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Convective Current Manipulation in Steel Castings

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ABSTRACT

In this study, convection and its effects on shrinkage indications and macrosegregation in large steel castings will be investigated. Two defects that are seen in steel foundries are shrinkage and macrosegregation of the elements. Depending on the alloy, the effects of macrosegregation may be critical to their tensile strength and composition requirements. Both macrosegregation and shrinkage indications can be affected by convective currents in large steel castings. These currents can be accurately simulated to both correlate to actual results and correctly adjust the project or process to alter the effects of convection. A large steel casting will be reviewed and simulated using advanced casting process simulation software. This process will allow for physical casting properties to be cross analyzed with simulation results.

Keywords: convection current, steel, castings, shrinkage, macrosegregation, simulation

INTRODUCTION

Natural convection caused by density gradients in the liquid metal during solidification has a direct influence on macrosegregation.[1] The density gradients evolve due to the combination of temperature gradients and variation in solute content as solidification progresses.[2]

The distribution of solute throughout the melt volume changes due to dendritic solidification and differences in solubility of elements between the liquid and solid state. Part of the alloying elements that cannot be incorporated into the solid phase are pushed into the liquid at the solidification front and moved from there with the resulting convective flows.[2,3]

The variation in solute content at the solidification front leads to a density difference between the liquid at the front (between dendrite tips) that works in conjunction with the density difference due to the temperature gradient.[4]

These two driving forces for natural convective flow work together, the temperature gradient's influence on density will provide a downward force at the solidification front due to this liquid being colder (denser) than the bulk liquid, but the density variation due to the solutes can be in either direction depending on the specific solutes and amounts.[5] In many steels carbon is typically the most deciding element, which will reduce the density and therefore work in the opposite direction of the temperature gradient.[6]

As solidification progresses, solute rich pools solidify in their location which produces macrosegregation. The solute pools also alter the local solidus and liquidus temperatures of the alloy which could affect the metal feeding patterns throughout solidification.[2,4]

The resulting convective currents and resulting distributions of macrosegregation of alloying elements can be accurately simulated to both correlate to real world results and correctly adjust the project or process to alter the effects of convection. A large steel casting will be reviewed and simulated using MAGMASOFT,® a casting process simulation software. This process will allow for physical casting properties to be cross analyzed with simulation results.

To control the level of convection and macrosegregation indications, the most common solutions have been to add/move/modify risers and contacts or add/modify/move chills to casting bodies to shorten or prolong a section's solidification time.[7,8] Other methods of using sands with different thermal properties (heat capacity / conductivity) to cool sections faster or slower have also been implemented like the use of zircon or chromite (i.e., As referenced in works by Campbell.[1] These methods cause a change in thermal gradients which changes the solidification rate and the convective patterns.[2,3,9]

DESIGN OF EXPERIMENTS

MATERIALS AND METHODS

A drive sprocket is being simulated for this study. This drive sprocket has an outer diameter of 40," a height of 15.7," and a thickness of 8" (Figure 1). Two rigging systems will be simulated, one rigging system which has four risers with a modulus of 3.28" (Figure 2) and another rigging system with a bullet core in the center of the drive sprocket with a singular riser with a modulus of 13.2" (Figure 3). A step gating system with a gating ratio of 1:1:1 was used with four ingate locations on the bottom of the part. An initial pouring temperature of 2912F (1600C) was used for the initial iteration, (Figure 4). The alloy composition of the Hadfield steel is given in Table 1. The liquidus temperature of this alloy is 2527F (1386C) as shown in Table 2. The mold material is ceramic sand, Table 3.

Rigging system changes will be implemented in this study to see how they affect the final carbon segregation indications in the casting. All following iterations of each riser setup will have hot topping and chills added to the cope and drag. The second iteration of each riser setup will have a chromite inner core. The final iterations of each riser setup will have a 2 inch thick chromite mold facing (See Table 4, located in the Appendix at the end of this paper).

