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Analysis of Permanent Mold Distortion in Aluminum Casting

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ABSTRACT

Mold distortion in permanent mold casting campaigns results in loss of mold productivity and shorter mold life and can result in out-of-dimensional tolerance castings. Remedies to avoiding distortion during a casting campaign include back-face mold machining, bolting and clamping, but permanent deformation occurs when these restraints are removed. An AFS research project was undertaken using finite element thermal and stress analysis to better understand the causes of permanent mold distortion. Phase I research, using a simple mold geometry, indicated mold-metal interface thermal shock and continued mold cycling resulted in cumulative permanent plastic strain. Phase II research, using a commercial mold insert, resulted in good agreement between the model plastic strain and the actual measured mold insert distortion. The study showed that mold material properties are significant, with higher mold thermal conductivity (better heat diffusivity beyond the mold-metal interface) and higher creep strength results in less plastic strain per casting cycle and less permanent mold distortion.

Keywords: permanent mold, distortion, aluminum casting, creep, casting cycle, thermal conductivity

INTRODUCTION

Iron-based molds are used in permanent mold casting of aluminum parts where dimensional control and surface quality are important. The molds are typically made of a tool steel (e.g., H13) with a high hot hardness and resistance to softening so it can withstand thermal cycle-associated stress gradients experienced during the casting process. However, distortion of these permanent molds is an historic problem that results in out-of-tolerance castings, excessive fin formation, mold leakage, and short mold life (e.g., high mold costs). Typical solutions to deal with mold distortion have included mechanical means to restrict distortion during casting, such as bolts and clamps, machining mold back faces, or using thicker molds, but distortion persists after the casting campaign ends and the constraints are released.

The results of a research project to investigate distortion of permanent molds is reported in this paper. The project was conducted by DANTE Solutions, Inc., with guidance from David Neff, and funded by the American Foundry Society. The AFS research project consisted of two phases. Phase 1 focused on demonstrating the feasibility of using the finite element method to model distortion mechanisms active in a simple mold geometry. Phase 2 focused on applying the knowledge gained to predict distortion of a commercial permanent mold. This paper summarizes the Phase 1 findings and reports mainly on the Phase 2 work.

Mold material properties that affect resistance to distortion include hot strength or hot hardness, resistance to softening at temperature, and the ability of the mold to distribute heat quickly (thermal conductivity). These properties are important to minimize the effects of thermally-induced stresses that can cause creep or plastic deformation. The mold extracts heat from the molten aluminum to facilitate solidification of the casting and a steep thermal and stress gradient is established in the mold from the hot face to the cold back face. If the stress exceeds either the hot strength or the creep strength of the mold at that high temperature, permanent strain will occur. The magnitude will be low because the time at temperature will be short, but the strain will be permanent, and it will accumulate with each casting cycle. The magnitude of strain will be a direct function of the mold properties, especially creep strength, thermal conductivity, and coefficient of thermal expansion.

In addition to the mold material properties, the casting process itself and the geometry of both the mold and the casting impact mold distortion. Significant process variables are the pour temperature, solidification temperature of the cast, mold preheat temperature, residence time in the mold, the use of a mold wash or coating, mold cooling, and mold constraints (e.g., bolts or hold downs). The local casting thickness, surface area/volume, and geometric features of the casting dictate how much heat must be removed from the castings, and the timing of the heat removal. The mold geometry may include grooves or cut-outs on the back face that facilitate cooling or reduce local stresses. With these many possible parameters that affect mold distortion, the feasibility had to be demonstrated that the finite element method could capture the essence of the mechanisms involved in mold distortion, and then could be used to accurately predict mold warpage. The end goal is to be able to design a permanent casting mold with improved mold life.

PHASE 1 SUMMARY

A simple mold shape was used in Phase 1 to investigate the capability of the finite element (FE) method to model the steep thermal and stress gradients that quickly form and dissipate in a permanent mold. H13 tool steel properties were gathered from published literature, and higher temperature behavior had to be estimated. Modeling efforts showed that thermal shock could be captured only if mesh size was extremely small (e.g., mesh thicknesses of several microns or finer adjacent to the hot face). The FE method could capture such gradients, and it predicted that these thermal stress cycles could cause plastic strain that would build with each cycle. Furthermore, the stress state generated during each cycle went through a reversal due to plastic strain, with hot face stress first being compressive as the surface tries to expand but is constrained by colder subsurface mold material, then neutral as it relaxes due to local plastic strain, then tensile as subsurface material heats and expands while the surface is cooling slightly, and finally compressive as the subsurface cools and pulls the surface into deeper compression. Phase 1 successfully showed that the FE method could predict mold behavior under these highly transient and nonlinear conditions. Phase 1 used a simple mold geometry, and a commercially used mold or mold component was to be used in Phase 2.

