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Experimental Determination Of The Effect Of Mould Thickness On The Solidification Time Of Aluminium Alloy (Al-Mn-Ni -Si) Casting In Rectangular Metallic Moulds

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Abstract

One of the very important parameters to assess the properties of materials produced by casting process is the solidification time. This paper presents the influence of mould thickness and temperatures on the solidification time of aluminium (Al-3.42%Mn; 2.38%Ni; 0.26%Si) alloy in rectangular metallic moulds. Experiments were conducted to measure the temperature fields in a solidifying casting against time. From the temperature fields solidification times were obtained for various moulds thicknesses as well as the mould temperatures. The results showed that mould thickness has significant influence on the solidification time. Smaller mould thickness produced shorter solidification time within the experimental specification. As the mould temperatures are increased the solidification time is prolonged and this influence grain development during the solidification process subsequently affecting the mechanical properties of the castings produced.

1. Introduction

Aluminium is a very important and common metal on earth because of its low density and excellent mechanical properties. It is alloyed with elements like magnesium, silicon, copper, manganese, and zinc to produce variety of wrought products from beverage cans to aircraft structural parts, to cast products like engine blocks and steering knuckles for automobiles [1, 2].

Aluminium alloys have a high castability rating and are considered to be amongst the most versatile of all common foundry casting alloys [3]. Aluminium castings are mostly used in the transport sector. Smaller percentages of aluminium castings are being used in general engineering, electrical engineering, building and construction sectors. Aluminium castings are being increasingly used as many key components [4]. This has resulted in the demand for highest quality and performance standards in producing these components in the foundry. To meet the ever increasing demands and challenges of quality, standards, productivity and faster return on investment, the aluminium casting industry has to adopt strategies and take advantage of the technical advances in the field.

Solidification of metals is the transformation of molten metal back into solid state after pouring into the mould [5]. Solidification differs depending on whether the metal is a pure element or an alloy. When molten metal is poured into a mould, a series of events take place during solidification of the casting and its cooling to ambient temperature. These events greatly influence the size, shape, uniformity, and chemical composition of the grains formed throughout the casting, which in turn influences its overall properties [3]. The significant factors affecting these events are the type of metal, thermal properties of both the metal and the mould, the geometric relationship between volume and surface area of casting, and the shape of the mould. The times involved in this activity may be as short as seconds or as long as hours depending upon the casting process and the size of the casting, the chemical composition of the metal being cast, the manner in which solidification occurs, and the subsequent solid state treatment determines the ultimate microstructure and therefore properties (mechanical and physical) of the casting [3].

Solidification of castings in metallic moulds has been reported in literature relevant to not just metallurgy but also fluid mechanics and heat and mass transfer. Various experiments have been performed to understand the mechanisms associated with solidification. Through the years several methods have been used with the purpose of analyzing the solidification of foundry pieces. At the beginning, analytic methods were used. Later, researchers turned to the employment of numerical methods. Many mathematical models have been developed to predict the phenomena of solidification through analytical or computational simulations. At the present time the variety of methods used to simulate metal solidification is numerous, depending on the type of the outlined problem, the geometry, material types and thermal properties. Manjhi [6]) applied the method of control volume approximation to the simulation of the solidification and thermal treatment of steel ingots.

The solidification process can be represented using cooling curves showing a variation of temperature with respect to time [7] Cooling rates are important in controlling the quality of a casting since by monitoring the cooling rate and the thermal gradient solidification shrinkage defects can be detected. The most important part of the cooling curve is the cooling rate which affects the microstructure and properties [8]. Cooling rate can be an indication of material quality. Areas of the casting that cool rapidly generally have a more favourable grain structure, with less deposition of partially soluble compounds at the grain boundaries [9]. Therefore, these areas tend to have better material properties such as strength, elongation and hardness. Those areas of the casting that cool more slowly generally tend to have poorer material properties.