Table 1. Composition of Hadfield Steel Alloy (wt. %)

C	Mn	P	S	Si	Fe
1.2	13	0.1	0.03	0.5	Balance

Table 2. Physical Property Parameters of Hadfield Steel Alloy

Liquidus Temperature	2527 ºF(1386ºC)
Solidus Temperature	2205 ºF(1207ºC)

Table 3. Thermal Sand Properties

Sand Material	Thermal Conductivity	Heat capacity
Ceramic at: 1472 ºF(800ºC)	0.231 BTU/h*ft*F	310.49 BTU/lb*
Chromite at: 1472 ºF(800ºC)	0.549 BTU/h*ft*F	604.28 BTU/lb*

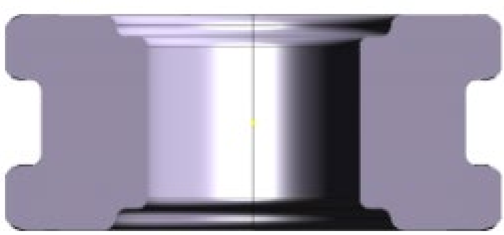

Figure 1. Cut image of drive sprocket.

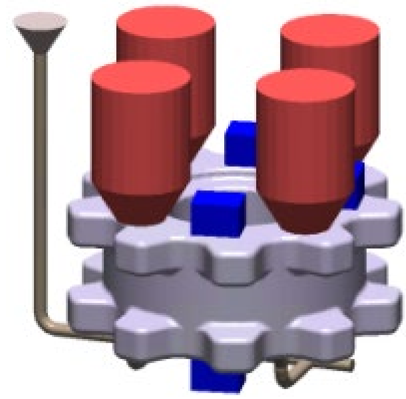

Figure 2. Drive sprocket with four risers.

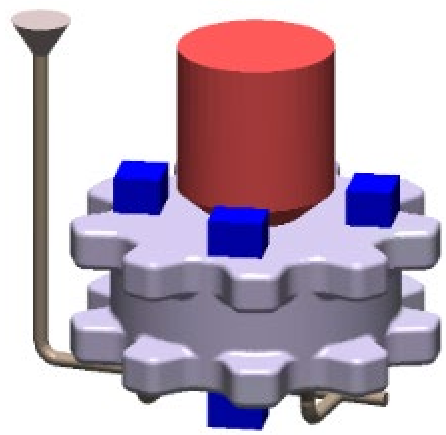

Figure 3. Drive sprocket with bullet core.

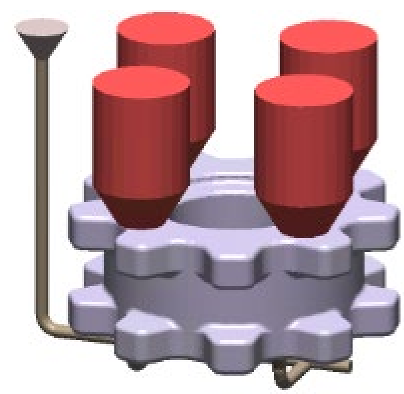

Figure 4. Isometric image of baseline drive sprocket.

MACROSEGREGATION – MATERIAL PROPERTIES

There are temperature dependent values considered in the current computational solver used in this study in addition to the regular thermophysical properties. The additional temperature dependent values used to calculate convection and segregation are the permeability of the steel alloy over the solidification interval, the solid diffusivity of each element, the partition coefficient of each element, and the expansion coefficient of each element.

RESULTS AND DISCUSSION

Iteration 1 is the baseline for the duration of this study. The first iteration has a fill time of 3 minutes and 21 seconds. Temperature distribution at the end of filling is added in Figure 5 There is a temperature gradient reaching 200°F (111°C) between the hottest and coldest locations in the casting (Figure 5). It is important to note that this iteration does not use chills on the cope and drag of the casting or hot topping on the top of the risers which produces significant macroporosity at the end of solidification and should not be considered an adequate rigging system in real practice, but was adopted here to illustrate effects.

Iteration 1 has carbon segregation values increasing in weight percentage from 1.02 wt. % at the bottom of the part to 1.35 wt. %. at the highest location of the part (Figure 6). The teeth of the drive sprocket solidify first. The remaining casting body solidifies from the bottom section, where the ingates are connected, to the top section where the risers are located. The velocity pattern of the melt due to convection displays a circular convective pattern throughout solidification (Figure 5).

