Hot Tears and Shrinkage Prevention in Aluminum Permanent Mold Casting

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Hot Tears and Shrinkage Prevention in Aluminum Permanent Mold Casting

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CHAPTER 1

INTRODUCTION.

Hot tears and shrinkage are the most common casting defects in foundry practice. There are several factors influencing on defect formation such as chemical composition, pouring temperature, casting and mold design, mold and core materials, and others. The review of literature revealed the fact that this problem was intensively studied for the last thirty years. The chemical composition is the major factor causing the defect formation in castings and originates a specific solidification behavior, which defines the hot strength of solidified metal, volumetric casting contraction and respectively tensile or shear stresses in casting. Some parameters such as metallurgical factors and casting/mold design may aggravate the defect formation as well as their correct use helps to reduce hot tearing and shrinkage. Thus, inappropriate design might cause the feeding problems, obstruction to normal contraction of casting, or hot spots and respectively thermal gradient transforming into the internal stresses. The hindered contraction and different solidification rate in some parts of castings are especially dangerous in permanent mold casting.

The well-known solution for reduction of the hot tearing is to uniform the solidification rate. For this purpose, a few designs of permanent molds are employed: air-cooled molds with fins, channeled water-cooled molds, air-cooled molds heated by burners, and molds with chill inserts. It is widely accepted that chill inserts acting as heat sinks are the more precise and effective methods to control the solidification behavior.

In case of permanent mold designing, the calculation of number and placements of heat sinks based on trials are too expensive. The modern computer software allows to simulate the casting filling, solidification behavior of liquid metal, and internal stresses and distortions appearing in castings. The simulation of solidification behavior is able to reveal the critical areas with high propensity of defect formation in castings.

Statement of Problem

Based on the literature review, the problem of this research can be defined as the lack of data about chill insert influence on the solidification behavior of permanent mold castings by the computer simulation.

Due to insufficient information concerning the methods of chill inserts designing in permanent mold casting using the computer simulation, it was decided to investigate the chill insert capability of prevention of hot tears and shrinkage formation by accelerating the cooling rate in critical parts of castings.

Because the hot tearing and shrinkage are the common problem in foundry practice, the development of methods, which enable to avoid the defect formation on the design stage of cast production, will significantly reduce the production and service costs.

CHAPTER 2

REVIEW OF LITERATURE

A problem of hot tearing and also attendant problem of shrinkage formation in casting production was intensively studied during few last decades. The hot tearing should be separated from hot cracking phenomena. According to Purvis, Kannatey-Asibu, and Pehlke (1992), hot tearing occurs when liquid is still present in solidified metal, while hot cracking can occur in casting only in completely solidified metal. In 1996, Sigworth reviewed the available technical literature related to these problem in details. The mechanism of hot tear formation in solidified metal is described using a stress-strain approach and mechanisms of liquid metal embrittlement responsible for hot tearing. A simplified cause can be described as low hot strength of semi-solid metal under acting stress. However, stress is originated by a few factors, and properties of solidified metal are also different.

Causes of Hot Tearing

Chemical Composition

The chemical composition of alloys is one major factor defining a few physical properties related to hot tearing such as coefficient of linear contraction, heat transfer coefficient, character of solidification. It is widely accepted that hot tearing can occur only when the coherential dendrite network is created. This condition depends on the amount of alloying elements and an example of Al-Si equilibrium phase diagram with semi-solid coherency line is shown in Figure 1 (Sigworth, 1996).

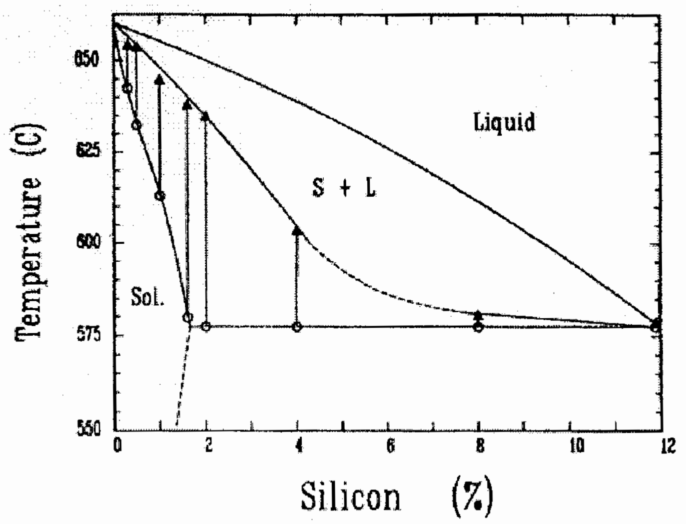


Figure 1. Portion of equilibrium Al-Si phase diagram (bars indicate the region of semi-solid coherency).

Ductility of semi-solid aluminum is defined by the character of solidified alloy (Kurdjumov, 1990). The presence of large portion of liquid up to solidus temperature makes the alloy more resistant to crack formation. If the rigid dendrite network appear around the liquidus temperature then, typically, the alloy has high susceptibility to hot tearing. Also, if strength of casting crust grows faster then resistance of alloy to hot tearing is increasing too.

Typically, a eutectic alloy is more preferable as casting material due to its highest castability, lowest coefficient of linear contraction and low pouring temperature. However, the eutectic composition can not be employed for all applications due to necessity of special properties originated by alloying. In some cases, the certain improvement can be obtained by finding of optimal chemical composition with additional alloying. Thus, Chamberlian, Watanabe, and Zabek (1977), have found the optimum Mg:Zn ratio in Al alloy for permanent mold casting, which allows to attain high resistance to hot tearing without sacrificing the needed strength and resistance to stress corrosion. But in common practice, another methods must be applied to prevent defect formation.

