Chapter

Heat Transfer Studies on Solidification of Casting Process

L. Anna Gowsalya and Mahboob E. Afshan

Abstract

This chapter deals with the heat transfer characteristics between the cast and the mold. Generally the heat transfer behavior between the cast and the sand mold is used and all the three modes of heat transfer are studied. The heat transfer characteristics from the cast is at a faster rate for a die mold than for the sand mold. Since the sand mold is used for most of the industrial applications for the complex shapes of metal the heat transfer and the shrinkage behavior in solidification has to be understood perfectly. In this chapter, since the heat transfer mechanism and the shrinkage behavior of the metal in the sand mold is interrelated, hence were predominantly discussed.

Keywords: solidification, casting, heat transfer, shrinkage, IHTC

1. Introduction

The modern metal forming industry has taken complete advantage and benefit offered by the advanced techniques in order to remain in today's competitive market. The solidification modeling is a phase-change phenomena which is amazingly complicated as well as critical in many areas of science and engineering and also very vital in the field of automotive and aerospace applications. In the field of foundry engineering, when the molten metal is poured into the mold cavity, the metal solidifies and discharges heat into the mold, the metal shrinks due to which an air gap is formed in between the cast and the mold. This air gap acts as an obstruction for the heat flow from the cast to the mold and is to be found as one of the moving boundary conditions to be given as input for the casting simulation software. In the simulation of a solidification of the casting process, many parameters play a significant role responsible for the quality of the cast.

The data base for the properties of commonly used materials such as density, thermal conductivity, specific heat, solidus temperature, liquidus temperature, latent heat release etc., for the simulation of casting parameters need to be maintained by the industries.

2. Heat transfer mechanism in solidification

To comprehend the heat transfer mechanism we need to know the behavior of solidification. The heat transfer from the liquid hot temperature cast to the mold is a very complex phenomenon and different modes of heat transfer can be observed while solidification in the cast. While heat transfer is predominant the resistance to the heat flow also has different dimensions to this solidification. This resistance mainly depends on liquid cast metal, latent heat release, interface, solidified cast, the type of mold and the ambient conditions. General solidification of an alloy is discussed in the **Figure 1** and specific cooling curve for Al6061 is shown in **Figure 2**.

Initially on pouring the liquid metal cast into the mold cavity the whole metal fluid flows and occupies the mold cavity, the liquid metal flowing with the velocity, mixes thoroughly and releases heat to the mold due to the very high temperature difference. Complete thermal contact is observed between the cast and the mold which causes the heat transfer to be purely conduction, where the resistance offered by this liquid metal is negligible since the entire fluid flow is the superheated cast metal. Once the cast metal reaches the liquidus point on cooling, the cast shrinks and releases latent heat and also a number of metal oxides are released which causes an air gap between the cast and the mold. Due to this air gap the heat transfer phenomenon now changes to a complex one where all modes of heat transfer can be observed simultaneously. This air gap is characterized with an Interfacial Heat transfer Coefficient (IHTC) "h" across the metal-mold interface. The rate of heat at the interface is found using the surface heat flux as q (W/m^2) and given by the Eq. 1.

$$q = h(Tc - Tm) \tag{1}$$

Tc and Tm are the cast and mold surface temperatures at the interface in K or deg. C.

The dynamics of solidification of cast metal, mold temperature and the cast temperature can be clearly understood from the cooling curves shown in **Figure 2**. Once the molten metal fills the cavity the alloy cast reaches the maximum temperature. Generally the heat transfer analysis starts from this point onwards as the temperature drops from the liquid cast metal to the liquidus temperature (T_L), the point at which the solidification begins and this freezing is called liquid cooling. The loss of superheat temperature of the cast metal after pouring is found due to