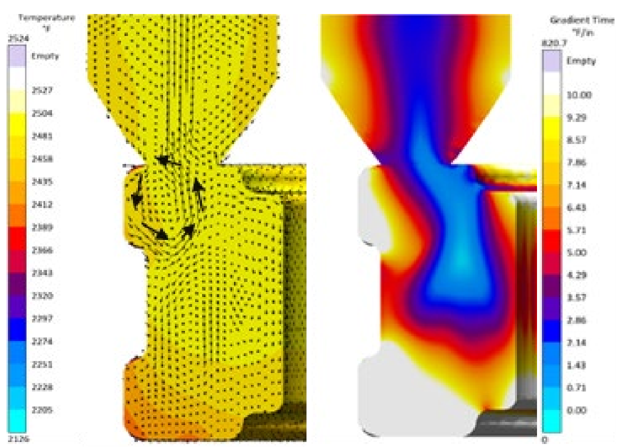

Figure 5. Iteration 1 temperature and thermal gradient plot with melt flow vectors.

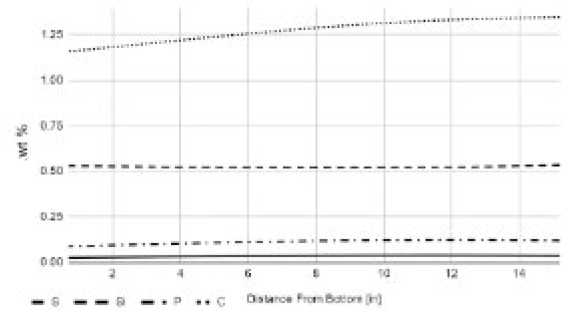

Figure 6. Iteration 1 Macrosegregation Ratio along the thickest section of drive sprocket.

The temperature plot at the start of solidification (Figure 5) of the baseline shows a minimum temperature of 2725F (1496C) and a maximum temperature of 2912F (1600C). The temperature profile of the casting has a low thermal gradient meaning that the minimum and maximum temperature values are near each other at the beginning of solidification. In Iteration 1 (Figure 5), a vortex pattern is observed at the contact point between the riser and the casting. This pattern is consistently present across all rigging systems featuring four risers. The formation of this vortex pattern is attributed to the temperature gradient during solidification. Specifically, the higher temperature melt rises into the feeder while the lower temperature melt sinks into the casting, leading to low thermal gradient values at the contact location. This phenomenon extends the local solidification time and contributes to an increased carbon segregation near a riser. The convective flows seen during solidification are also affected by the section size of the casting and riser. As section size increases, the open area where convective flows can move and form patterns increases. This is why these circular currents are not seen in the bullet core simulations.

Carbon segregation is a function of both the solidification pattern and the direction in which these convective pools are moving. The direction these convective pools move can aid in pushing carbon segregation in different locations on the part. As more chilling factors were introduced to the rigging system the total melt velocity during solidification reduced to values below 0.002in/s in the iterations with mold facing (Figure 7). This further prevents the movement of the melt throughout solidification and traps carbon segregation values in place faster than in iterations with longer solidification times and larger low gradient volumes. There are higher velocities at the riser contact allowing for more melt movement and low velocities in areas that have more chilling features as seen in Figure 8.

As seen in every iteration, risers extend the local solidification time and increase the volume of low thermal gradient indications in a casting (Figure 9). This is seen to raise the carbon segregation values leading to the riser (Figure 10). In each iteration that did not have significant chilling factors added, the low gradient volumes in the casting body remained connected to the risers throughout solidification.

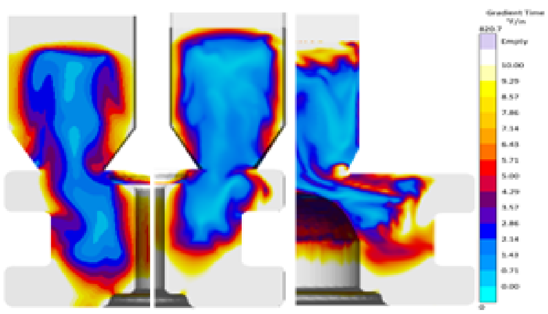

Figure 7. Velocity patterns of iterations 2, 3 and 4 at 1 hour and 30 minutes into solidification.

