Effects Of Radiation Heat Transfer On Part Quality Prediction

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ABSTRACT

The most significant mode of heat transfer in an investment casting process is through radiation. It is critical that this be fully understood and accounted for when planning the process parameters for any casting. One must understand the radiation effects during the metal pouring and cooling cycle, as self-radiation and external casting conditions will affect cooling rates and solidification patterns. Additionally, pre-pouring soaking determines the shell temperatures before the pour and if this is not taken into account accurately, it will adversely affect the desired outcome.

This paper delves into radiation and the downstream effects in the casting of certain process scenarios, like heat loss in the mold before pouring, self-radiation affects on solidification, cooling of the shell and poured casting in ambient conditions versus an enclosed chamber (i.e., a can), effects of kaowool and other insulating mediums. These scenarios will be demonstrated using computer analysis with the ProCAST Casting Simulation Software by ESI.

INTRODUCTION

The investment casting or “lost wax” process, as it is commonly called, is one of the oldest known manufacturing processes. The ability to produce near net shapes leading to minimized machine cost makes the investment casting process one of the most attractive casting processes, especially for making exotic casting with expensive alloys. This process can be used to make complex shapes from aircraft jet engine components to small intercret castings used to make jewelry. The investment casting process does not require elaborate or expensive tooling and has the ability to produce several casting in one pour.

THE INVESTMENT CASTING PROCESS

This process can be broadly described in the schematic sketch given below. The various stages include creating the wax pattern, growing the investment shell, dewaxing and pouring the casting.

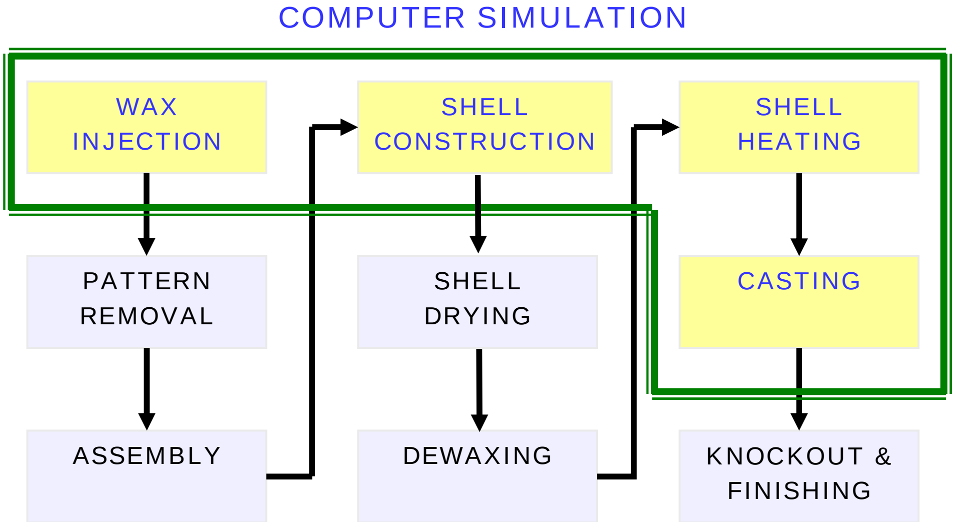

Figure 1: Flow Chart of the Investment Casting Process

In order for a simulation program to model the physics of the process, the computer program has to mimic accurately the various stages from wax injection to the actual pouring of the molten metal and solidification process. In addition to the mold flow and solidification analysis, advanced computer simulation programs such as ProCAST can also evaluate the thermally induced stress in the casting and underlying grain structure and mechanical properties of the final cast part.

Accurately modeling the trapped air and shrink porosity is critical to determine the validity of an existing gating system and feeder locations. Defects are usually observed in last areas to fill, especially if the permeability of the shell is not appropriate and if the last liquid area during solidification is in the casting and not properly fed. In badly designed gating systems, the liquid metal can prematurely solidify, leading to cold laps and other such defects. In order to accurately model the physics, it is essential that the proper heat extraction from the casting to the investment shell is calculated. There are 3 modes of heat transfer: conduction, convection and radiation. In the investment casting process the radiative heat transfer is dominant over the other modes of heat transfer.