Stresses in Castings

Stresses in castings arise owing to non-uniform and non-simultaneous contraction of some areas. Depending on reasons causing this non-uniformity of contraction, stresses are subdivided on three types (Kurdjumov, 1990):

- thermal σ_t, caused by differences between temperature of different areas of casting;
- phase σ_{ph}, caused by non-uniformity of phase transformation in casting;
- contraction σ_c, caused by hindered contraction.

Thermal and phase stresses are residual. Contraction stress is temporal and disappears when casting is removed from mold and cores are removed from casting. Contraction stress is especially dangerous in permanent mold casting due to its strong rigidity in comparison with sand mold casting, where the strength of mold walls can be varied.

Improper Design

Mold and casting design is also important to achieve needed quality of casting. Improper design can aggravate the defect formation as well as the correct design may help to reduce and/or eliminate the hot tears and shrinkage in castings.

The feeding system might be not providing the normal feeding of solidified casting causing shrinkage and hot tearing (Analysis of Casting Defects, 1974). It can happen due to its faster solidification than casting section.

Abrupt variation in section thickness results the variation of cooling rate, thermal gradient, and finally stresses causing hot tear formation. Moreover, these variations often accompanied with obstruction in normal contraction.

The T-, I-, L-, and U- channel-shaped section are also exposed to hot tearing and shrinkage. These shapes originates significant stresses during hindered contraction of solidified metal and can be aggravated by hot spots located in variations of thickness as shown in Figure 2.

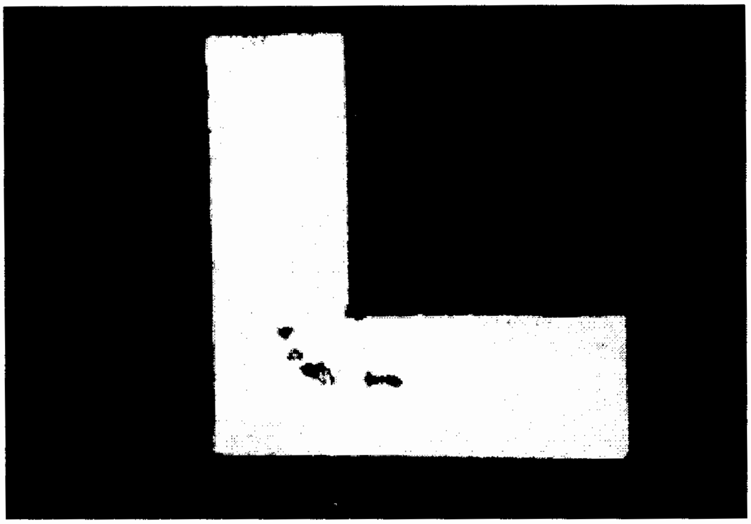


Figure 2. Cross-section of L-section, showing the position of shrinkage cavity and hot tear.

Means to Eliminate Defect Formation

The widely accepted way to eliminate defect formation in solidified casting is to equalize the solidification rate through the whole casting. There are several approaches providing the control of solidification.

Cooling Systems

The use of cooling jacket on the permanent mold is one method to accelerate cooling rate. A few design of cooling jackets are described by Lerner (2000). This method allows to establish a desired cooling rate, but it acts on the entire casting and does not eliminate the hot spots in casting. In case of channeled water-cooled jacket, the water passages can be contoured; however, the uniformity of solidification rate is too hard to achieve.

Channeled water-cooling permanent mold employs the drilling passages. Water (or in some cases oil) circulates through the passages withdrawing the excessive heat from near casting sections. This approach is flexible not enough. The drilling passages can not be made of complex configuration and as result, do not precisely control the solidification rate in the critical sections. Moreover, water passages require the periodic cleaning due to continuously furring during operation cycles.

The modification of this method is the prefabricated piping in permanent mold providing more structured cooling system. However, because the piping system goes through the mold material with one certain thermal conductivity, the cooling area around passage is still wide. The advantages of permanent mold with prefabricated piping system are the more complex configuration and less cost in comparison with drilling passages.

Chill Fins

Chill effect in casting can be achieved by using the fins made of as a part of casting (Creese, Sarfaraz, 1987). The fins act as a heat sink and allow to equalize solidification rate in appropriate manner. Chilling effect depends on fin dimension and its placement. The use of fins is more suitable for sand casting due to relatively simple fin installation by gluing thin plate on the pattern. Machining the hole for fin in permanent mold is more difficult. Figure 3 shows the effect of chill fin on elimination of defect formation in L-section of casting (in comparison with Figure 2).

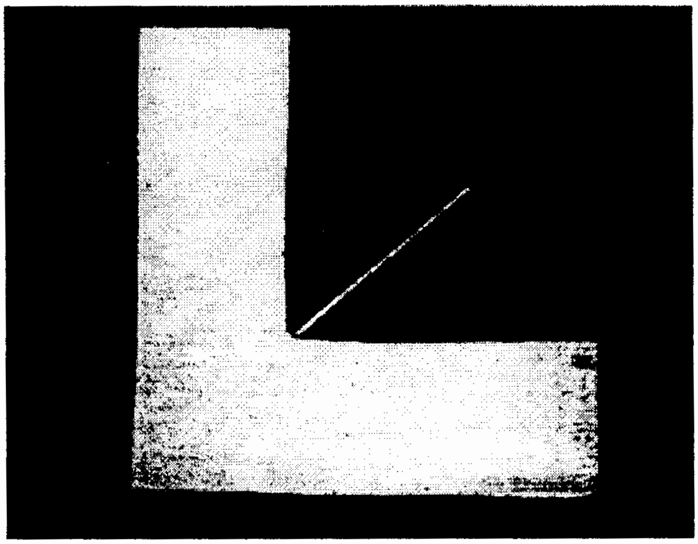


Figure 3. The effect of 7.62-cm x 0.25-cm casting fin, showing no shrinkage cavity.