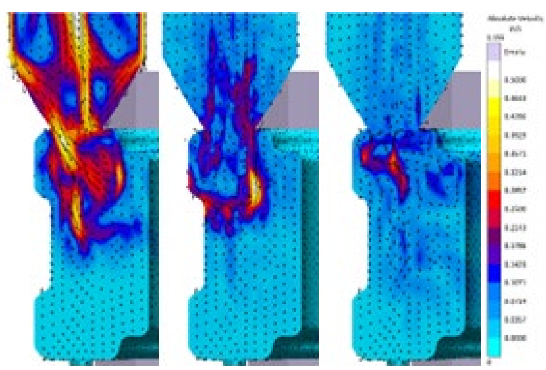

Figure 8. Velocity patterns of iteration 2 at riser location and chill location. (3hours and 24 minutes into solidification.)

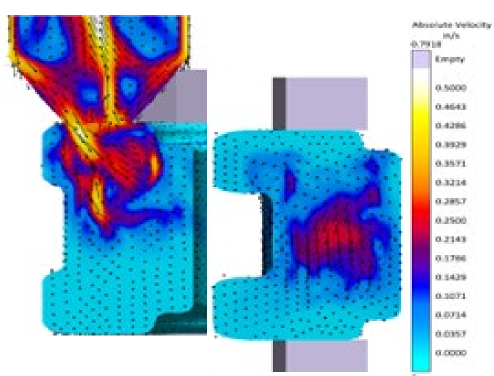

Figure 9. Iterations 1, 2 and 5 thermal gradient at riser contact. Gradient time is a result that displays the progressive thermal gradient from 100% liquid to 0% liquid. The units are degree change per distance and this result describes the thermal gradient in the melt during solidification.

In each of the iterations with four risers, the lowest thermal gradient values focused on the riser contacts and the thickest section of the casting, with gradient values consistently below 3°F/in. (0.657°C/cm.), see Figure 11. These sections experienced minimal temperature change over time and remained in the liquid phase longer than other areas. As the thermal gradient was systematically altered and reduced across different iterations, both in the four-riser and single-riser systems, the liquid body solidified more rapidly. This accelerated solidification time and pushed the available path for thermo-solutal segregation away from the contact surface.

Chills and mold material with higher thermal conductivity reduce the local solidification time and push low thermal gradient volumes away from the chilled surface. This can be seen in the reduction in solidification time in the teeth of the drive sprocket when moving from iteration 5 to 7 due to the changing mold material (Figure 12). In later iterations with substantial chilling factors added (Iteration 4, 6 and 7), the low thermal gradient volumes were cut from the risers 30% into solidification. This reduced the melt's ability to flow and move carbon through the casting (Figure 11) and prevented the melt with higher carbon wt.% to move closer to an area with low thermal gradient indications which would generally be connected to a riser. This generated castings that had higher carbon wt.% values deeper in the casting body when compared to earlier iterations.

When using a chill, the solidification time around a chill is approximately 45 minutes. The chill also reduces the average velocity to approximately 0.002in/s. Due to a very low velocity throughout the majority of solidification and a fast solidification time at the chilled surface, the carbon segregation indications near chilled surfaces tend to be closer to the average weight precent of the alloy (Figure 13).

Iteration 3 appears to have the most preferable carbon segregation plot. A large area of this casting has carbon wt.% close to the target percentage of this alloy at 1.2wt.%. This casting is a four riser setup which splits up the total low gradient indications in the part but does not "over chill" the part which may be seen in iterations that have substantial chilling factors. The iterations with substantial chilling factors split the low thermal gradient body which seems to generate worse macrosegregation indications in the part. In a single riser setup, the low thermal gradient volumes in the casting are all connected to the central riser. In a four riser setup the low thermal gradient indications are split up per riser (Figure 14). This reduces the total area that low thermal gradient covers.

Reducing the area of low thermal gradient may be a main contributor to reducing macrosegregation of carbon.

This design also has an inner hollow core made of chromite which decreases the local solidification time at the contact location. This further reduces low thermal gradient values and causes the locations near the core to solidify earlier than with no core. This also restricts the melt's ability to flow due to convective patterns which aids in freezing carbon in place. Lastly, the block chills on both the cope and drag aid in reducing the local solidification time further without cutting off feeding from the riser. The combination of these variables produces a casting that has a lower standard deviation of carbon wt. % values throughout the casting body.