RADIATION VIEW FACTOR ANALYSIS

Due to the elevated temperature of the mold relative to its surroundings and the nature of the system setup, the radiative heat transfer is the dominant mode of heat transfer. Since each location on the mold surface sees a different view of its environment, each will have a different rate of heat loss. For example, faces around the outer perimeter of the mold are exposed mostly to the environment, while the view space of those facing the inside of the mold see mostly other hot regions of the casting. As a result, radiative view factor calculations are required to accurately account for the heat exchange variations across the geometry. The initial mold temperature and heat loss to the environment prior to casting dictate the thermal profiles that exist at the time of pour. This creates a thermal gradient from the inside to the outside of the shell, depending on the self radiating effects of the whole assembly.

Most analysis packages on the market today assume basic radiation heat transfer calculations making single body assumptions that do not account for multiple bodies or shapes. Calculating view factors allows for multiple bodies and the shapes of those bodies to be involved in the radiation heat transfer to give a much more precise and accurate calculation. By not including multi-body radiation, part to part radiation effects or self-radiation effects would not be seen. As a result, irrespective of the casting orientation on the tree, each casting would heat or cool exactly the same – even if it was a casting on the end of the runner, or a part that was fully surrounded by other hot parts.

Planning setup design for investment casting involves visualizing the "invisible" radiation heat transfer effects. Therefore, to further understand radiation effects, analysis tools that are able to calculate the view factor radiation and shadowing effects will be used to present various common investment casting scenarios.

A simple example given below shows four test bar castings, one with the effects of self-radiation and the other without. Figure 2a, which does not have the effects of self-radiation, shows all the four test bars losing the same amount of heat at the given time. Even though the radiative heat effects are considered, there is no reflective heat back from the hot surfaces, thus all the test bars show exactly the same temperature profile, irrespective of their location in the model. Figure 2b, on the other hand, shows the effects of self-radiation on each specimen. As expected, the interior test samples are hotter than those on the outside as they receive reflected heat from the test bars on either side of them. The outside bars only receive heat from one side. This temperature gradient effect is also reflected in the solidification rate and porosity location and size in both the test configurations.

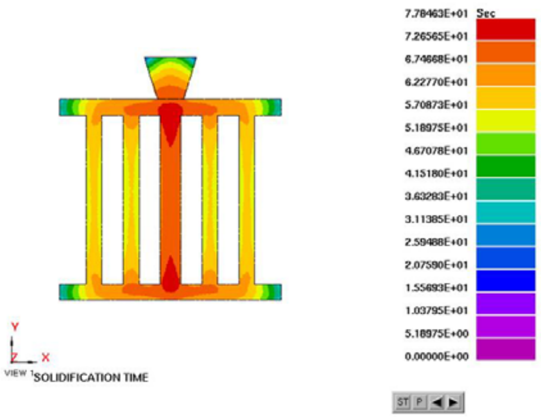

Figure 2a: Without Self-Radiation

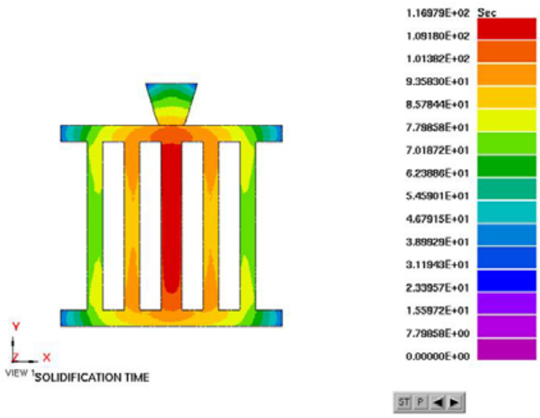

Figure 2b: With Effects of Self-Radiation

The amount of heat that is transferred can be expressed by the following (efunda):

$$\dot{Q}_{1\rightarrow 2} = A_1 F_{12} \varepsilon_1 T_1^4$$

Where,

$\dot{Q}_{1\rightarrow 2}$	=	Thermal Power From Body 1 To Body 2
A_1	=	Area of Body 1
F_{12}	=	View Factor from Body 1 to Body 2 (see below)
ε_1	=	Emissivity of Body 1
σ	=	Stefan-Boltzmann Constant
T_1	=	Temperature of Body 1

Furthermore, the View Factor calculation itself describes the geometric effect of the radiating bodies (Incropera):