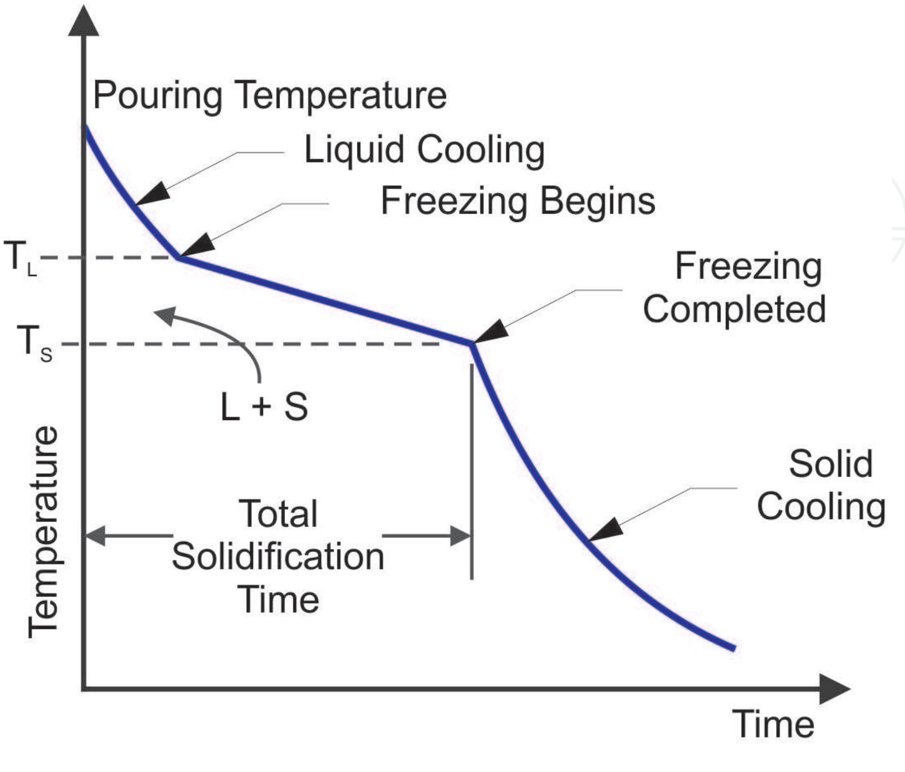

Figure 1.
Solidification curve for alloy.

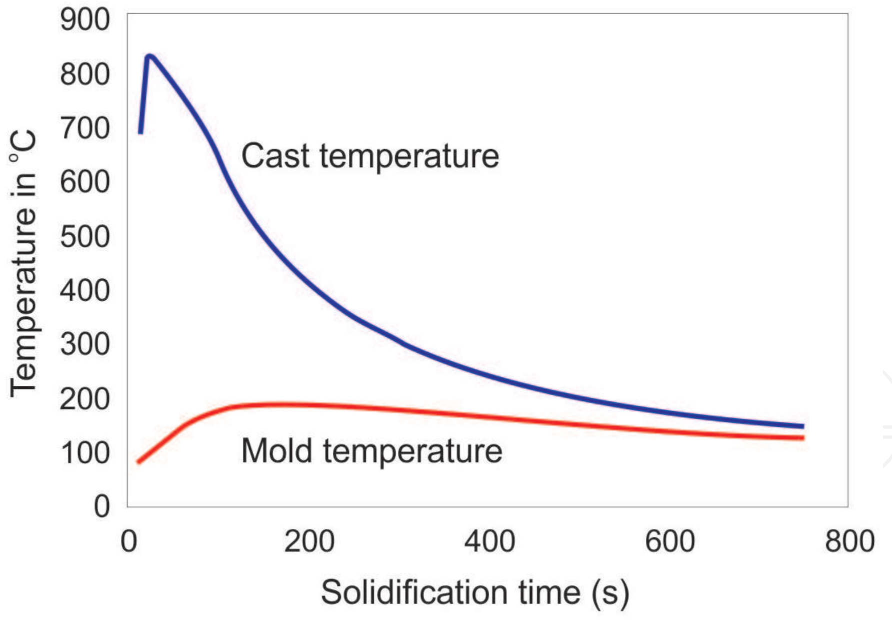

Figure 2.
Aluminum alloy (Al6061) solidification curve.

the turbulence in the liquid metal. This rate of cooling is linear and a minimum amount of heat is transferred from the cast to the mold as it is having a complete contact with the mold surface.

As the solidification progresses with time it reaches the liquidus point at the same time where the mold temperature increases significantly to a maximum temperature. Further the solid skin forms on the outer cast surface, the metal shrinks and an air gap starts forming between the metal and the mold. When the cast solidifies further the air gap separates the two surfaces. This is a common phenomenon in most of the alloys. The rate of heat transfer from the cast to the mold is very high as it releases larger quantity of latent heat to the mold and the cast temperature gradually reaches a solidus (T_S) temperature of the alloy. The air gap plays a significant role in varying IHTC with various factors influencing solidification.