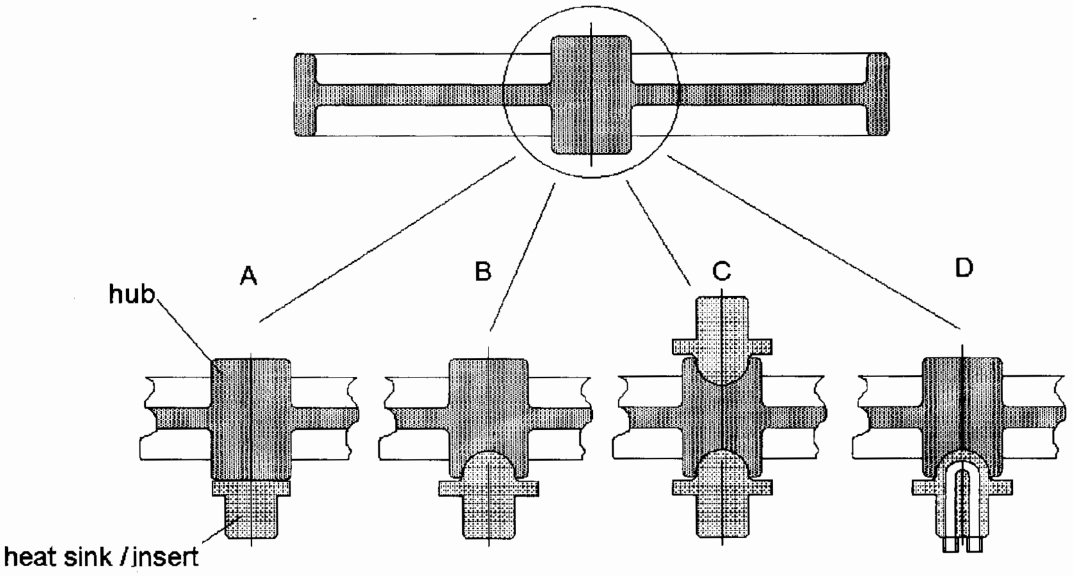
Anti-Chills

For some applications, so-called anti-chill can be used to slow down the solidification rate in thin wall sections of the permanent mold (ASM handbook 15, 1992). For this purpose, the gas burner is used. The disadvantages of this method are obvious: wide zone of influence, additional source of fuel, reducing of mold lifetime, dangerous in operation.

A more widely used method to slow down the solidification rate is the use of thermo-isolating cover on permanent mold such as a sand mix.

Chill Inserts

The chill inserts seem to be a most effective and precise method of controlling the solidification rate. The chill inserts are made of material with more thermal conductivity than mold material has. In this case, the chill insert acts as a heat sink withdrawing excessive heat from precisely defined parts of casting. For aluminum casting in permanent mold made of cast iron for example, the chill inserts can be made of copper or graphite. Typically, one side of chill insert is open to casting cavity, and other side is open to ambient. The cooling rate can be accelerated by using hollow water-cooled chill inserts. Figure 4 shows the typical design of thick hub wheel/pulley and four possible locations of chill inserts.



A--flat-end design of insert to draw heat out of one side of the hub; B--projected-end design of insert to draw heat out of one side of the hub; C--two projected-end inserts to draw heat from two sides of the hub; D--projected-end insert with water passages to draw heat from the hub.

Figure 4. Typical design of thick hub wheel/pulley and 4 possible locations chill inserts.

Disadvantage of this method is that chill inserts are exposed to thermal erosion and need to be changed from time to time.

Prediction of Defect Formation

The cost of mold design production can be significantly reduced by the use of computer simulation of the mold filling, solidification behavior, and casting distortions. During last decade, computer simulation was intensively studied. Thus, Dudley J. (et al., 1992) has shown typical applications of numerical modeling of castings for quality improvement. The simulation of filling allows to avoid unfilled cavities through the subsequent model redesign and consecutive simulation. The simulation of solidification behavior allows to analyze the temperature fields and predict the intensity and location of casting defects such as porosity and shrinkage. The prediction of such defects would be useful in preventing them without carrying out the costly trial-and-error process in real production.

Typically, the numerical computation of heat transfer during solidification is based on accurate techniques, such as the finite element method (FEM) or finite difference method (FDM), which are often used for the highly nonlinear processes (Purvis, Kannatey-Asibu, Pehlke, 1992). However, two major problems were found. One of them is a problem of accurate description of physical model. Second problem is a lack of the computation power.

The first problem involves the difficulties with obtaining the real physical parameters such as surfaces heat transfer coefficients between the model components and simplification of physical behavior (Chiesa, 1995). Thus, Chiesa studied the solidification behavior of cast Al wheels in permanent molds by use the commercial software AFSolid (version 3.31). It was assumed that thermal properties and surface heat transfer coefficients are temperature-independent, and only empirical "effective" coefficients were considered for modeling. Due to lack of computation power, only 2D model was developed but with applying a "depth factor" (so-called 2-1/2-D or quasi-3D model) and also the number of nodes in the mesh is limited by 7200 nodes per whole model or critical part. Due to symmetry, only half of model was simulated. In the absence of a fluid flow solution to the filling of the mold and the simulation of part of casting, the initial temperature distribution was suggested. In spite of mentioned limitations, this simulation allowed to analyze the temperature distribution during solidification, locate hot spots in the casting and define the areas with high propensity of porosity and shrinkage formation.