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi R^2} dA_i \, dA_j$$

Where,

A_i, A_j	=	Elemental Area of Body i and Body j
Θi, Θj	=	Polar Angles From the Elemental Normal to the Direction of the Other Face
R	=	Distance Between Elements i and j

PRE-POURING COOLING

To prevent freezing of the metal or cold flow during filling, it is desirable to pour the casting as soon as possible when the mold is removed from the furnace. This is especially so for thin-shell molds or very thin parts. For "small" castings, where the mold is typically hand-moved from the furnace to the pouring bed, it is typical to have 10 to 20 seconds elapse before the metal is poured. Even this small amount of time can cause a significant reduction in temperature on shell faces that are open to the environment, especially if a thin shell mold or highly-conductive shell material is used. Figures 3a and 3b show the effects of shell cooling between the time it takes the shell to be extracted from the furnace to the beginning of metal entering the mold cavity. In the casting shown below a 25-30 second time delay can cause certain regions of the casting to drop 300-400 degrees. Note how the shell on the end has cooled much more rapidly than the interior regions.

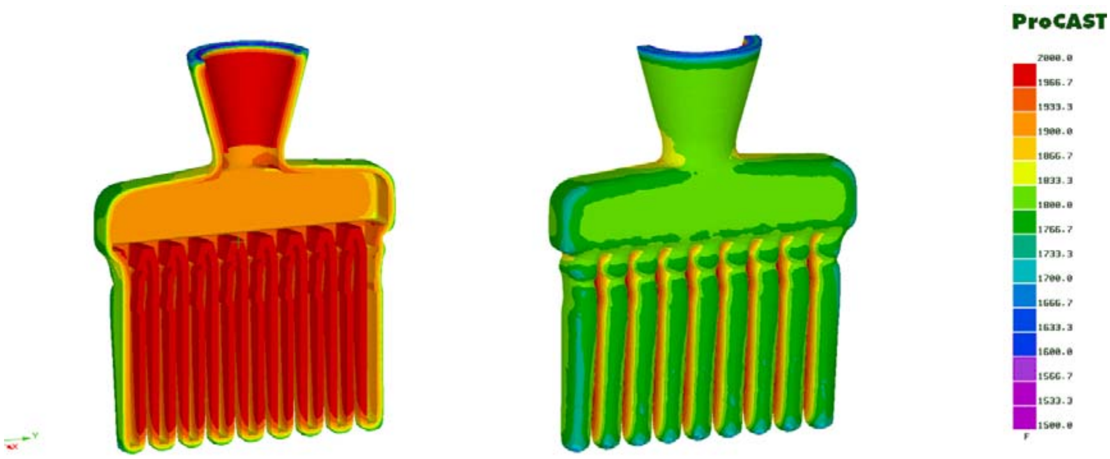

Figure 3a: Cool Down Inside **Figure 3b: Cool Down Outside**

With large shells or ones that must be moved from a furnace into a vacuum chamber, the elapsed time can be much more, and thus the difference between internal shell temperatures and external temperatures may be quite large – potentially resulting in unexpected filling issues or patterns.

SELF-RADIATION AND AFFECT ON SOLIDIFICATION AND POROSITY

In many investment castings, when the casting is poured, the shell glows, indicating the large amount of heat inside. During and after mold filling, solidification starts to take place. The energy content of the metal continually decreases by heat conduction with the cooler mold and by radiation from the mold surface. Exterior faces radiate this heat freely and allow for a relatively high rate of cooling. However internal surfaces or locations where there is mostly part to part radiation are, in essence, insulating each other by radiating heat on to itself. It is quite common to have internal parts or parts involved in a high amount of radiation have a solidification pattern that is much different than parts that may be on the end of a row or more exposed to the ambient conditions. Therefore, it may be beneficial to design casting setups such that all of the parts experience the same heat transfer (aka, radiation) effects. By having the same cooling pattern, any changes to the design or rigging of the part will apply evenly to each part. Otherwise, the casting engineer may be chasing a defect that occurs in one part position that does not occur in another.