CONCLUSION

A Hadfield steel alloy drive sprocket was created to simulate filing and solidification patterns of the casting. Convection and the segregation of elements was considered in the computational solver to reveal how convective heat transfer effects macrosegregation in large steel castings. The main conclusions of this research are summarized:

Low gradient volumes contribute the most to areas that may have higher carbon wt.% values. The areas that these low thermal gradient indications are in tends to increase the carbon segregation indications near these volumes. Reducing the total volume of low thermal gradient bodies or moving these volumes in different locations in a casting causes the casting to have a more normalized carbon wt. % with a smaller standard deviation. Severing the low thermal gradient indications in the casting from the riser causes more severe and concentrated area of high carbon wt. %. Ensuring that the low thermal gradient volumes from the riser to their respective feeding area is connected throughout solidification reduces the severity of macrosegregation.

Risers extend solidification and feed melt into the casting which commonly forms vortex convective flows as a function of section size. This allows for a longer local solidification time and low gradient values near the riser contact which produces higher carbon segregation values.

Chills promote solidification and freeze off liquid melt thus pushing solidification tangential from the surface of the chill. This significantly reduces the melt velocity near the chill which tends to prevent carbon segregation values from reaching their extremes near the contact location. This also pushes low thermal gradient indications away from the chilled surface.

Mold material with a higher thermal conductivity and heat capacity also promotes solidification and pushes low thermal gradient further from the contact surface similar to a chill. This pushes higher carbon segregation values from the surface of the casting and remain in the areas that have the highest solidification time and low thermal gradient.

In rigging large castings prone to macrosegregation of elements, targeting specific areas of a casting that need to meet mechanical properties may be more useful in rigging a casting. In this case a rigging system can be made to normalize carbon segregation in a specific area rather than targeting the entire casting.

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APPENDIX

Table 4. Rigging System Changes Per Iteration

Iteration	Riser Configuration	Hot Topping	Chills	Core	Mold Facing
1	4 Risers	No	No	Ceramic	N/A
2	4 Risers	Yes	4 cope/ 4 drag	Ceramic	N/A
3	4 Risers	Yes	4 cope/ 4 drag	Chromite	N/A
4	4 Risers	Yes	4 cope/ 4 drag	Ceramic	Chromite
5	1 Riser	Yes	4 cope/ 4 drag	Ceramic	N/A
6	1 Riser	Yes	4 cope/ 4 drag	Chromite	N/A
7	1 Riser	Yes	4 cope/ 4 drag	Ceramic	Chromite

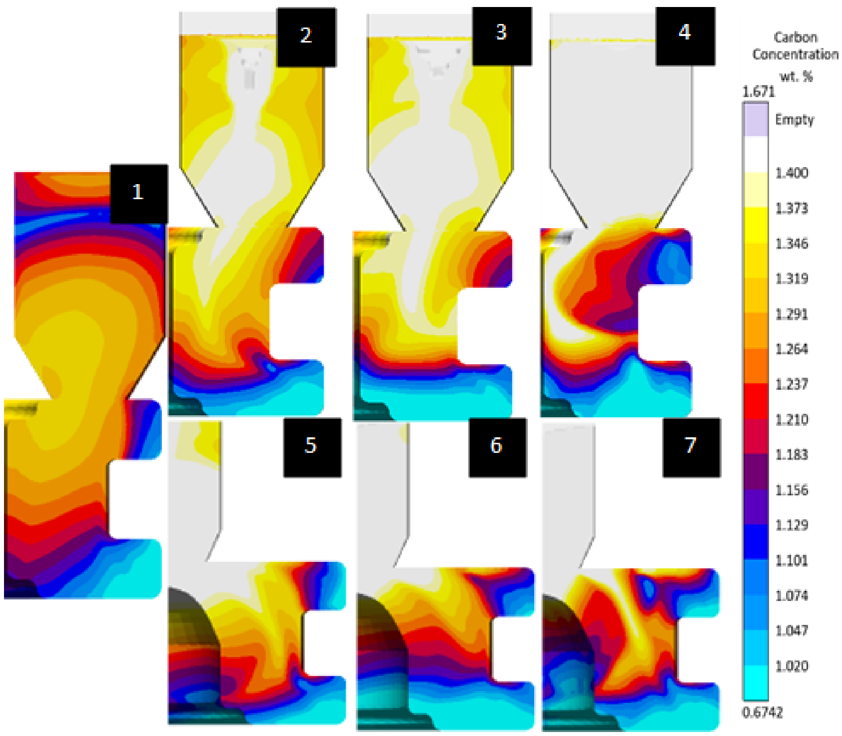

Figure 10. Carbon segregation of each iteration.