PHASE 2 RESULTS

Mold Insert

Carley Foundry donated an insert that was part of a permanent mold assembly used to cast an aluminum part. The inset was roughly 12 in. (304.8 mm) square and 1 in. (25.4 mm) thick. Figure 1 shows a view of the insert looking down on the hot face. For reference, the recess shown in the hot face is 0.030 in. (0.76 mm) deep. Flatness of the casting is critical, and the insert distorts during casting production. Carley Foundry has tried several different mold materials, including H13 and cast iron, and several different mold constraints. Figure 2 shows non-contact laser measurements of the cold insert hot face. This was taken at room temperature after a production run, and the hot face is cupped, with the corners displaced upward 0.054 in. (1.37 mm).

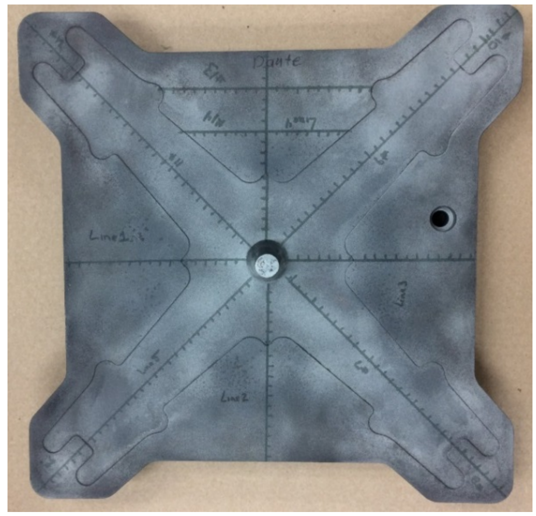

Figure 1. Permanent mold insert showing lines used for measurements. The spacings are 0.25 in. (6.35 mm).

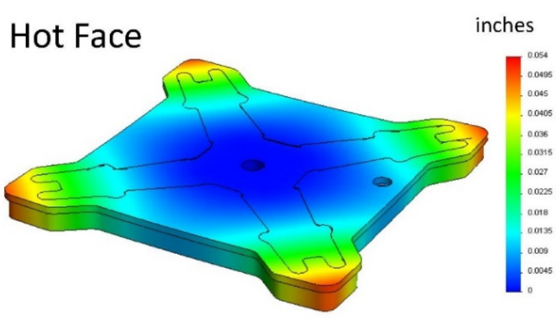

Figure 2. Displacement measurements of the hot face of the mold insert after cooling to room temperature.

The scrapped insert supplied by Carley Foundry was used to document the distortion that occurred. Figure 1 shows lines and measurement locations that were scribed on the hot face; the point locations were at 0.25 in. (6.35 mm) spacing along the lines. Measurements were made using a dial indicator with a resolution of 0.001 in. (0.025 mm) so that the out-of-plane displacements could be mapped and later compared with model predictions. Figure 3 shows the mold insert and the measurement setup. Figure 4 shows the results of these measurements, averaged for the two families of lines, diagonal (running center to corner) and orthogonal (running center to mid-side). In Figure 4, the CAD-1 and CAD-2 lines show that the insert face should be flat and that the recess is 0.030 in. (0.76 mm) deep.

Figure 3. Mold insert showing the measured lines and locations, dial indicator, and the granite block used for measuring flatness.

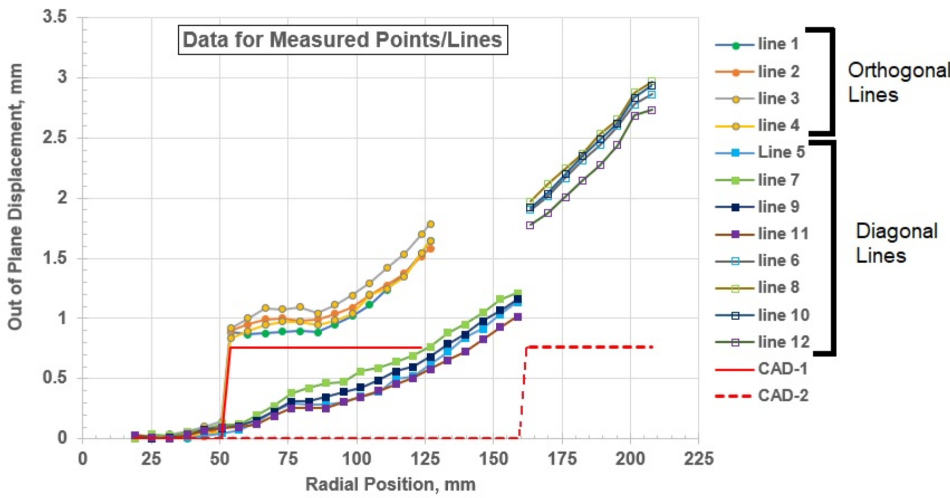

Figure 4. Hot face measurement results for orthogonal and diagonal lines. CAD-1 and CAD-2 refer to original positions of the hot face planes, with the 0.030 in. (0.76 mm) recess evident in the line traces.