The case study shown in Figures 4a and 4b shows an in-line gating design. The initial setup shows nine castings stacked next to each other with a common top fed runner design. A coupled fluid and solidification analysis was run to understand the problems associated with molten metal flow and porosity. A quick review of the computer analysis run in ProCAST gave a very good indication on the flow pattern of the mold. The molten metal seems to fill most of the central casting as the sprue is located right above it, then the other castings fill from the center outwards. As the central casting is already filled before the other castings, the temperature in the center casting is initially lower than the others. As the filling progresses to fill the entire mold cavity, the shell starts to become heated, thus reflecting heat to the outside. The central casting remains much hotter than the "outer" casting region due to the self-radiation effects as explained in the earlier section. A quick look at the solidification plots shows similar results. The outside castings solidify quicker than the inside ones even though the filling sequence was reverse, where the hot metal filled the outside casting the last. Figure 4b shows the porosity plot for the in-line gating design. The varying degree and size of porosity validates the fact that even though each part is exactly the same, the location on the tree greatly influences the solidification rate and porosity.

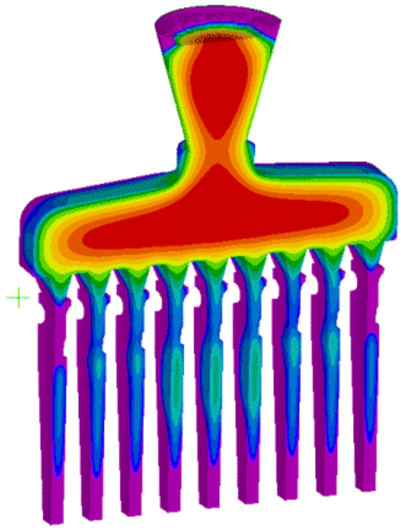

Figure 4a: Temperature Plot

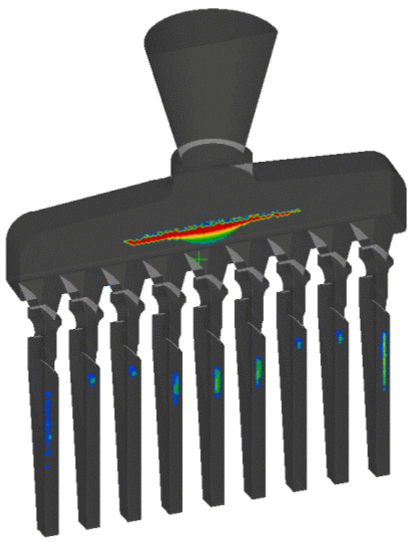

Figure 4b: Porosity Plot

In order to minimize the erratic flow and solidification pattern, a circular gating design is introduced. A ring gate on the top fed the castings from a central sprue. Due to the symmetric nature of the gating design, the flow pattern for the entire casting is very similar. Also, the fill rate for each part on the tree is same, so the effects seen in the in-line design where the central casting filled much earlier than the others is not observed. Also, due to the circular ring gate design, the radiation view factor that each part "sees" is the same for each part, leading to a similar behavior in radiative and reflective heat from each other. An additional benefit of using a ring gate was that this design accommodated 12 casting on the tree instead of 9 in the in-line design. Figure 4a and 4b show the temperature and solidification plots of the ring gate design at a critical time in the cooling process. Though the filling pattern showed improvement with the ring gates design, the solidification pattern was similar to the one observed in the in-line design. The porosity magnitude was reduced by about 30% compared to the worst porosity observed in some of the in-line design castings.