The same problem was investigated by M. Jolly (1999). Figure 5 shows the solidification time contour plot with thermal isolations and predicted macro- and micro-porosity in real low-pressure die-casting (LPDC). The spoke –rim porosity was reduced (but not eliminated) by placing cooling fins radially at each junction.

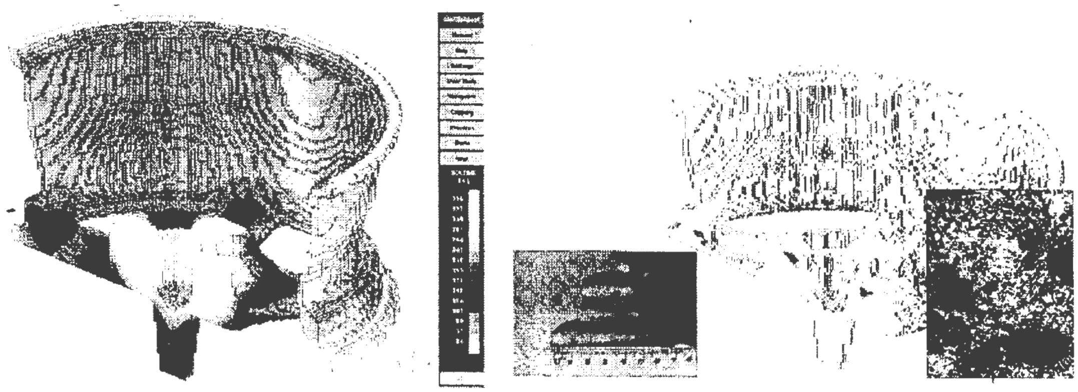


Figure 5. The solidification time contour plot with thermal isolations and predicted macro- and micro- porosity in real LPDC.

Currently, the dramatic growth of computation power simultaneously with development of simulation software provides the complex, more precise simulation in the way of transition from simple one- and two-dimensional models to three-dimensional models with better resolution, as well as in the way of improvement of physical model.

The conducted literature review revealed a lack of information about the simulation of chill insert influence on solidification behavior in permanent mold casting for prediction and elimination of hot tearing.

CHAPTER 3

METHODOLOGY

Design of the Test Object

The test object for current study is a wheel made of Al 206 alloy. The wheel comprises a massive central hub, eight cross-shaped spokes, and rim. Figure 6 illustrates the vertical gating system design of permanent mold with two attached wheels.

Figure 6. The vertical gating system design of permanent mold with two attached wheels.

The test-object in a shape of wheel was chosen because this configuration indirectly involves two widely accepted tests for hot tearing susceptibility and extremely prone to defect formation. An example of ring-test (similar to wheel rim) is described by Kurdjumov (1990), and a schematic of restrained bar casting (so-called “I-beam”, similar to spoke with junctions) is described by Sigworth (1996).

The casting model was drawn using software ProE2000 and exported in STL format. The rim and hub have a draft 2° and rounded, all spoke-rim and spoke-hub junctions are rounded too.

Simulation Parameters

The simulation software is AFSolid 2000 (version 5.20), which is based on the finite difference method and allows to simulate the filling and solidification behavior in real 3D model. The properties of casting alloy are shown in Table 1. The material list with simulation coefficients is shown in Table 2. Table 3 comprises the surface heat transfer coefficient.

Table 1

The Properties of Casting Alloy.

Alloy Name	Al 206.0
Thermal Conductivity, (BTU/HR-FT-F)	70.1
Specific Heat, (BTU/LBM-F)	0.2
Density, (LBM/CU FT)	174.5
Solidification Temperature, (F)	1058
Freezing Range, (F)	144
Latent Heat of Fusion, (BTU/LBM)	167.0
Initial Temperature, (F)	1350
Filling Time, (sec)	10

Table 2

The Material List.

	Type	Initial Temperature, (F)	Thermal Conductivity, (BTU/ HR-FT-F)	Specific Heat, (BTU/ LBM-F)	Density, (LBM/ CU FT)
Cast Iron	Normal Mold	500	26	0.11	489.6
Copper Chill	Cooling Channel*	140	223	0.092	559
Ambient	Normal Mold	90			

Note. *Cooling channel is chosen as "High Limit" and required additional parameters: Temperature is 140 F, Heat Transfer coefficient is 5000 BTU/HR-SQFT-F, and thermocouple location at X=9, Y=-1.5, Z=0.

Table 3

The Internal Heat Transfer Coefficients (BTU/HR-SQFT-F).

	Casting Material	Riser Material	Cast Iron	Copper Chill	Ambient
Casting Material	Al 206	400	800	5000	6
Riser Material			400	5000	8
Cast Iron				5000	6
Copper Chill					10
Ambient					

The Niyama point is 50%, and Critical Fracture point is 35%. The cooling curves are shown in Figure 7.

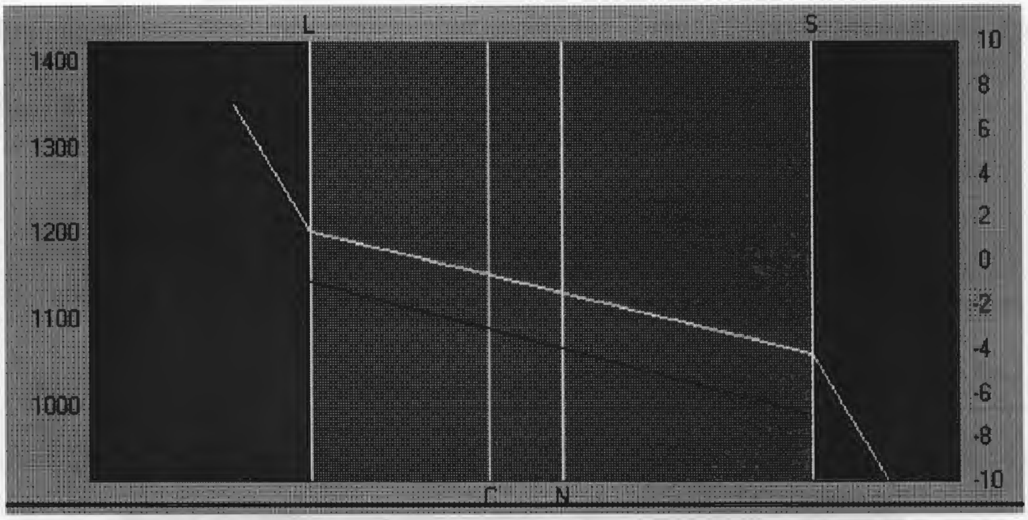


Figure 7. The cooling curves with Niyama and Critical Fraction Solid points.

