range was considered as the left hand side in equation (1), and only the plastic component of the equation was considered on the right hand side. The analysis showed that the maximum strain range occurred at approximately 20 seconds after the molten copper was injected. The nodes where the strains were observed to be highest were along surfaces 1 and 2 shown in Fig. 3. As stated earlier, surfaces 3 and 4 in Figure 3 (the biscuit section) were not included in the fatigue life analysis. To determine the specific areas in the die where the strains were highest, the strains were plotted along surfaces 1 and 2. Fig. 4 shows the plot of strains on the nodes on surface 1 at 20 seconds.

TABLE 3. Temperature dependent properties of Inconel 617 alloy and Haynes 230: Thermal Conductivity (k), Specific Heat (C), Thermal expansion coefficient (a) and Modulus of Elasticity (E).

	Inconel 617 Alloy				Haynes 230 Alloy			
Temperature (°C)	**k (W/mK)**	**C (J/Kg-K)**	**a x 10^{-6} (m/m-C)**	**E (GPa)**	**k (W/mK)**	**C (J/Kg-K)**	**a x 10^{-6} (m/m-C)**	**E (GPa)**
Room Temp	13.4	419	-	211	8.9	397	-	211
100	14.7	440	11.6	206	10.4	419	12.7	207
200	16.3	465	12.6	201	12.4	435	13.0	202
300	17.7	490	13.1	194	14.4	448	13.3	196
400	19.3	515	13.6	188	16.4	465	13.7	190
500	20.9	536	13.9	181	18.4	473	14.0	184
600	22.5	561	14.0	173	20.4	486	14.4	177
700	23.9	586	14.8	166	22.4	574	14.8	171
800	25.5	611	15.4	157	24.4	595	15.2	164
900	27.1	660	15.8	149	26.4	609	15.7	157
1000	28.7	662	16.3	139	28.4	617	16.1	150

TABLE 4. Temperature dependent properties of Inconel 617 alloy and Haynes 230: Ultimate tensile strength (UTS), Yield strength at 0.2% offset (YS), Elongation (e) in 2 inch (50.8 mm) and Tangent Modulus (TM)

	Inconel 617 Alloy				Haynes 230 Alloy			
Temperature (°C)	**UTS (MPa)**	**YS (MPa)**	**e**	**TM (MPa)**	**UTS (MPa)**	**YS (MPa)**	**e**	**TM (MPa)**
Room	750	350	-	-	860	390	48	-
538	600	250	71	491	710	275	58	783
649	575	260	51	619	670	270	55	729
760	450	240	75	-	585	285	46	-
871	300	200	85	117	400	225	59	297
982	130	100	88	34	225	120	71	149
1093	80	40	70	57	120	57	50	127
1149	60	30	65	46	79	39	40	101

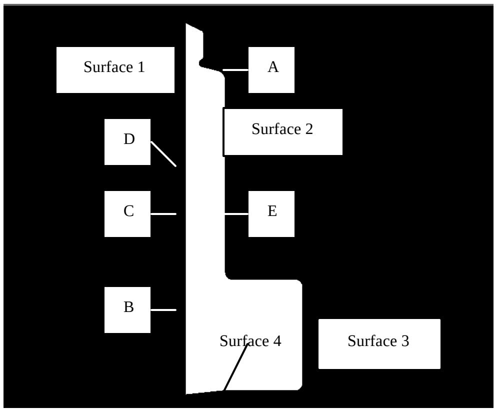

FIGURE 3. Nodes of interest on surfaces A and B considered for fatigue life [6].

The strain-distance plot in Fig. 4 was used in determining which nodes demonstrated the highest strain range. Model nodes A, B, C, D and E shown in Figure 3 were those selected for the "worst case" fatigue life predictions.