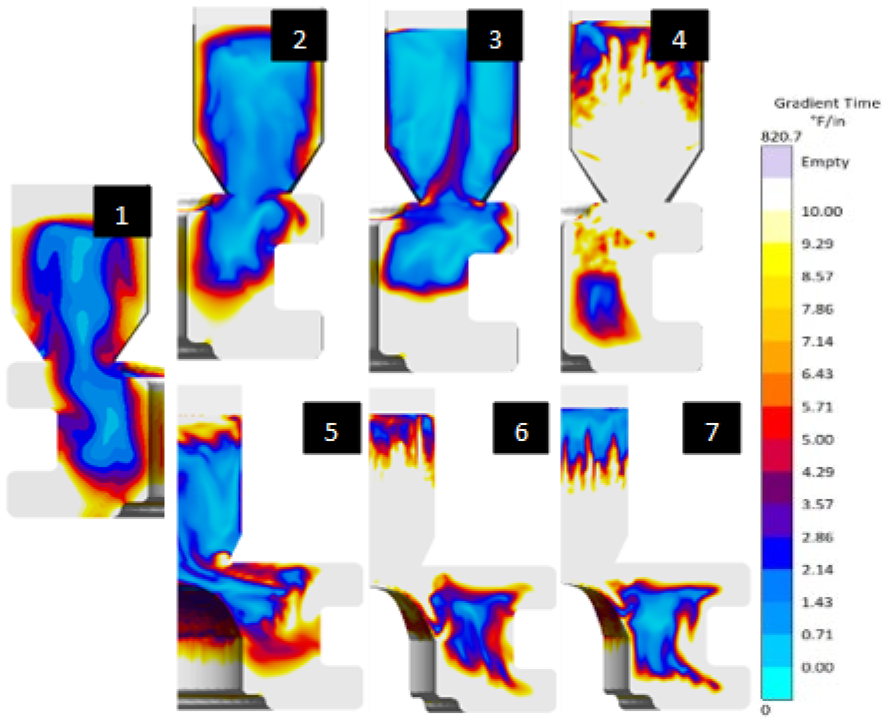

Figure 11. Thermal gradient of each iteration 2 hours and 5 minutes into solidification.