Simulation and Data Gathering

Before the simulation started, the casting model was imported from ProE 2000 in STL format and adjusted to the real dimensions in AFSolid2000 software. To provide casting functionality, the conical risers on the top of each wheel, thin plate of filling material on the top of sprue to enable mold filling, and copper chill inserts symmetrically on the hub of second wheel were added. Because the casting model consist of two wheels located symmetrically from the sprue line, it is possible to install the set of chill inserts onto the one wheel to provide simultaneous simulation of both cases with and without chills with the same other conditions. This experiment consisted of two computer simulations with different sets of chill inserts. The simulation #1 employed the chill inserts with diameter 2" and length 1.5", and simulation #2 employed the chill inserts with diameter 2.8", length 2.5".

The permanent mold is made of cast iron in a shape of rectangular block with dimensions 31" x 5" x 18.5". The top of mold is open, and chill inserts are open by one side to ambient and by another side to casting cavity. Figure 8 shows the experimental casting/mold design.

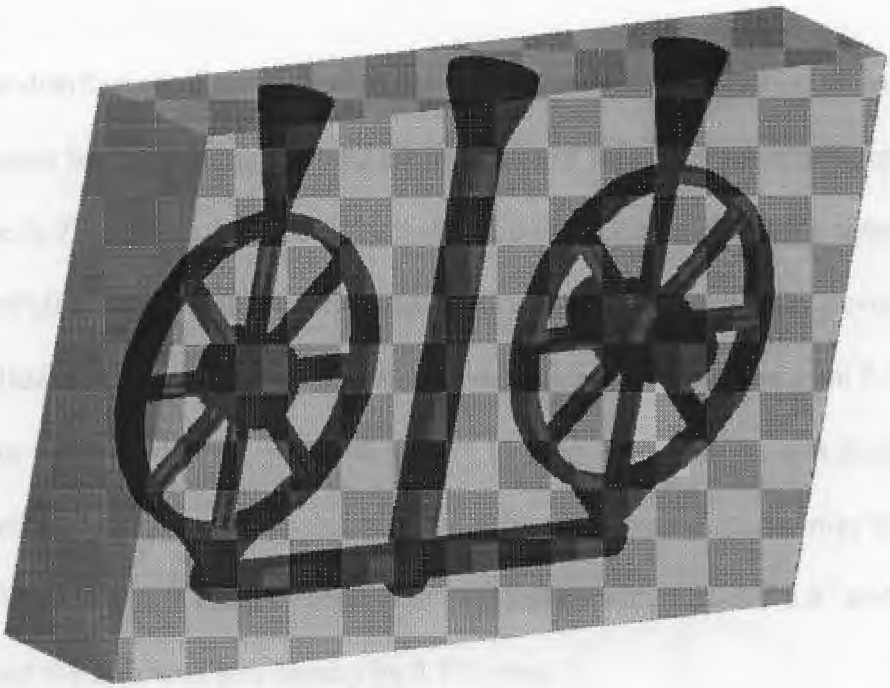


Figure 8. Schematic view of casting with risers, filling material, and chill inserts.

A mesh is generated with 1500000 nodes with the mold option "none" because the mold is a part of model. The simulation process is started as a permanent mold casting process. This process comprised 5 cycles to obtain the stable temperature distribution through the mold from cycle to cycle. Each cycle consisted of mold filling, solidification, and mold opening for 30 sec (needed for casting removal and preparation for the next cycle in real production).

After the simulation was done, the distributions of Temperature Gradient, Density of casting material, Solidification Time, Temperature of Whole Model, Niyama Criterion, Critical Fraction Criterion, and Hot Spots were obtained.

CHAPTER 4

REPORT OF FINDINGS

The distribution of parameters in the simulation #1 and simulation #2 have the same character but in the simulation #2 the influence of chill inserts is more expressed.

The X-Z cross-section of density distribution in Figure 9 shows the significant influence of chill insert. The area with less density and maximum density deviation in the hub influenced by chill is less. The density reduction was improved from 0.79 to 0.92, and the area with less density was reduced by 2.12 times. Because the less density of casting is directly related to the porosity or shrinkage, the casting quality may be improved by use of chill inserts. The use of chill inserts with diameter 2.8" and length 2.5" reduced the area with less density by 2.37 times.

Figure 9. The X-Z cross-section of casting density distribution.

The full solidification time of hub cooled by chill inserts in comparison with the hub without chill inserts was also reduced from 44 to 35 sec for the first set of inserts (diameter 2", length 1.5") and to 24 sec for the second set of inserts (diameter 2.8", length 2.5"). The solidification time of riser on the side with the chill inserts was reduced too due to its feeding trough the hub cooled by chill inserts. Figure 10 illustrates this reduction for the first set of chill inserts. The same effect was observed for the Hot Spot distribution and Critical Fraction Solid time distribution. The larger chill inserts have more effect on the solidification time as well as on other parameters.