From Equation 1, one of the most influential parameters in calculating the number of cycles to failure is the percentage reduction in area (R_A) or ductility. Unfortunately, R_A values for Haynes 230 and Inconel 617 alloys are not available in the literature for the high temperature ranges obtained via the FEA thermal analysis. However, reasonable values for R_A can be estimated from the constancy of volume relationship for plastic deformation. The relationship is,

$$A_f L_f = A_0 L_0 \tag{2}$$

where A_f and L_f are area at necked region and gauge length at fracture during a tension test, respectively. A_0 and L_0 are initial area of gage section and length, respectively. The calculations for R_A are based on an initial gage length of 2 inch (50.8 mm). The maximum temperatures encountered during a cycle on each of the five nodes (A-E in Figure 3) were recorded. The elongation was assumed to be constant for a particular temperature range. For example, Inconel 617 within a temperature range of 750 – 850 °C was given an elongation of 75% [6]. Then the percentage elongation (e) was used to evaluate R_A values at the five nodes of interest for the two alloys. This temperature range, the corresponding % elongation and the calculated R_A are as shown in Table 5. The R_A values were the then input into equation (1) to calculate number of cycles to failure (N_f) at the five nodes of interest for the two alloys considered. The N_f values are listed in Table 6.

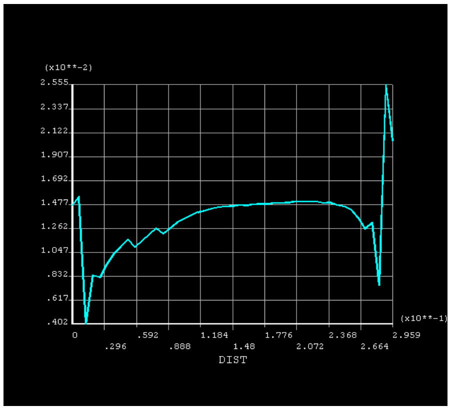

FIGURE 4. Strain versus distance plot for surface 1 at t = 20 s [6].

TABLE 5. % Elongation (e) and % Reduction in area (R_A) for Inconel 617 and Haynes 230 alloys at different temperature ranges

Temperature Range (°C)	Inconel 617		Haynes 230	
	e	R_A	e	R_A
750 - 850	75	42.9	46.1	31.5
850 - 950	85	45.9	60.0	37.5
950 - 1050	88	46.8	70.5	41.3

TABLE 6. Number of cycles to failure (N_f) at nodes of interest. N(S) refers to Node (Surface). Temp in °C

N(S)	Inconel 617			Haynes 230		
	200	350	650	200	350	650
A (2)	478	548	1038	267	345	919
B (1)	1593	2082	4197	1335	1732	3768
C (1)	1787	2067	4211	1338	2012	3900
D (1)	2260	2745	4219	1527	2981	4872
E (2)	1996	2272	5604	1486	2307	4509

CONCLUSIONS

As shown in Table 6, of the three temperatures simulated (200, 350, and 650 °C) an initial bulk die temperature of 650 °C resulted in the best thermal fatigue life performance for both Haynes 230 and Inconel 617 alloys. The predicted thermal fatigue life of the tooling was increased by a factor of approximately three for the nodes evaluated when the bulk die temperature was increased from 200 °C to 650 °C. When considering Haynes 230 versus Inconel 617, the Inconel 617 was predicted to perform slightly better in thermal fatigue resistance at 650 °C at four out of the five locations analyzed in Fig. 3 (A, B, C, and E). The results of this research suggest that replacing H-13 with either Inconel 617 or Haynes 230 nickel based alloys, along with increasing the bulk die operating temperature to 650 °C, would significantly delay the onset of heat checking in the metal delivery system of copper rotor casting tooling.

Finally, the predicted number of cycles to the onset of heat checking in this research should be considered somewhat conservative for two reasons. First, the analyses were performed in the metal delivery area of the die – known from experiments to demonstrate the earliest heat checking. Second, due to lack of available high temperature mechanical property data, the R_A values used in the model were most likely conservative.

ACKNOWLEDGEMENTS

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