High Pressure Die Casting

Simulating Thermal Stresses and Cooling Deformations

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Introduction

In the casting industry, the ability to predict thermal stresses and resulting deformations during solidification and cooling continues to be a challenge. Flow Science has recently developed its fluid-structure interaction (FSI) and thermal stress evolution (TSE) models to provide these kinds of predictions to its customers. With the addition of solid mechanics to its existing fluid focused modeling portfolio, *FLOW-3D** (www.flow3d.com) is now one of the few simulation tools that provide a fully coupled fluid-structure interaction model within one software package. The built-in finite element analysis along with *FLOW-3D*'s proven record in free surface flows makes it an attractive choice to the casting industry.

Many users have been coupling multiple software packages in order to simulate fluid-structure interaction problems including casting processes. The modeler solves the fluid mechanics separately, then imports the surface boundary conditions into a solid mechanics package, obtains the stresses and deformations and then feeds the deformed geometry back into the flow solver and the cycle continues. The manual implementation of this process proves tedious and automating it through scripts and wrappers is challenging. Besides, most of the time, this coupling has to be done on a per case basis. *FLOW-3D* has seamlessly integrated both aspects of this process into one package where both solutions come out as the result of a single simulation.

In this article, a case where the simulation results are compared to deformations from an actual cast part is presented. The part and experimental results were provided by Mark Littler of Littler Diecast Corporation.

The Casting Process

The part is an aluminum (A380) cover and is cast within a steel die. The length and width of the part are 9.45 by 7.01 in, and its overall thickness is 0.51 in. One of the concerns with this part is that during cooling, it bows at the mounting tabs which can prevent clamping and sealing of the lid. Figure 1 shows the top and side views of the cast part with the mounting tabs highlighted.

In order to be cost effective, the casting process should result in a part that is near its final shape requiring only minimal machining. Even with carefully orchestrated runner design, filling patterns, and cooling lines, thermal stresses can cause deformations that lead to deviations from the final geometry.

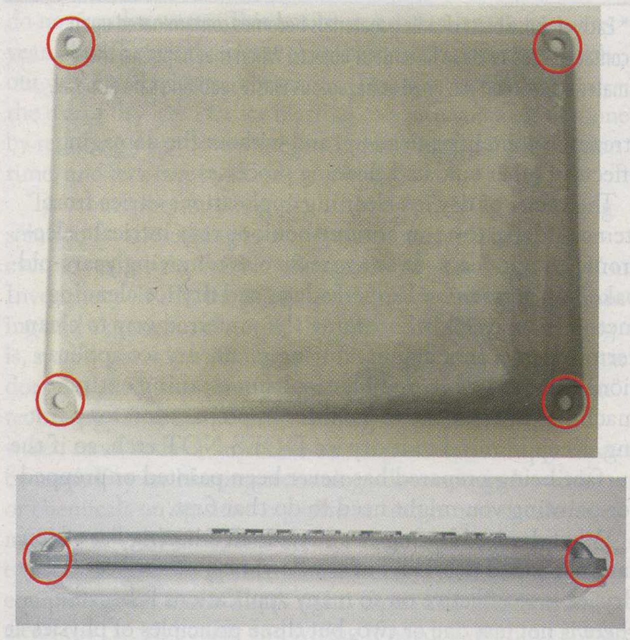

Figure 1 – Top and side view of the cast part (courtesy of Littler Diecast Corporation).

Simulation of Thermal Stress Evolution

The simulations included the following stages of the casting process: after (instant) filling, the part was cooled in the die for 6 seconds (stage 1), then it was removed from the die and air-cooled for 10 seconds (stage 2), and finally, after the runner system was removed, it was cooled for another 10 seconds (stage 3). Figure 2 shows the geometry used for the simulations. Full energy transport, solidification, and thermal stress evolution were the major computational steps throughout the simulation process. A material database pro-

Figure 2 – Over and under side of the geometry (courtesy of Littler Diecast Corporation).

vided the necessary properties for aluminum A380 alloy and H13 steel die.