<u>Material Properties</u>

Material properties used in these models are shown in Figures 5 and 6 for elastic properties and plastic properties as functions of temperature. Table 1 contains values for thermal conductivity, specific heat and thermal expansion. A portion of the data in Table 1 and Figures 5 and 6 were extracted from Reference 1.

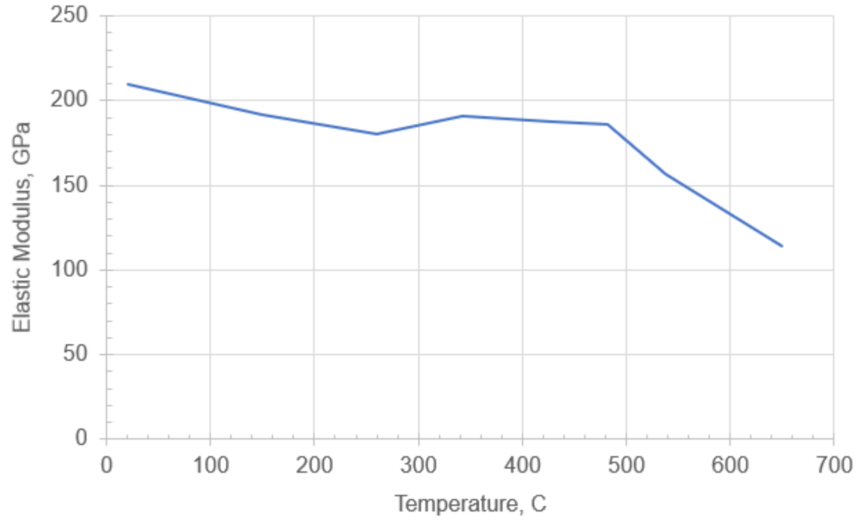

Figure 5. Elastic modulus used for model material.

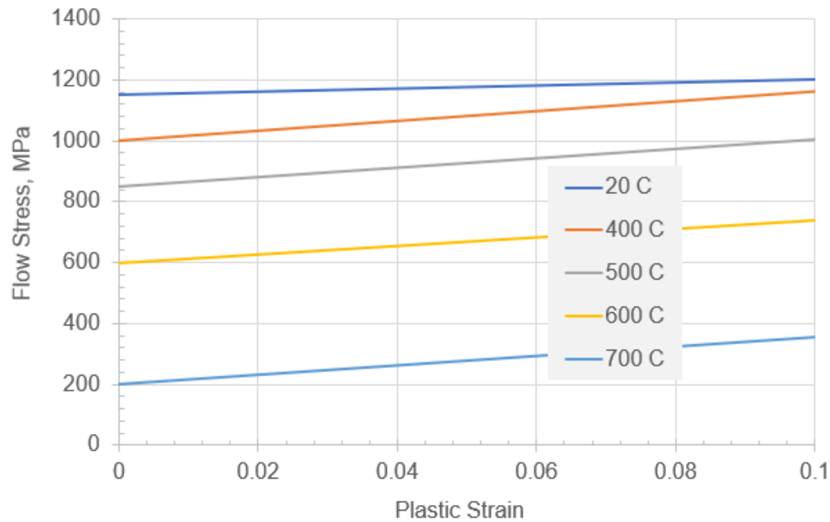

Figure 6. Flow stress properties used for model material.

Table 1. Thermal Properties of Model Material

Temperature	Thermal Conductivity	Specific Heat	Thermal Expansion
68°F (20°C)	15.6 BTU/ft/hr/°F (27 W/m/°C)	0.11 BTU/lb/°F (460 J/kg/°C)	
212°F (100°C)		0.12 BTU/lb/°F (483 J/kg/°C)	6.11e-6 /°F (1.10e-5 /°C)
392°F (200°C)	14.79 BTU/ft/hr/°F (25.6 W/m/°C)	0.124BTU/lb/°F (520 J/kg/°C)	6.39 e-6 /°F (1.15e-5 /°C)
572°F (300°C)		0.14 BTU/lb/°F (570 J/kg/°C)	6.66 e-6 /°F (1.20e-5 /°C)
752°F (400°C)	15.14 BTU/ft/hr/°F (26.2 W/m/°C)	0.14 BTU/lb/°F (590 J/kg/°C)	7.00 e-6 /°F (1.26e-5 /°C)
932°F (500°C)		0.15 BTU/lb/°F (646 J/kg/°C)	7.50 e-6 /°F (1.35e-5 /°C)
1112°F (600°C)		0.18 BTU/lb/°F (735 J/kg/°C)	7.67e-6 /°F (1.38e-5 /°C)
1292°F (700°C)	15.66 BTU/ft/hr/°F (27.1 W/m/°C)	0.24 BTU/lb/°F (1008 J/kg/°C)	7.83e-6 /°F (1.41e-5 /°C)