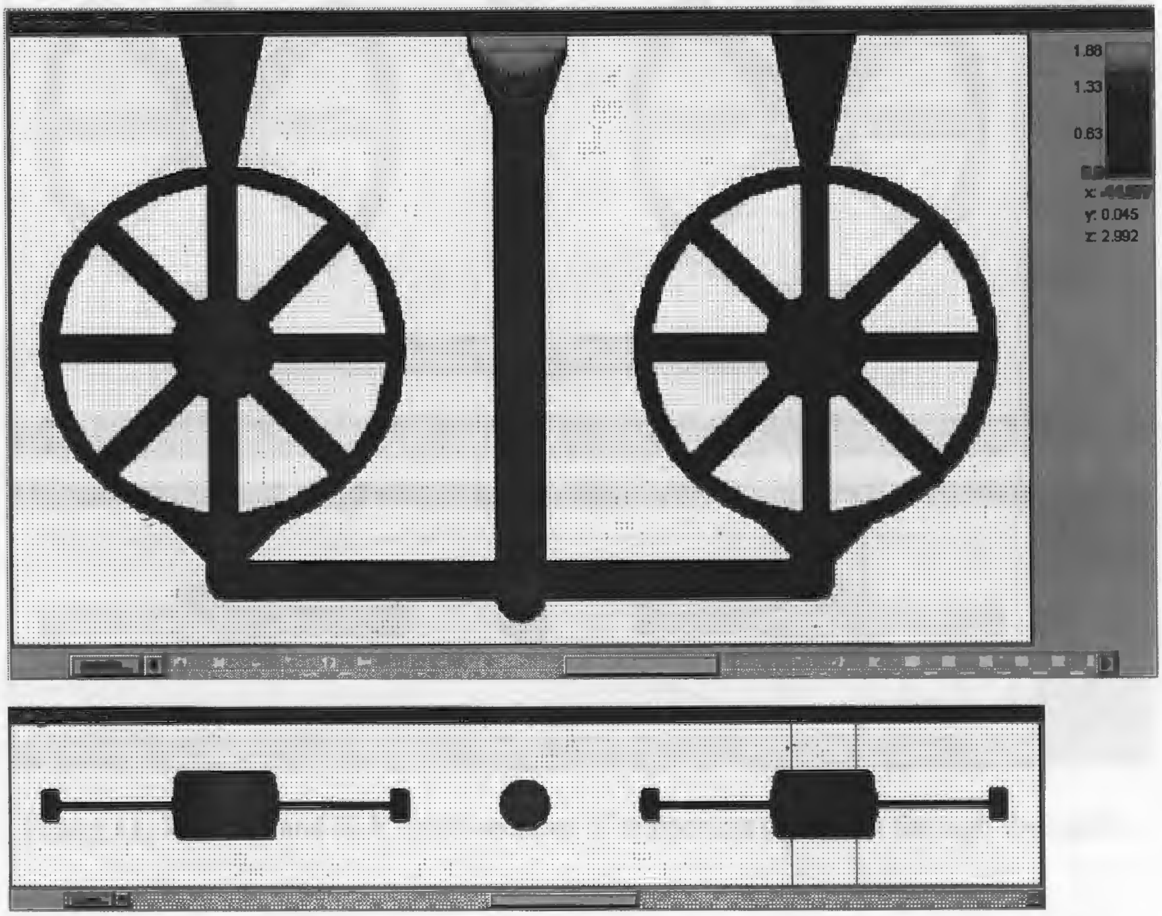


Figure 10. The X-Z and X-Y cross-sections of the solidification time through the casting.

The distribution of temperature gradient and Niyama criterion are important characteristics. Because the abrupt changes of temperature in castings originate the thermal stresses acting on solidifying metal, the reduction of temperature gradients in castings should reduce the hot tear formation. The distributions of temperature gradient for the use of second set of chill inserts is shown in Figure 11.