Further solidification reduces the cast surface temperature, however the inner cast metal shrinks and it further releases the heat to the mold and there is rise in the mold temperature as shown in **Figure 2**. Thereafter further reduction in the cast temperature after the solidus point (Ts) was found as the third stage of solidification. The air gap size is further increased as the solidification time increase and its effects are felt till the end of solidification. However there is still a temperature difference between the cast and mold for the further heat transfer to continue.

Once the complete air gap is formed between the cast and the mold, the gap will contain almost all kinds of gaseous except air that contradicts the air gap term. The sand mold which is used for the casting application, generates the mold gases which are often high in hydrogen, containing typically 50 percent which fills the air gap. The hydrogen gas thermal conductivity increases the heat transfer by 7 times more as the mold temperature rises to a high temperature of 500°C due to radiation. Therefore it is very essential to know or analyze the interface during the solidification process as it is further discussed in the next section.

On comparing the green sand mold with dry sand mold the green sand mold expand homogeneously and release heat to the surrounding which leads to a lesser resistance for the heat flow whereas dry sand mold offers more resistance than the green sand mold. The high thermal conductivity die mold material has uniform temperature variation and assumes homogeneous expansion.

3. Shrinkage behavior of casting

While melting the metal in the furnace has a higher specific volume hence it occupies more space by the metal and on pouring it results in the solidification in the mold which increases the complexity of the solidification [1]. After pouring the temperature of the cast reduces and the specific volume also reduces which causes shrinkage in the poured volume as shown in **Figure 3**. To understand the complex behavior of solidification we need to understand three different stages of shrinkage of metal during the solidification process; it includes liquid shrinkage, liquid- solid shrinkage and solid shrinkage.

3.1 Liquid shrinkage

The superheated metal which is poured in the liquid state has more specific volume than the liquid metal in the cavity [2]. This liquid metal occupies the mold cavity and is in superheated state and comes in complete contact with the mold surface. Here the mode of heat transfer is purely conduction shown in **Figure 3**. On solidification there is a liquid contraction due to reduction in specific volume, the metal cools further and reaches to a liquidus temperature. This contraction of liquid metal separates cast and mold surface and imitates the air gap formation which is assigned as liquid shrinkage.

3.2 Liquid- solid shrinkage

Actually the liquid contraction leads to a solidification which is a complex problem in the casting industry. This requires a proper feeding mechanism to fill the cavity by maintaining high liquid cast temperature while pouring and if not then the partial liquid - solid contraction leads to shrinkage porosity. The specific volume of the solid metal is lesser than the liquid metal. All the solidifications are planned for the directional solidification which refers to the faster cooling rate at which solidification progresses from the cavity metal to the feeder mechanism. The faster cooling