Finite Element Model

Both the laser measurements shown in Figure 2 and the measurements plotted in Figure 4 showed that the cupping of the insert was symmetric about the center post. Therefore, a one eighth section of the mold insert was used to define a three-dimensional mesh. Shown in Figure 7 are two of these sections which defines one quarter of the insert. The geometry was simplified by eliminating the 0.030 in. (0.76 mm) recess on the hot face; this feature was thought to have a minor effect on distortion. The finite element mesh was finely spaced adjacent to the hot face so that it would capture the steep thermal and stress gradients experienced as the casting solidified. The cast aluminum itself was not modeled but the heat imparted to the mold insert was modeled by application of surface heat transfer coefficients and ambient temperature change.

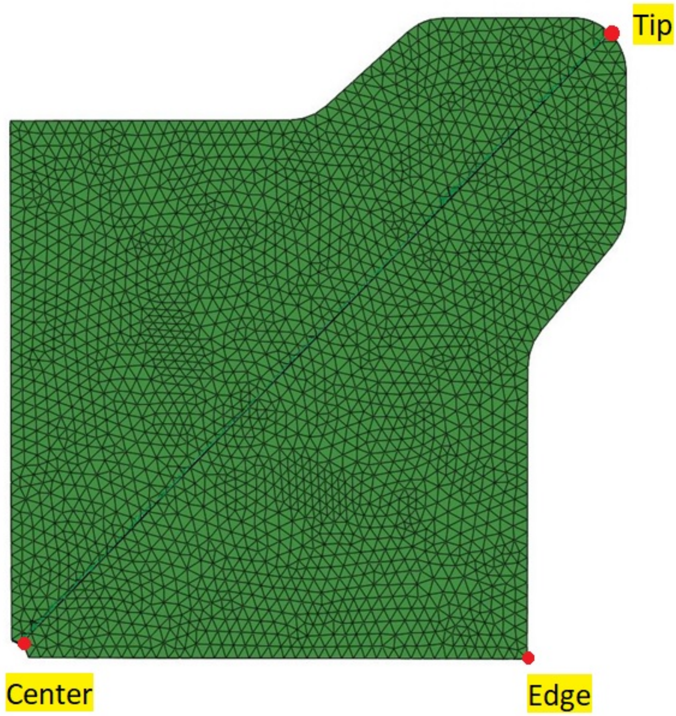

Figure 7. Mesh defined to model the mold insert. A quarter view shows two one-eighth sections, each with 35,750 nodes and 86,809 tetrahedral elements and 36,708 wedge elements. Locations referenced in later figures are indicated.

The baseline insert preheat temperature was assumed to be 650F (343C). The casting cycle that was modeled is given in Table 2. This cycle is similar to actual permanent mold casting cycle production. The heat transfer on the hot face was assumed to be high when the mold was being filled and the casting was resident in the mold, and lower when the mold was opened. The heat transfer from the back side of the insert was assumed to be 17.61 BTU/ft^2/hr/°F (100 W/m^2/°C). The ambient temperature at the hot face was a function of time, ranging from to 1328 to 650F (720 to 343C) over the 700 second casting cycle.

Table 2. 700 Second Total Casting Cycle Used for FE Simulations

Step	Time	Heat Transfer Coefficient	Ambient Temperature
Molten Aluminum into Mold	0.5 seconds	1585 BTU/ft^2/hr/°F (5kW/m^2/°C)	650 to 1328F (343 to 720C)
High Heat Transfer into Hot Face	15 seconds	1585 BTU/ft^2/hr/°F (5kW/m^2/°C)	1328F (720C)
Casting Cooling in Mold	300 seconds	17.61 BTU/ft^2/hr/°F (100 W/m^2/°C)	1328 to 650F (720 to 343C)
Open Mold	384.5 seconds	17.61 BTU/ft^2/hr/°F (100 W/m^2/°C)	650F (343C)

RESULTS & DISCUSSION

Finite element (FE) models were run to examine the effects of casting parameters and material properties on mold distortion. The casting cycle was evaluated in terms of mold temperature experienced and resultant stresses over time. Results are presented to show changes in stress state and mold displacement and strain during the transient changes in temperature that occur.