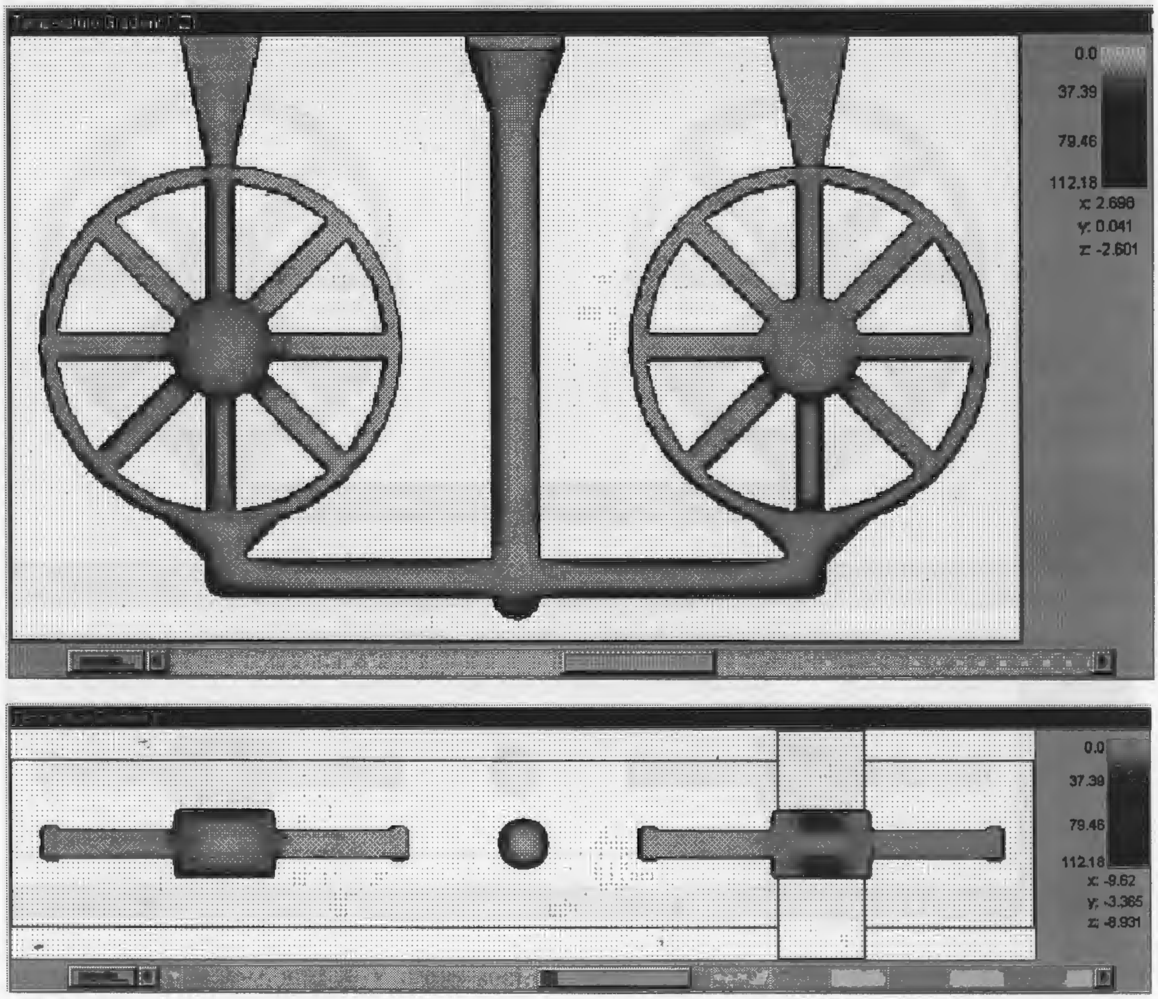


Figure 11. The X-Z and X-Y cross-sections of temperature gradient through the casting.

The Niyama criterion is basically a prediction of directional solidification and equal the temperature gradient divided by the square root of the Cooling Rate. The larger value of

Niyama criterion means the better directional solidification occurring in areas with strong temperature gradients. Thus, the reduction of Niyama value is also positive to prevent hot tearing. The distribution of Niyama criterion for the use of second set of chill inserts is shown in Figure 12.

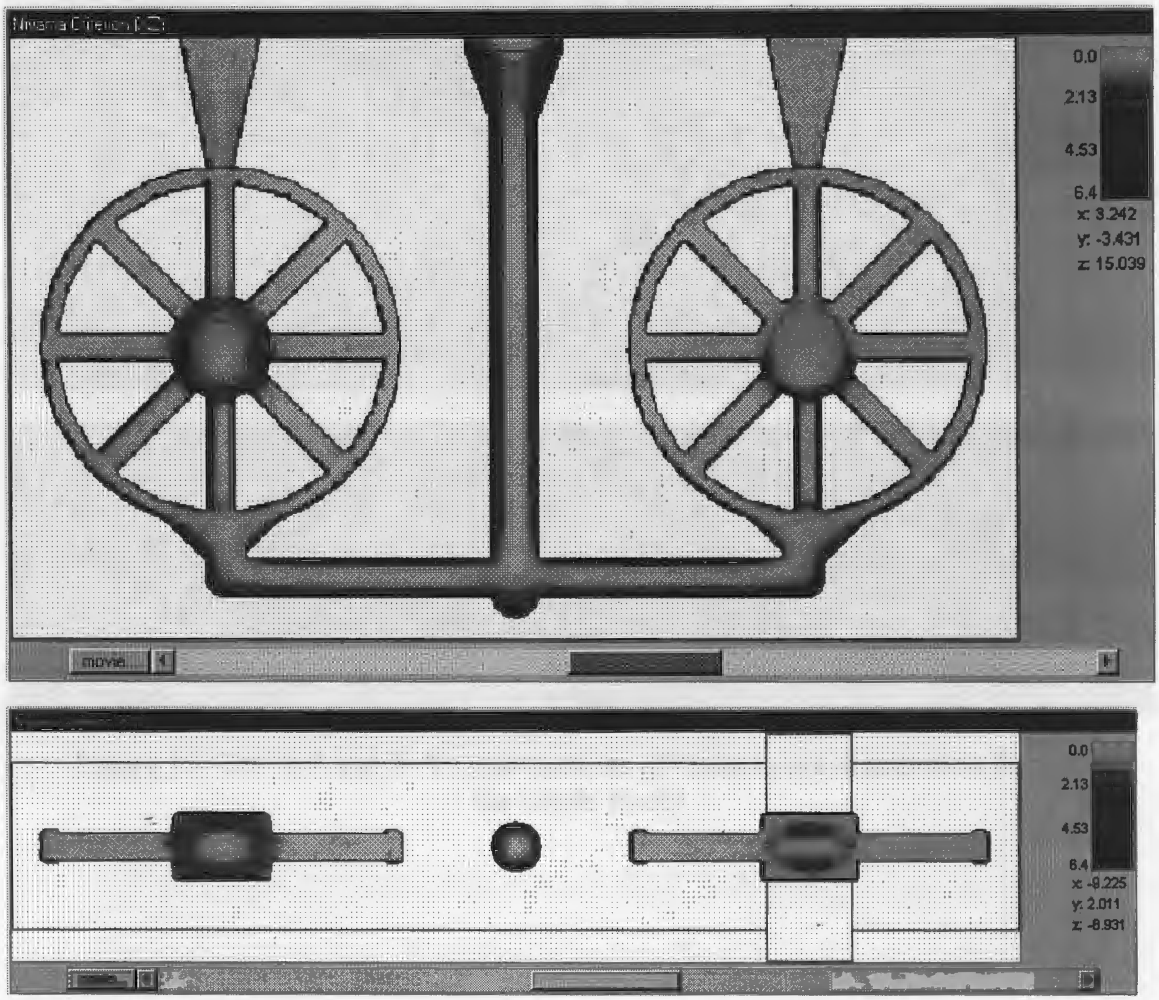


Figure 12. The X-Z and X-Y cross-sections of the Niyama criterion through the casting.