The fluid computations were performed on a rectangular Cartesian grid, and the strain-stress equations were solved on a finite element (FE) body fitted mesh. The fluid mesh has a uniform resolution of 0.08 in and the finite element edges have a uniform size of 0.04 in. The resulting FE mesh has 254,353 elements and 301,292 nodes.

The FE mesh generation is a step that requires only minimal input from the user. An encompassing Cartesian mesh around the solid component is used as a starting point to generate a body fitted mesh. Alternatively, an FE mesh could be imported independently of the structured fluid mesh. Figure 3 shows an example of how fine features of a part can be resolved with localized grid refinement. The elements are hexahedrons except at the surface, where they can have anywhere between four (tetrahedrons) to eight (hexahedrons) nodes.

Figure 3 – Finite element meshing of a stereolithography CAD part with fine features. A localized finer resolution captures the details of the part.

The computational domain occupied by the metal is discretized by finite elements as well. These elements are inactive until the metal solidifies and therefore, do not impose any computational cost. As soon as an element is fully solidified, the finite element solver is activated for that element. Metal pressures, thermal gradients, and body forces contribute to stresses and deformations in the solid. These deformations are then fed back into the fluid flow. The standard output for the FE analysis includes all the components of the stress and strain tensors, deformations in three dimensions, normal displacements, volume expansion, mean isotropic stress, and the von Mises stress.

During stage 1, the solidifying molten alloy cooled non-uniformly due to varying thicknesses and heat transfer coefficients as the part pulled away from the die walls locally. This generated large stresses but minimal distortions because the part was constrained by the die. This matches the reported behavior from the actual casting of the part. The simulation shows that the stresses are larger in regions where thin and thick sections meet, where the temperature gradients are larger, and in corners and around the holes of the mounting tabs, because it is here that the part is constrained the most by the die.

During stage 2, immediate removal of the part from the die and subsequent cooling for 10 seconds resulted in large deformations due to release of the built-in stresses produced during stage 1. However, rapid cooling led to growth of the magnitude of local stresses as the part was still partially constrained by the runner system. Figure 4 shows the temperature contours at the end of stage 2 when the part has been cooled outside of the die.

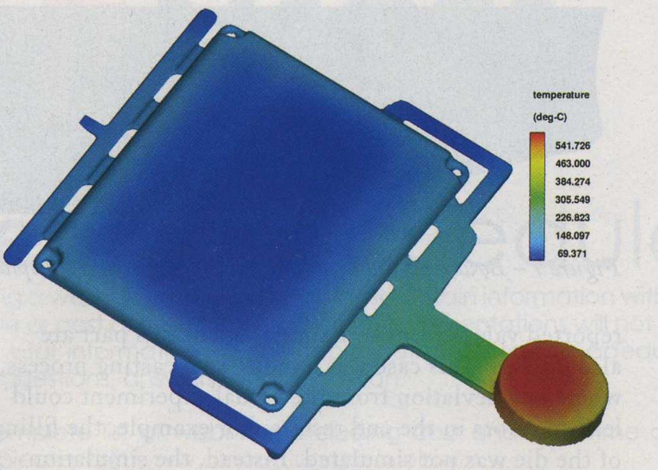

Figure 4 – Temperature contours after cooling outside the mold for 10 seconds and before removal of the runner system.

In stage 3, the part underwent another deformation phase because the constraint of the runner system was removed. Figure 5 shows the FE mesh for one of the mounting tabs. Although there is more shrinkage due to further cooling during this stage, the deformation is more uniform than it is at the end of stage 2. Also, the residual stresses are further reduced because the constraint of the runner system is removed and therefore, the stresses are partially relaxed. Figure 6 highlights the actual shrinkage at the end of the simulation relative to the non-deformed geometry.