Model results for temperature, displacement and von Mises stress at three locations on the hot face for one casting cycle (700 seconds) are shown in Figure 8. The positions of the referenced locations, corner tip, mid-side or edge, and insert center, are indicated in Figure 7.

Temperature

The locations quickly heat up as the mold is filled, with the location temperatures reaching 1166F (630C) to nearly1328F (650C). After about 40 seconds the mold surface begins to reduce in temperature as heat conducts toward the back face, and the hot face at these locations cools steadily for the next 300 seconds. Then, at about 340 seconds, the temperature falls to almost the preheat temperature, and for the next 360 seconds the hot face temperature slowly falls to the preheat temperature of 650F (343C).

Displacement

The hot face surface expands quickly as the temperature rises, causing the tip and edge locations to bow downward. As the temperature reduces after peaking, the subsurface layers expand while the surface layers start to contract, resulting in a change in the displacement direction for the edge and tip. The result is cupping of the hot face, with the peak displacement occurring at about 280 to 290 seconds into the cast cycle. As the hot face cools to the preheat temperature, the cupping is reduced, with a small amount remaining at the end of the casting cycle (2.6 microns). The first cycle gives more cupping than subsequent cycles of a casting run.

Stress

The von Mises stress or equivalent stress is a way of representing the three-dimensional stress state in uniaxial terms, so it can be compared to tensile yielding. The von Mises stress peaks very quickly and then decays. There is a second much smaller peak when displacement is the highest positive value. However, the von Mises stress gives no indication of stress direction.

Figure 9 shows the 20th casting cycle, and it is similar to Figure 8 except equivalent strain is plotted instead of displacement. The shaded section shows that the first 200 seconds of the casting cycle are responsible for plastic or permanent strain. This is the time increment when the temperature of the hot face is high, and the combination of temperature and stress is enough to cause local plastic deformation. Upon heating the hot face, the surface stresses are compressive. As the mold insert hot surface cools and the subsurface layers heat up, the surface stress state becomes low tension.

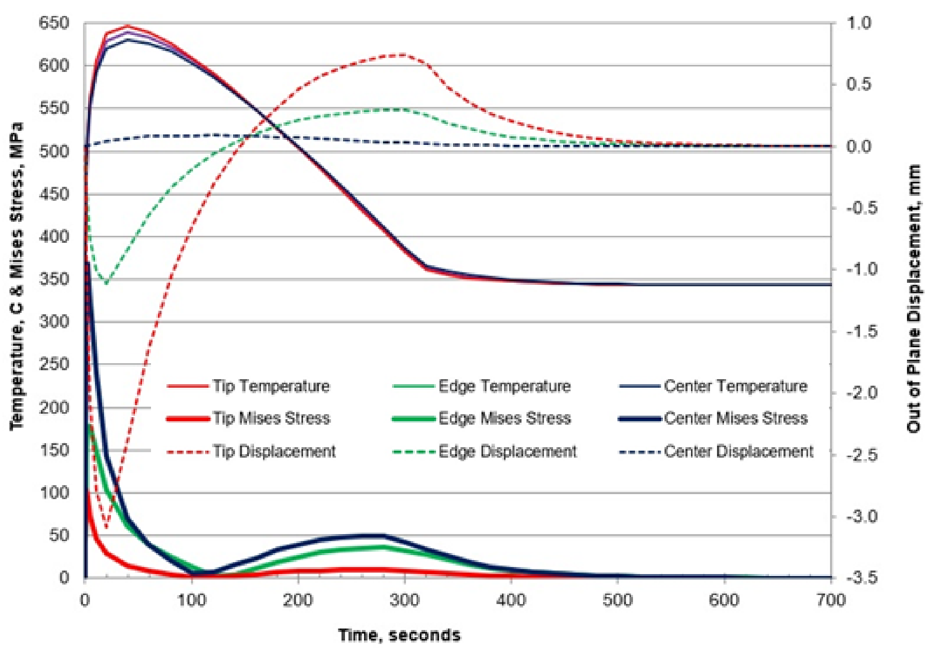

Figure 8. Predicted temperature, von Mises or equivalent stress and out-of-plane displacement for three locations of the hot face during the first casting cycle. Tip is the mold insert outer corner, edge is the middle of a straight edge location, and center is the mold insert center location.