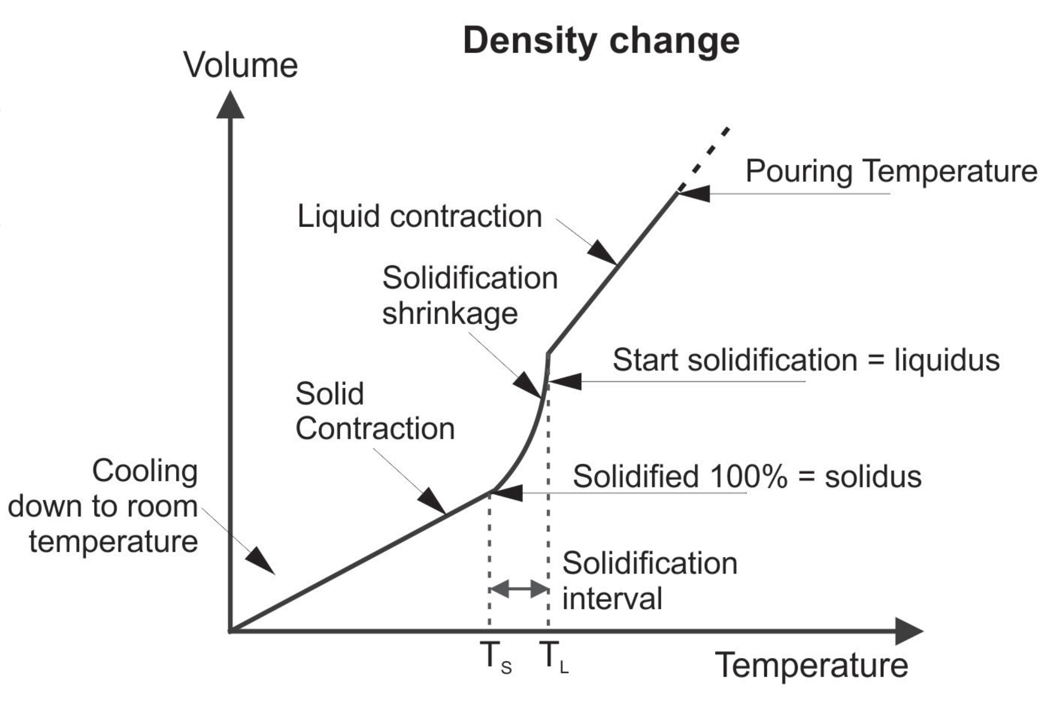

Figure 3.
Specific volume changes against cast surface temperature.

rate and the movement of liquid in the solidification is due to the area of the surface which enables the liquid metal to drop its high temperature to solidus temperature. The runner, riser and the gating system is designed in the mold pattern enhances the directional solidification by transferring proper heat flow from the cast to the mold.

The alloys of eutectic type allow lesser solidification shrinkage volume and also have a lower sensitivity to the solidification problems caused by sudden geometry changes. While they involve smaller risers, these can be omitted completely in certain cases by gates placed strategically and because the metal feed avenues stay open longer, it ensures a uniform solidifying process. While eutectic type of solidification is the most simplest, it requires the least reciprocity and can withstand a range of geometries. Directional solidification is more complex; however, when it has an ideally designed geometry, it is highly capable of extremely higher interior unity. Heat transfer is in fact the main process behind the bilaterally symmetrical and mutual state of connectedness in the process of solidification shrinkage and geometrical patterns. The heat transfer during solidification of castings involves three modes of heat transfer, namely radiation, conduction and convection, the rate of heat transfer is still dependent on the geometry of the casting as discussed later in the interfacial heat transfer coefficient section.

3.3 Solid shrinkage

The final stages of shrinkage in the solid state which can cause a separate series of problems. As cooling progresses, and the casting attempts to reduce its size in consequence, it is rarely free to contract as it wishes. This stage of solidification is usually complex either by the types of mold, or by the other casting parts like the runner and riser that have already solidified and cooled as the air gap formed. The air gap formed is mainly due to the various factors like metal oxide formation, coefficient of thermal expansion, latent heat released, evaporation moisture in the case of sand mold, interfacial gap, mode of heat transfer etc. this type of solidification shrinkage is also called as pattern shrinkage.

These factors are the major causes for the heat to flow from the cast to the mold and it is found that it majorly affects the solidification and in turn affects the quality of the cast product. The amount of solid metal stretches like plastic casting, makes the solidification again into a complex problem. This shrinkage behavior leads to difficulty in predicting the size of the pattern since the degree to which the pattern is made oversize (the 'contraction allowance' or 'patternmaker's allowance') is not easy to quantify. This shrinkage also causes hot tearing or cracking of the casting which lead to more localized problems.

In general, liquids contract on freezing because of the rearrangement of atoms from a rather open 'random close-packed' arrangement to a regular crystalline array of significantly denser packing. The densest solids are those that have cubic close packed (face-centred-cubic, fcc, and hexagonal close-packed, hcp) symmetry. Thus the greatest values for contraction on solidification are seen for these metals.

4. Interfacial heat transfer coefficient (IHTC)

The heat transfer characteristics during casting are governed by IHTC. The molten metal is poured into the cavity it first enters the mold due to the fluidity of the metal, it occupies the cavity and ensures complete contact between the metal and the mold. In the early stage of solidification, the fluidity of the molten metal conformance and contact between the cast and mold surfaces is good. At this early stage of solidification due to the nucleation of the metal, higher initial surface heat flux is reached. Further the solid skin forms and then spreads to cover the entire casting surface. As the solidified layer forms with sufficient strength, simultaneously air gap forms and as a consequence the contact between the casting and the mold are reduced. This leads to the sudden drop in the heat flux and the solid skin forms on the outer cast surface [3]. The cast liquid - solid shrinks/contracts away from the mold surface. This further releases heat and it is absorbed by the mold surface and in turn increases the temperature of the mold as it expands. The mode of heat transfer is not only due to conduction at this stage because the heat from the metal to the mold takes place across the interface region but also due to other modes of heat transfer convection and radiation. The air gap varies for the different cast metals and depends on their factors of the release of metal oxides, hydrogen gases and material properties of the cast and mold, geometry etc.