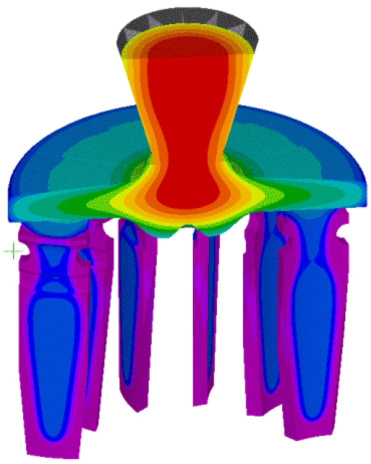

Figure 5a: Temperature Plot

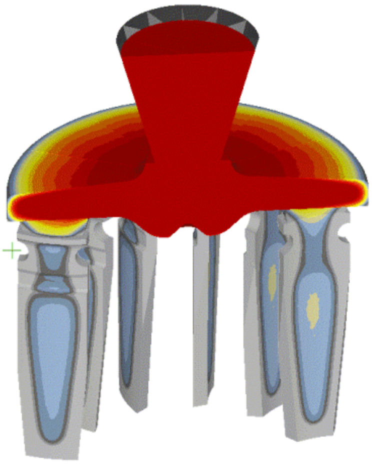

Figure 5b: Solidification Plot

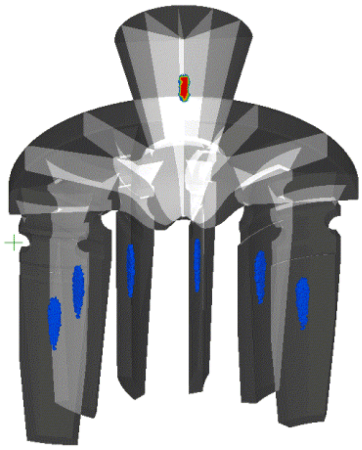

Figure 5c: Porosity Plot

CONTROLLING RADIATION HEAT TRANSFER

The casting engineer has a few variables with which to adjust and optimize when considering the rigging design. The preceding paragraphs focused on the configuration of the tree – how to place the various parts in reference to each other. The other parameters involved in radiation are also controllable by the engineer: the emissivity off of the shell faces, the temperature surrounding the shell (ambient or controlled enclosure temperature) and the emissivity of the casting environment (open-air cooling versus cooling in some "chamber"). To an extreme case, radiation can be removed completely by the depth at which the shell is buried in a sand bed. Figure 6 displays the cooling pattern on the shell for the in-line casting design when local insulation is applied on the shell. By putting a ½" or 1" thick Kaowool insulation on the critical regions that require insulation to enhance the feeding of the casting, the temperature in any area of the shell can be effectively controlled by controlling the radiation heat transfer loss through that region.

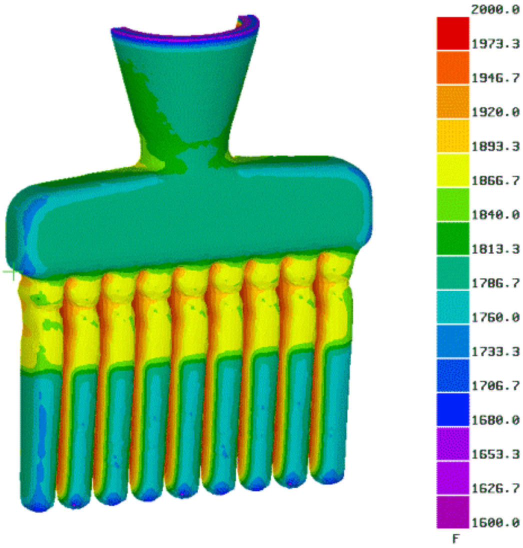

Figure 6: Temperature Plot with Local Insulation

To aid a more balanced and even cooling of the exterior faces of the shell compared to the interior shell locations, adding a can or other enclosing structure can provide this effect. Technologically advanced chambers, such as those used in single crystal casting, are even engineered to force certain solidification behaviors and resultant microstructures by controlling the amount of radiation to and from the casting. With a can, the temperature is not controlled; however, the can itself holds in heat by reflecting some of the heat back onto the part. With a casting chamber, the enclosure emissivity is controlled with specific chamber wall materials and the temperature can be controlled with heaters or cooling systems placed on or in the chamber.

CONCLUSION

Fully envisioning affects of radiation in investment casting is a requirement for determining the quality of the castings to be produced with a given setup. ProCAST properly calculates shadowing and shape factor effects of radiation and clearly presents the resulting temperatures, porosity and other information related to these radiation effects. As presented by the examples, the setup of the tree, quickness of pour and "environmental" conditions (kaowool, chamber, etc.) have significant effects on the cooling and solidification pattern of the casting. Being able to visualize these effects enables the process engineer to properly define the entire casting process before the first pour – from the orientation of the setup to pouring temperatures, pouring rates and exterior thermal controls – thus ensuring that the casting is right the first time.

REFERENCES

Incropera, Frank P., DeWitt, David P., *Fundamentals of Heat and Mass Transfer*, 3rd ed., pp 696-795, John Wiley & Sons, New York (1990).
eFunda, "Heat Transfer: View Factors," http://www.efunda.com/formulae/heat_transfer/radiation/view_factors.cfm, 2006
ProCAST Users Manual, v2006.0.