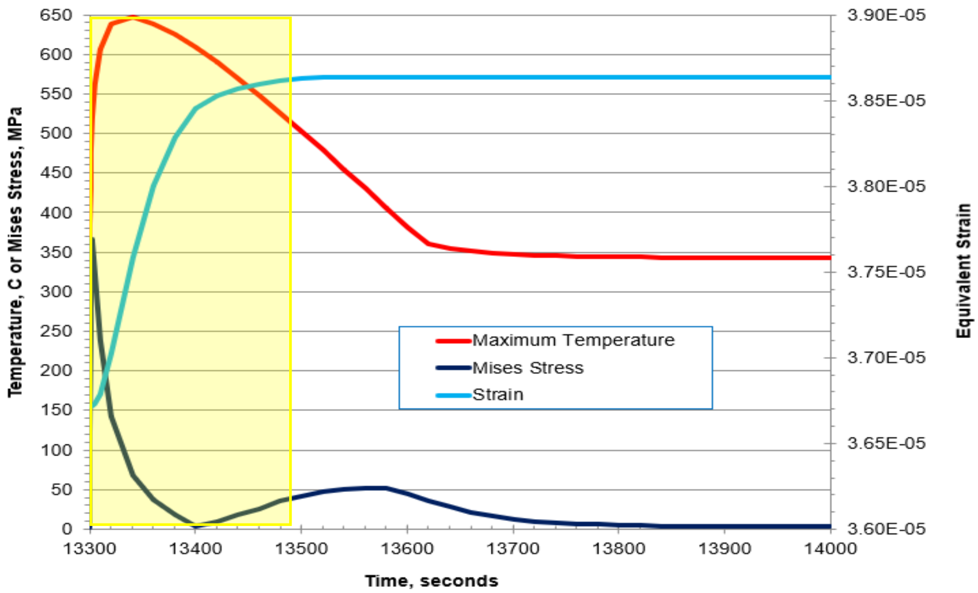

Figure 9. Graph showing the temperature, equivalent strain and von Mises stress for the 20th casting cycle. The shaded box shows the temperature and stress conditions that result in permanent strain or distortion. The localized creep deformation accumulates with each casting cycle.

Mold Preheat Temperature

The model prediction is that the out-of-plane displacement builds with each casting cycle, so that even though the magnitude per cycle is small, the mold distortion accumulates and will become an issue over mold usage time. Figure 10 shows model predictions over 20 casting cycles for three different preheat temperatures, 550F (288C), 650F (343C) and 750F (400C). The dashed lines are temperature predictions for each of the twenty cycles, and the solid lines show the build-up of plastic strain with each cycle. The casting cycle starts and ends at the mold preheat temperature, and this constraint shows that a higher preheat temperature will results in more distortion for a given casting campaign. The time at elevated temperature will be greater for the higher preheat and allow more creep strain to occur for each cycle.

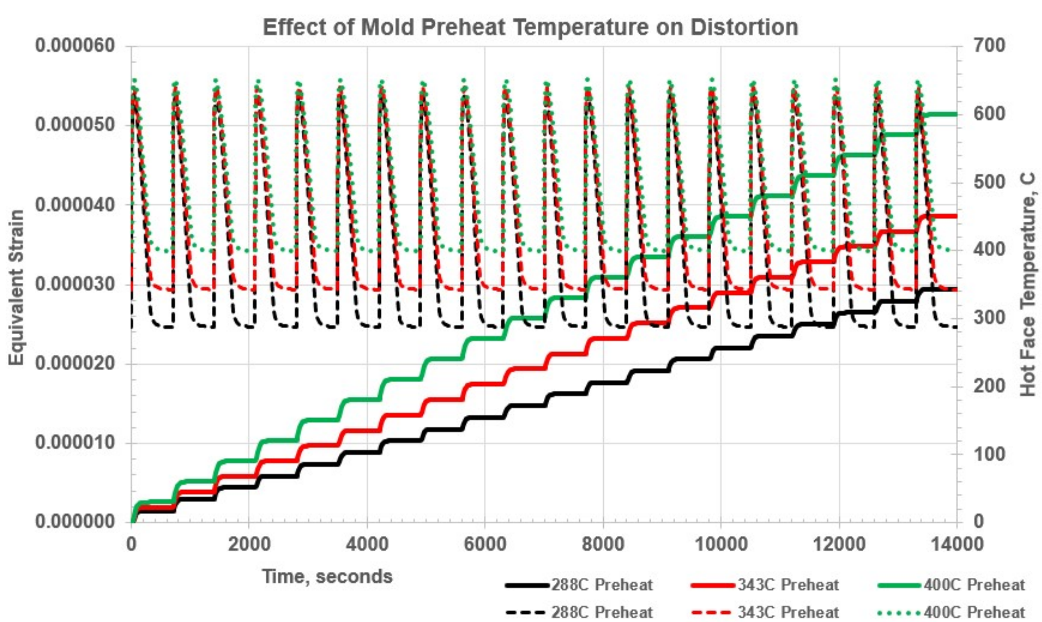

Figure 10. Predicted strain and temperatures for the indicated mold preheat temperatures for twenty casting cycles.