Further the third stage of solidification is identified between the liquidus to solidus temperature of the cast as the fall in the casting surface temperature is suddenly halted, due to the release of latent heat. After the complete solid skin formation on the cast the heat transfer further diminishes and gap size increases and the mode for heat transfer is assumed to be conduction of heat through the gaseous phase in the interface using the air gap method. This air gap size is measured as x by assuming the expansion to be homogeneous, and the interfacial heat transfer coefficient is estimated as $h = k/x$: where k is thermal conductivity of the air (W/mK) as shown in **Figure 4**. This concept of conduction as a mode of heat transfer in IHTC is reported by Kai- Ho and Robert D Pelhke, [4]. There are many factors that influence the IHTC and practically the IHTC becomes highly unpredictable if all the factors are not taken into account while designing. The various factors listed by the authors Lewis and Ransing, [5] and Guo Zhi-Peng et al. [6], that affect the interfacial heat during solidification is listed below.

1. Die coating thickness: The initial high peak value of IHTC is reduced with an increase of die coating thickness. While pouring the metal at the liquid stage the effect of die coating behaves as a weaker influence at the interface as the air gap formed.

2. Insulating pads, chills, etc.: The IHTC has different behaviors with insulating pads and chills. It is obvious that always the insulating material reduces the IHTC and the chills increases the IHTC.

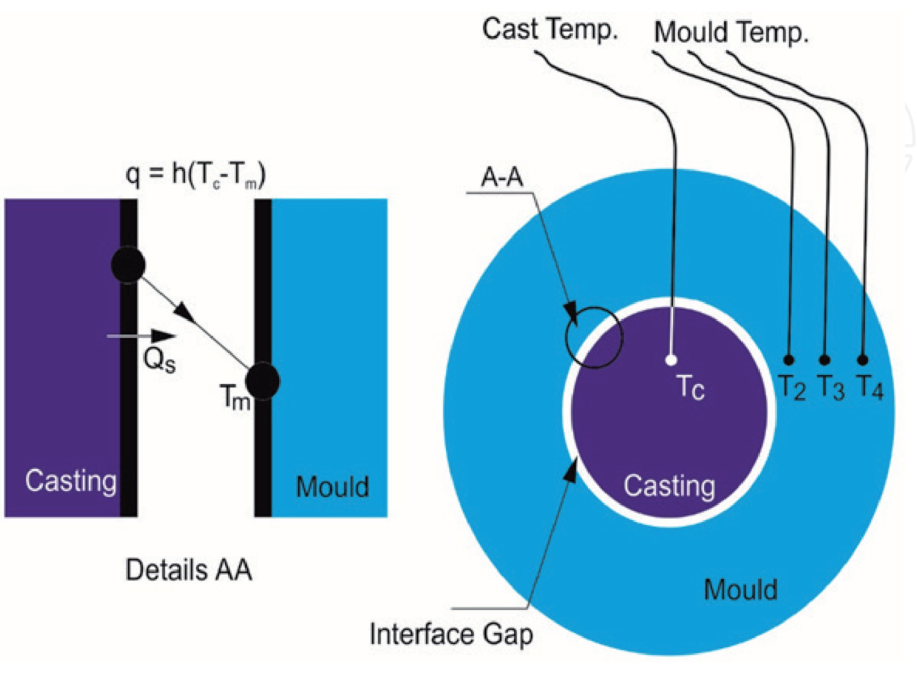

Figure 4.
Schematic representation of IHTC during solidification of casting.

3. Geometry of Casting: The area of contact with the mold and the directional solidification will have higher IHTC.

4. Pouring temperature: Higher values of superheat will increase the initial value of IHTC.

5. Surface roughness: Higher initial value of IHTC for the better contact when the surfaces are smooth.

6. Alloy composition: Higher initial value established for an alloy with a larger freezing range.

7. Latent heat: Cast from superheat temperature to liquidus temperature ensures sharp slope in IHTC due to the evolution of latent heat.

8. Metallostatic pressure: During the pouring of molten metal into the cavity rises the metallostatic pressure, this is also responsible for higher IHTC at the initial stage.

9. Mold temperature: During initial stage higher IHTC due to the higher mold temperature and smaller temperature difference for higher peak heat flux.

10. Die Coating thickness: Increase of die coating thickness decreases the IHTC. While pouring the metal at the liquid stage the effect of die coating behaves as a weaker influence at the interface as the air gap formed.