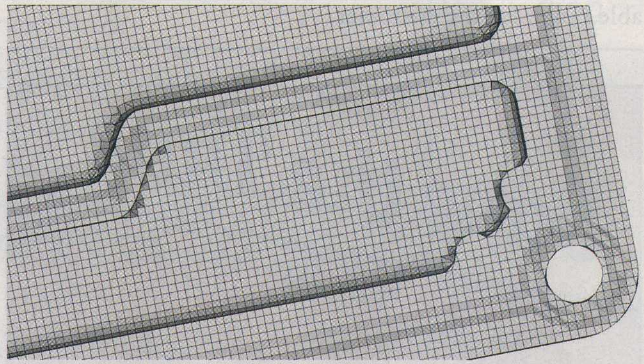

Figure 5 – Finite element mesh used to solve for thermal stresses.

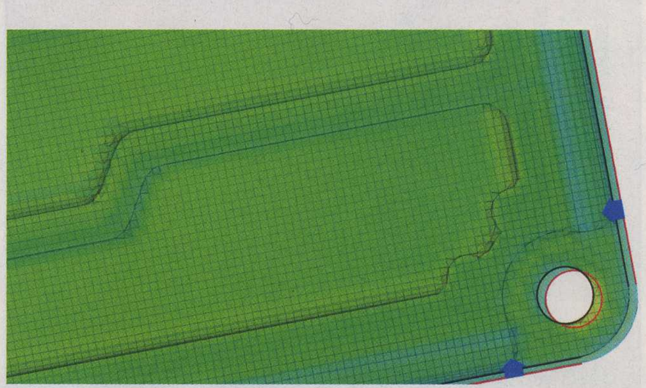

Figure 6 – Shrinkage of the part after cooling with the runner system removed. The outer perimeter corresponds to the un-deformed geometry and the meshed part shows the solid after cooling.

Figure 7 shows the normal displacements of the part at the end of the simulation. It shows that the part bowed up by 0.017 to 0.02 in at the mounting tabs. The

Figure 7 – Bowed edge. For visualization purposes, the displacements are exaggerated by a factor of 40.

reported values from actual castings of this part are also 0.02 in. This case was a multi-step casting process, where any deviation from the actual experiment could lead to errors in the end results. For example, the filling of the die was not simulated. Instead, the simulation started with the cooling of a filled die. The simulation used a relatively simple approach to cooling; during the various stages of the manufacturing of this part, the actual effective heat transfer coefficient may vary by more than what was assumed in the simulation. Greater rates of cooling could easily cause greater temperature gradients and therefore, different stresses and deformations. Additionally, the solid mechanics are solved using a linearized elastic model. At such high temperatures and temperature gradients, plastic deformations are a common occurrence. Therefore, more elaborate formulation including a non-linear plastic deformation model has been planned for future releases of the software. In this case, an error of around 15% was within an acceptable range for the customer.

Conclusions

FLOW-3D has recently added the capability of simultaneously simulating the fluid flow while computing the solid mechanics. There are only a few software packages in the industry that can solve a fully coupled fluid-structure interaction within a single simulation. Although the model is based on a linear Hookean model, large deformations are possible because the stress is computed incrementally during each time step. In this method, the stress-strain relationship during each small increment can be assumed to be linear in most cases. Furthermore, temperature-dependent elastic properties of the die and solidified alloy can be specified.

This model is particularly beneficial to the casting industry where thermal residual stresses cause the part to deform from the desired geometry during cooling. Casters can predict these deformations and correct for them by changing the die ever so slightly so that in fact the final deformed geometry is the desired shape.

This work represents an exciting new path for *FLOW-3D* users and serves as a foundation for several new capabilities in future releases. Such efforts will include plastic deformations and full coupling between neighboring solid components and between solid components and solidified fluid regions.

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About the Authors:

Amir H. G. Isfahani has been a developer at Flow Science since early 2009. He received his Ph.D. in Theoretical and Applied Mechanics from the University of Illinois at Urbana-Champaign. He has been involved in a multitude of projects in areas such as fluid-structure interaction, biological flows and turbulence modeling.

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