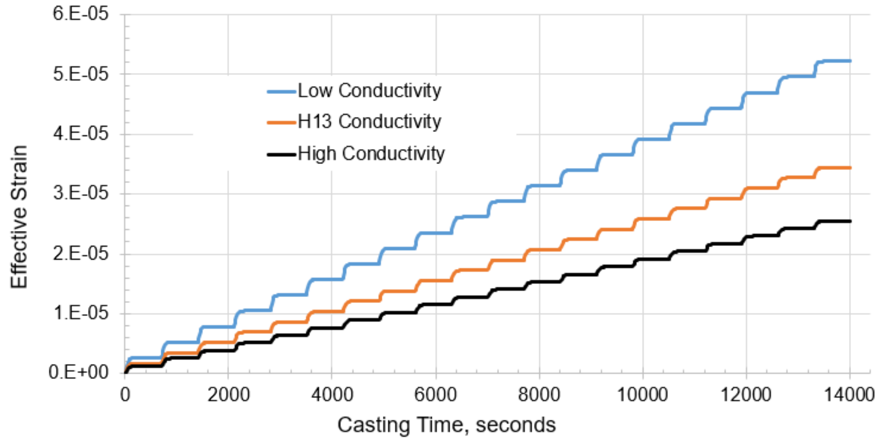

Figure 11. With no change in hot strength and creep resistance, a mold material with higher thermal conductivity will distort less than a material with lower thermal conductivity. The plot is for strain build-up over twenty casting cycles.

<u>Mold Thermal Conductivity</u>

Higher mold thermal conductivity will reduce the distortion per cycle, as shown in Figure 11. The higher thermal conductivity diffuses heat more quickly from the mold hot face to reduce the time that creep is active. The caveat for this statement is that the creep behavior in the model is the same for the three conductivity levels

<u>Comparison of Model Predictions and Measured Insert Displacement</u>

The number of cycles that the measured insert was in operation was not documented. This makes an actual distortion prediction for comparison against the measured displacements difficult. Model results for 5,000 casting cycles show that cupping builds with each cycle, with the first cycle having a tip displacement of 2.6 microns and subsequent cycles having additional tip displacements of approximately 0.35 microns. Figure 12 shows a plot predicting the cupping displacement for 5,000 casting cycles, and this matches well with measurements made in the center region of the insert. Using these same predicted tip displacements to estimate the actual insert usage based on the measured tip displacement, the projection is that the insert was removed from service after approximately 5,900 casting cycles.

This comparison shows that the model predictions are reasonable, given the lack of accurate material property data and the assumed boundary conditions for heat transfer during the casting cycle. Figure 13 demonstrates displacements predicted by the model over 10,000 casting cycles. Comparing typical permanent mold materials such as H13 and cast iron, H13 has greater creep resistance and higher thermal conductivity than most grades of cast iron, and hence will predict less distortion for H13 molds.

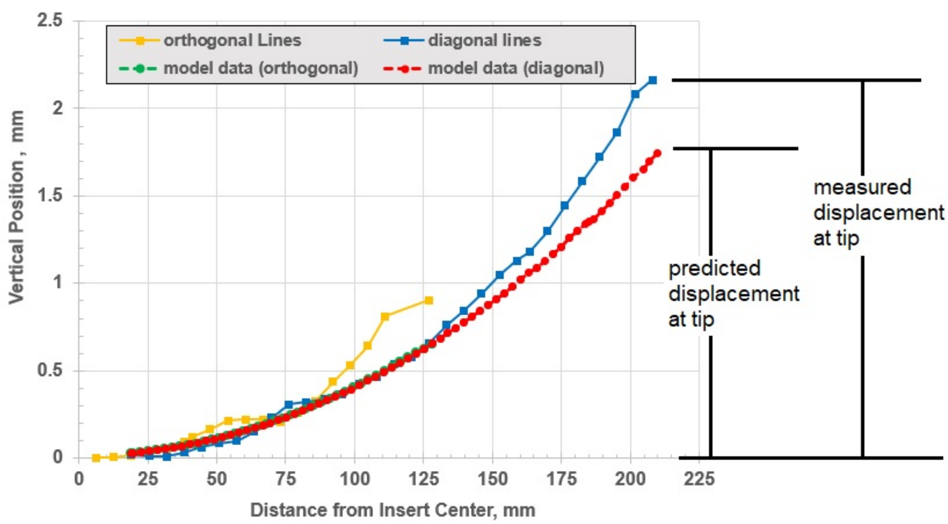

Figure 12. Comparison of model predictions for 5,000 casting cycles and measurements for the distorted mold insert.