11. Mold materials

12. Type of castings

As it is pointed out by many researchers the gap size mainly depends on the gas that is formed in the interface. The rate of solidification of castings made in a sand mold is generally controlled by the rate at which heat can be absorbed by the mold. In fact, compared to many other casting processes, the sand mold acts as an excellent insulator, keeping the casting warm. However, of course, ceramic investment and plaster molds are even more insulating, avoiding premature cooling of the metal, and aiding fluidity to give the excellent ability to fill thin sections for which these casting processes are renowned. It is regrettable that the extremely slow cooling can contribute to rather poorer mechanical properties.

Extensive literature reviews have been made, in order to determine the interfacial heat transfer behavior during the solidification of casting at the metal-mold interfaces, since the 1970's. The boundary conditions as a surface heat flux and mold surface temperature established at the metal mold interface were used to determine the precise interfacial heat transfer coefficient value by using many mathematical methods described in the literature. The most common approaches can be distinguished here as follows for the determination of IHTC at the metal-mold interface including surface heat flux and mold surface temperature:

1. Air gap measurement technique

2. Pure Analytical approach

3. Semi-analytical method

4. Numerical Methods

The following section explains the detailed procedure of these methods listed above.

4.1 Air gap measurement technique

This method calculates the IHTC based on entrapped gas properties present at the interface. The thermal conductivity of the air between the cast mold interface and the distance of air gap measured as x with the LVDT [7]. The formula used for IHTC calculation is, h = k/x, W/m^2K. The mode of heat transfer assumed in this method is conduction at the interface, but the other modes of heat transfer are also practically possible as we have discussed in the above section. Hence this method is not widely accepted by the researchers.

4.2 Numerical approaches (inverse method)

In this approach, experimental cooling curves were obtained at certain locations of the cast surface and on the mold to estimate the IHTC. The IHTC is calculated based on measured cast temperature, estimated mold surface temperature and estimated mold surface heat flux. Generally solidification heat transfer problems as shown in **Figure 5** were categorized as

- Direct Heat Conduction Problem (DHCP)
- Indirect Heat Conduction Problem (IHCP)

In the DHCP the boundary conditions were known at the metal mold interface (which is a moving boundary problem and is difficult to acquire the parameters at the interface) and the effects were determined, mathematically it is known as a well posed problem. But in solidification of casting, knowing the boundary condition is very difficult because of its high transient nature, moving boundary problem, high temperature region, combination of all modes of heat transfer, etc., at the interface. So the inverse heat conduction problem is used to approach the problem. In order to calculate the boundary condition at the interface as a surface heat flux and surface temperature of the mold, experiments were carried out to determine temperatures in the mold to get the input data. This leads to a method of adoption of an ill-posed problem or the inverse heat conduction problem (IHCP) [8]. This ill-posed nature makes IHCP conduct experimentation to determine the boundary conditions at the interface before it has to be solved from the available data rather than using a DHCP approach.

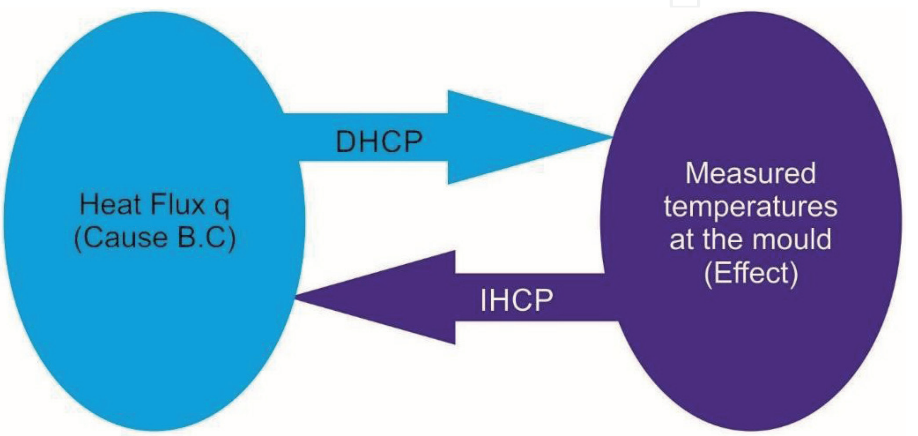

Figure 5.
Schematic diagram for DHCP and IHCP conditions.