All data were recorded after the simulation cycle was repeated five times. The total temperature distribution through the whole model is shown in Figure 13 for the second set of chill inserts.

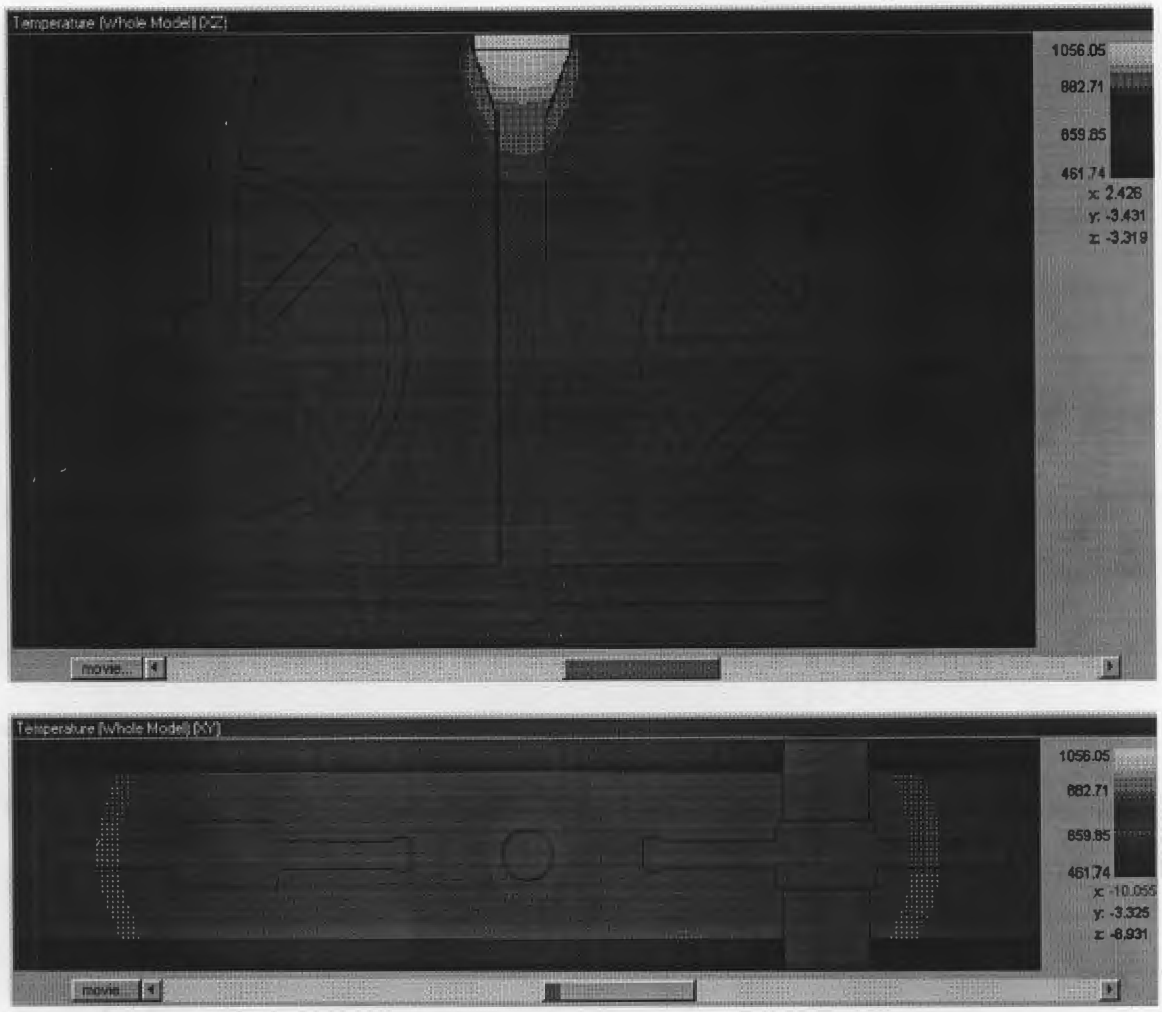


Figure 13. The X-Z and X-Y cross-sections of temperature distribution through the whole model.

CONCLUSIONS

Summary and Conclusions

The current research proved the fact that the simulation of solidification behavior influenced by the chill inserts can be successfully done by the use of modern simulation software.

This research demonstrates the significant positive influence of the use chill inserts in aluminum permanent mold casting. The use of chill inserts installed around thick parts of casting is able to essentially equalize the temperature distribution through the permanent mold assembly and as a result to reduce temperature gradients between relatively hot and cold parts of casting. This effect means that the solidification defects such as shrinkage, porosity, and hot tears may be partially or completely avoided in real permanent mold casting production.

According to the gathered data, the assumed null hypothesis was rejected and the alternative hypothesis was accepted.

Recommendations for Further Research

This research seems to be important and needs to be continued. In further stage of research, the different types of chill inserts should be investigated (copper or steel water-cooled insert, air-cooled graphite inserts). It will be useful to simulate the shell type of mold and a few aluminum alloys with different propensity to the defect formation.

Finally, the simulated data should be checked by conducting a real experiment with some typical cast design.

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