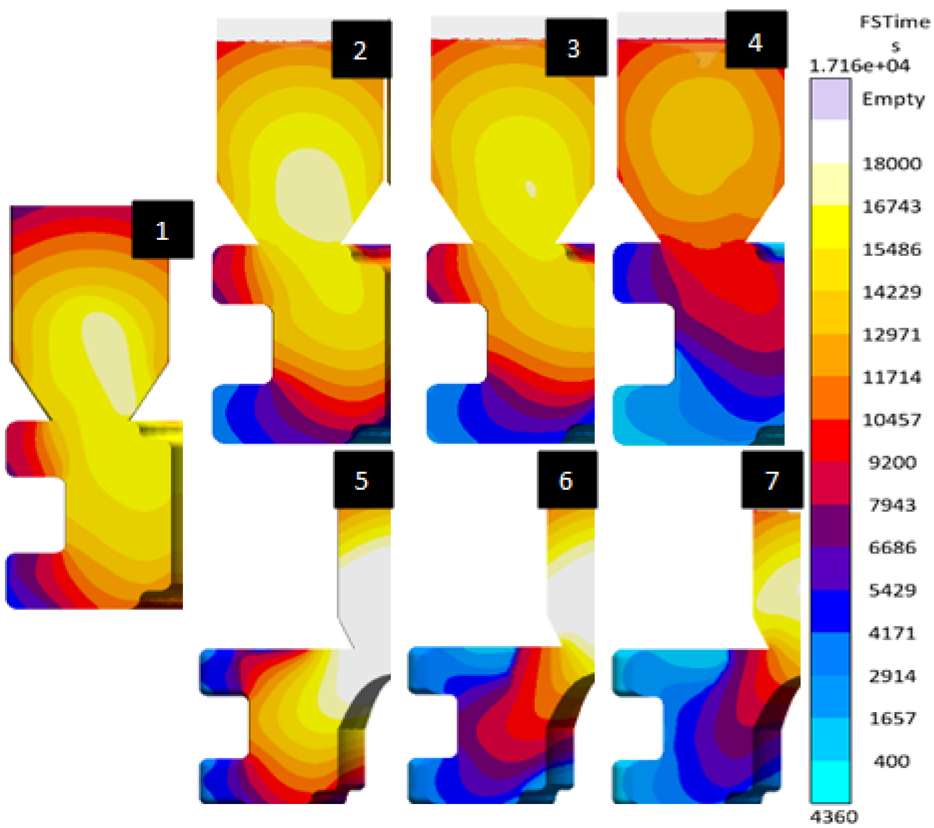

Figure 12. FSTime of each iteration at the end of solidification. FSTime is a result displaying the time it took to reach the critical fraction solid value. At the critical fraction solid point, melt can no longer feed other sections of melt or be fed by liquid melt above the critical fraction solid point.

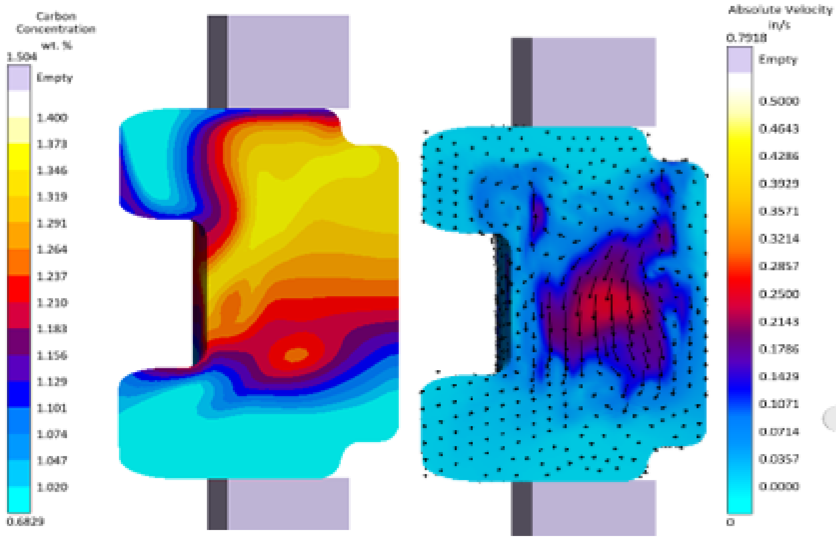

Figure 13. Carbon concentration and velocity 40 minutes into solidification for iteration 2.

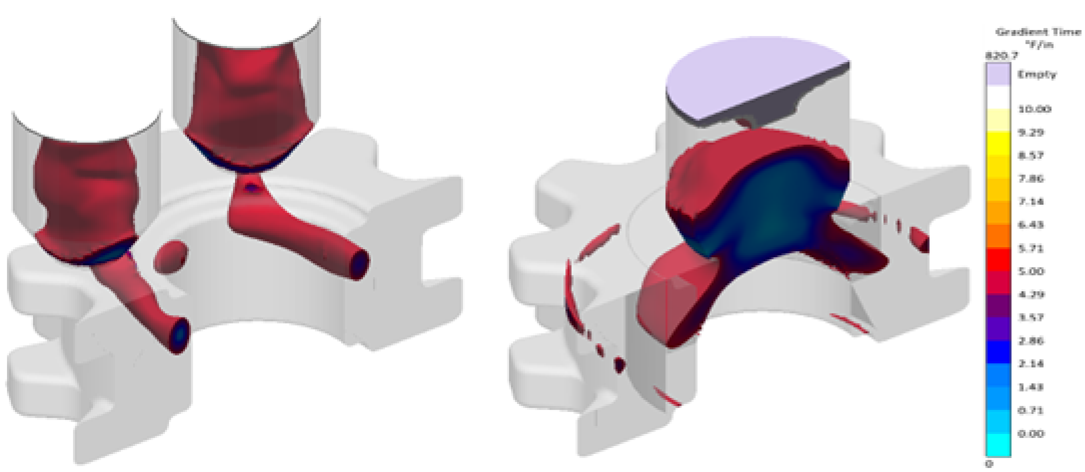

Figure 14. Thermal Gradient volumes with 5ºF/in and below X-ray applied to iterations 2 and 5.