The interfacial heat transfer coefficient at the cast mold interface can be calculated based on Eq. (1), requiring the transient surface heat flux. Cast and mold surface temperatures are measured using thermocouples during solidification regardless of its uncertainty in the physical measurements. The pure analytical or other methods mentioned above are unable to determine the surface heat flux at the interface. This leads to the numerical approaches and their formulation of inverse heat conduction problem (IHCP) at the interface to determine the boundary conditions. The boundary conditions at the interface are explored or determined by the IHCP. This has been studied by various techniques like FDM, FEM, FVM and CV methods. One of the common and mostly used method is mainly based on the function minimization technique based on the numerically calculated and measured data [6].

$$F(h) = \sum_{i-1}^{N} (T_i - Y_i)^2 \tag{2}$$

Where, F(h) is the minimization function, Ti, Yi are calculated and measured transient temperatures at the same locations, i= 0 to N, nodal point. The errors in the temperature measurement may also lead the IHCP into ill-posed. This problem leads the researchers to propose many techniques to solve for IHCP to determine boundary conditions at the interface with the measured temperature histories.

1. Polynomial extrapolation method: The temperature at the interface was deduced by extrapolating any one of the polynomial curve fitting techniques. This method needed many measurements inside the cast and mold surfaces. This mathematical tool failed to minimize measurement errors.

2. Regularization method: In order to minimize the error from the measurement obtained a sensitivity analysis can be carried out using the Tikhonov regularization theory. This was used to regularize some function to relate the measured data and this was improving the accuracy and stability of the results obtained. This method could achieve an excellent solution and could be applied to any complex geometry, but the computation takes a very long time.

3. Boundary element method and Laplace transform: the unknown temperature were transformed into equations as well as written as matrix format. This could be easily solved and written into a computer program. But it has some restrictions. It was an effective method to solve a simple linear problem. But the measured temperature data always has more noise (disturbances) in the data, this could fluctuate the result obtained as heat flux.

4. Beck's function specification with finite difference method (implicit & explicit): It was another minimizing error technique used based on heat flux, where sum of squares of assumed and calculated data are used into the function. This method could be used for linear or nonlinear problems. Also, it has long computation time and also could achieve an accurate solution with efficient computation.

5. Control volume method: This method works, based on energy balance applied over a control volume drawn on each nodal point. The next one is the governing equation for the transient heat conduction written as a partial transient heat conduction equation changed into an ordinary differential transient equation. This involves both energy and mass conservation on each node, leads to a complex formulation equation containing up to 4th order, which may be difficult to program using computer languages, and can only be applied to simple geometrical shapes and one dimension.

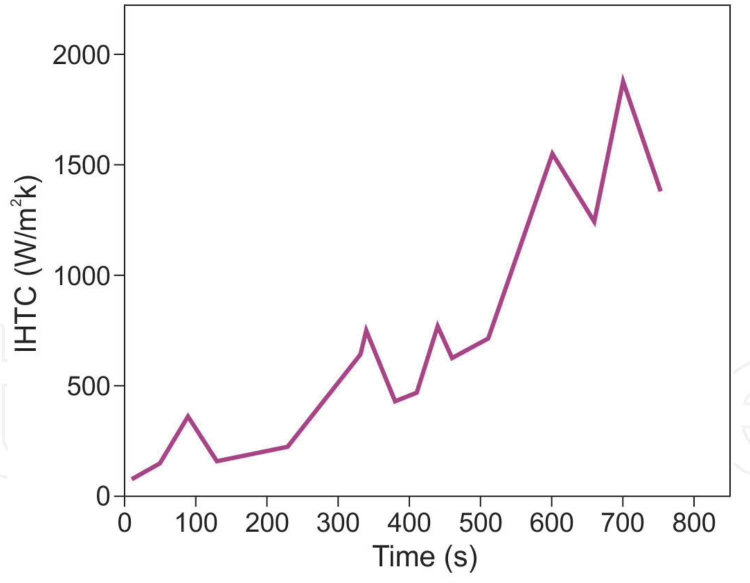

Figure 6.
IHTC variation for the rectangular aluminum casting with sand mold.

A sample of a rectangular geometry with an aluminum (Al6061) cast volume of 45 cm^3 was solidified and the IHTC was calculated as shown below in **Figure 6**. Here the IHTC curve was calculated using the control volume method and it shows a gradual increase. Various characteristics of the IHTC and the heat transfer can be discussed [9].