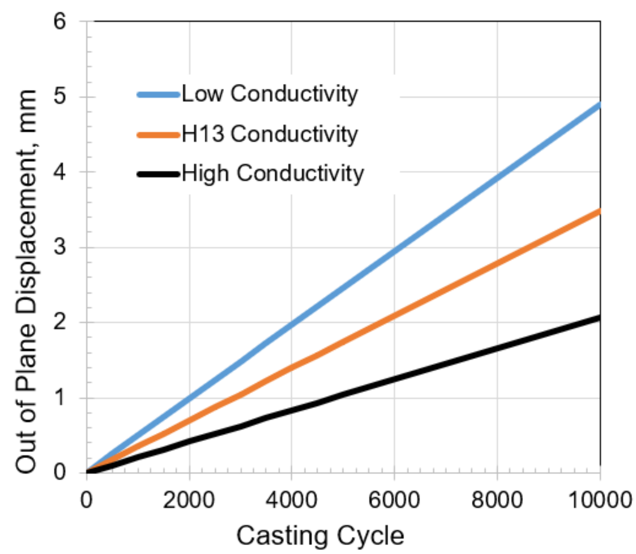

Figure 13. Extrapolation of model distortion prediction results to 10,000 casting cycles.

Summary

The results of this work suggest several methods to minimize mold distortion issues. Since the steep thermal and stress gradients for each casting cycle occur, methods to reduce the gradient and/or dissipate it quickly can minimize mold distortion. It is not possible to eliminate mold distortion, but it can be minimized. Methods should include:

Mold Preheat Temperature

This study has shown that mold preheat temperature affects the level of stress generated in the mold. During a casting campaign, the mold will assume a quasi-steady state temperature cycle that is mainly set by the rate of production. A higher mold 'resting' temperature can minimize the thermal stress during the high heat extraction period of the cycle, but two facts limit what this temperature should be: 1) the creep strength of the mold material has to be high if the mold is going to experience higher temperatures for longer times; and 2) the casting cycle will be lengthened since the thermal gradient will be lowered. The thermal gradient is the driving force for extracting heat from the solidifying casting, so a reduced gradient will mean slower heat extraction from the casting.

Mold Material Thermal Conductivity

Lowering the mold thermal conductivity means that the casting cycle will be longer as it will take more time to remove heat from the casting. Also, to maintain a higher production rate, the mold will operate at a higher temperature. The relationship between the thermal conductivity of the mold and creep strength will dictate what temperature and production rate are suitable for a particular cast product.

Consequently, one means to reduce possible mold distortion is to use a mold material with higher thermal conductivity, i.e., higher thermal diffusivity.

Methods are available to overcome material creep strength and thermal conductivity limitations, and they involve the use of artificial cooling as described in the following bullet items.

- *Mold contouring*—by contouring the mold backface to maintain a relatively thin mold thickness where the backface temperature can be maintained, the heat extraction through the mold can be more uniform and the stresses can be dissipated more quickly. Also, the stresses in the casting can be lower, minimizing distortion of the casting and promoting shorter casting cycles. Work is needed to determine mold thickness requirements for safe performance. These include investigating the role of mold material conductivity on heat extraction vs. stress cycle. While promising, this method will be limited to relatively smooth surface geometries that have no abrupt section thickness changes in the casting. The latter will generate large local differences in heat flux into the mold and high local stresses.
- *Internal cooling lines, channels and heat extractors*—to augment heat extraction and overcome some of the local stress issues, water-cooling lines, channels, or the use of local heat extractors (copper pins, etc.) can be used. Each application would be a unique case for these

designs, so a comprehensive software package is needed to eliminate mold design by trial-and-error. Again, these types of molds will not eliminate distortion, but they can extend mold life and improve the dimensional accuracy of the cast product and achieve a consistent production rate.

CONCLUSIONS

This study showed that the finite element method is capable of modeling the permanent mold material responses during a casting cycle. The quality of the mesh is important as the mesh must capture the transient temperature and stress state of the mold as it extracts heat from the casting. Phase 1 of the AFS research project, briefly summarized, focused on thermal shock which is a main cause for thermal fatigue of die casting molds. A major problem in permanent mold casting is distortion of the mold members. Here, creep strength or stress relaxation, in conjunction with hot strength of the mold metal, is a main concern.

1. Mold distortion is related to creep strength and thermal conductivity of the mold material. Higher creep strength and thermal conductivity for these properties will reduce permanent mold distortion.
2. Mold distortion is a cyclic event, with low levels of permanent strain occurring with each casting cycle.
3. During a casting cycle, the hot face of the mold first experiences compression as expansion of the surface is restricted by colder sub-surface layers. As heat diffuses into the mold from the solidifying casting, the compressive stresses are reduced and transition to low magnitudes of tensile stresses as the mold cools.
4. Material properties of the mold material are important to the accuracy of the model. These properties are often not reported and must be determined.

ACKNOWLEDGEMENTS

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