4.3 Behavior of IHTC for the given Al 6061

The behavior of the sample rectangular cast was considered as it summarizes most of the heat transfer modes in solidification of the cast. On pouring the IHTC was found to be 370 W/m^2 K at 90 s, the higher initial surface heat flux was due to a perfect thermal contact. As further solidification starts, vaporization takes place in the sand mold because of the moisture content, presence of hydrogen release along with metal oxides across the interface and the reduction of specific volume of metal creates an air gap and decreases the value of IHTC rapidly to a minimum value of 163 W/m^2 K at 130 s. The shrinkage of metal causes release of latent heat and rise in the IHTC, then heat transfer reduces once the solid skin is formed [10]. Again the inner metal leaks and flows out from the solid skin to outside and gets cooled which again releases latent heat and so IHTC increases and decreases. Continuous rise and fall of the IHTC shows peak formation, which is shown till the end of solidification. The fourth peak value of 1718 W/m^2 K at 600 s and further again at 720 s the IHTC reached the highest peak value of 1918 W/m^2 K. The vapor pressure developed in the sand mold is due to the escape of moisture content to the ambient, which is sufficient to allow the heat to flow from the solidifying metal to sand mold hence the sharp rise in IHTC is observed in the final stage of solidification. Not only vapor pressure but also huge temperature differences causes high heat flows. Due to the thermal resistance induced, as the metal solidifies and contracts, a fall in the IHTC is vividly observed.

5. Conclusion

The materials that change phase during solidification to room temperature can be much more complicated. The heat transfer in the solidification is a complicated phenomenon as shown in the above sections. Understanding the heat transfer characteristics while solidification will help to link the various developments in the micro structure of the materials and the dislocations present. When solidification is complete the strength of the material can be assessed and the formation of the grains in the material can be directed by control of the temperature and heat flow on solidification.

The IHTC of a sample of Al6061 is thoroughly explained to comprehend the various modes of heat transfer while solidification is taking place. Proper cooling helps to govern the solidification and as the temperature is sufficiently low the strains of dislocations will not be sufficiently mobile to migrate into low energy positions, forming low-angle boundaries. Thus the alloy will become sufficiently strong to retain any further strain as elastic strain. Once the metal solidifies properly the structure of the alloy will no longer be affected during further cooling. Hence a complete idea of IHTC at all the times of solidification is the best option to minimize the errors and maximize the strength.

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References

[1] John Campbell: Castings, Butterworth Heinemann, Oxford, 2002.

[2] Bhagavath S, Cai B, Atwood R, Li M, Ghaffari B, Lee P.D, Karagadde S: Combined Deformation and Solidification-Driven Porosity Formation in Aluminum Alloys, Metallurgical and Materials Transactions A, 2019; 50, 4891-4899.

[3] Rajaraman R, Velraj R: Comparison of interfacial heat transfer coefficient estimated by two different techniques during solidification of cylindrical aluminum alloy casting, Heat Mass Transfer, 2008; Vol. 44, 1025-1034.

[4] Ho F, Pelhke R.D: Metal –mould interfacial heat transfer, Metallurgical Transactions B, 1985; 16, 585-594.

[5] Lewis R.W, Ransing R.S: A Correlation to Describe Interfacial Heat Transfer during Solidification Simulation and Its Use in the Optimal Feeding Design of Castings, Metallurgical and Materials Transactions, 1998; 29B, 448.

[6] Guo Z-P, Xiong S-M, Murakami M, Matsumoto Y, Ikeda S: Study on interfacial heat transfer coefficient at metal/die interface during high pressure die casting process of AZ91D alloy, China Foundry, 2007; 4, No.1.

[7] Griffiths W.D: The Heat-Transfer Coefficient during the Unidirectional Solidification of an Al-Si Alloy Casting, Metallurgical and Materials Transactions B, 1999; 30 B.

[8] Anna Gowsalya L, Jeyakumar P.D, Rajaraman R and Velraj R: Estimation and validation of interfacial heat transfer coefficient during solidification of spherical shaped Aluminum alloy (Al 6061) casting using inverse control volume technique, Frontiers in Heat and Mass Transfer (FHMT), 2019; 12, 21.

[9] Rajaraman R, Anna Gowsalya L, Velraj R: Estimations of interfacial heat transfer coefficient during the solidification of rectangular aluminum alloy casting using two inverse methods, Frontiers in Heat and Mass Transfer (FHMT), 2018; 11, 23.

[10] Zhang A, Liang S, Guo Z, Xiong S: Determination of the interfacial heat transfer coefficient at the metal-sand mold interface in low pressure sand casting, Experimental Thermal and Fluid Science, 2017; 88, 472-482.