1.1. Alloy solidification

In alloyed form metals are stronger, melt at lower temperatures, solidify slowly, and have better fluidity and castability. Solidification of alloys occurs over a temperature range-(liquidus temperature) above which all is liquid and (solidus temperature), below which all is solid. A two-phase solid-liquid region called the mushy zone is formed within this temperature range [10]

Most industrial products are made of alloys, and their solidification is essential in many technological processes. Solidification in alloys begins when the temperature drops below the liquidus temperature, (T_L), and is complete when it reaches the solidus temperature, (T_S), as shown in Figure 1. Within this temperature range, the alloy is in mushy or pasty state and is characterized by a very complex solid-liquid microstructure that develops with time. The formation of this region has a serious effect on the final microstructure and quality of the product. Generally, two dendritic structures are distinguished in the mushy zone: the columnar and the equiaxed dendrites. The columnar mushy zone appears in the form of a dense crystalline-like matrix filled with inter-dendritic liquid having strong directional nature. In the equiaxed zone the crystal grains are freely moving in the melt [10]. Dendrites have three-dimensional arms and branches, and the arms eventually interlock. The width of the mushy zone, where both liquid and solid phases exist, is an important factor during solidification and depends on the mould material, cooling rate and the temperature gradient.

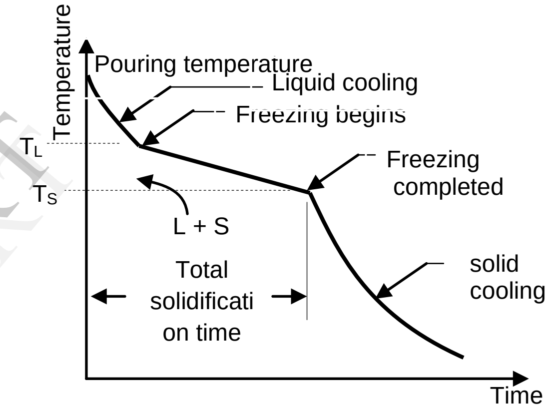

Figure 1. Schematic cooling curve for alloy solidification

1.2. Solidification time in metallic moulds

Solidification in metallic mould casting is much faster than in sand mould due to its high thermal conductivity. The rate of heat transfer is also at the interface between the solidifying metal and the metallic mould where air gap quickly develops. The parameter which determines the heat transfer is the heat transfer coefficient of the air gap developed. The heat flow within the casting and the mould is very high compared to the relatively slow transfer across the air gap at the metal/mould interface. Thus the rate of heat removal and consequently solidification rate depends on the heat transfer coefficient across the metal/mould interface [9].

The solidification time in metallic moulds can be described mathematically by considering the heat transfer between the liquid metal and the metallic mould and taken cognizance of the heat transfer coefficient at the metal/mould interface as a result of the formation of air gap during solidification [11]. This is given as:

$$t_s = \frac{\rho_M\left[L + C_M(T_p - T_m)\right]V_M}{h(T_m - T_o)A_M} \qquad (1)$$

Where, T_o is the initial temperature of the mould; T_m is melting temperature of metal; T_p is the pouring temperature of metal; L is the latent heat of fusion; h is the interfacial heat transfer coefficient; ρ_M is the density of the metal; C_M is the specific heat of the metal; V_M is the volume of metal; A_M is the surface area of metal.

Equation (1) can be expressed as Chvorinov’s rule thus [12]:

$$t_s = B_s\left(\frac{V_M}{A_M}\right) \qquad (2)$$

Where, Bs is a mould constant and $\frac{V_M}{A_M}$ is the modulus of the casting.

The total solidification time is the time from pouring to completion of solidification. In metallic moulds the total solidification time varies linearly with casting modulus unlike in sand moulds where it varies with the square of the casting modulus.

2. Material and Method

Experiments were carried out to establish the solidification time as well as the temperature profiles within the cast as it cools and also in the mould as it heats up. The temperature measurement in the cast was to provide an insight of the transient phenomena during solidification.

2.1. Metallic moulds specification

The experiments were conducted in top poured, vertically parted rectangular shaped metallic moulds made from low carbon steel. The thermophysical properties of metallic moulds are shown in Table 1.

Table 1. Thermophysical properties of steel mould [13]

Symbol	Properties	Values
K_{st}	Thermal conductivity (W/m°C)	78.2
C_{st}	Specific heat capacity (J/kg°C)	456
ρ_{st}	Density (kg/m^3)	7870
$h_{st\text{-}air}$	Heat transfer coefficient (J/sec m^2 °C)	9.93

2.2. Experimental Setup

To be able to study the temperature profiles in both the cast and the mould, K-type (Chromel/Alumel) thermocouples were placed at specified locations in both the mould and the metal as shown in the experimental setup in Figure 2 as follows:

AI1 - Centre of casting
AI2 - Half cast thickness
AI3 - Metal - Mould interface
AI4 - Half mould thickness
AI5 - Mould-Air interface

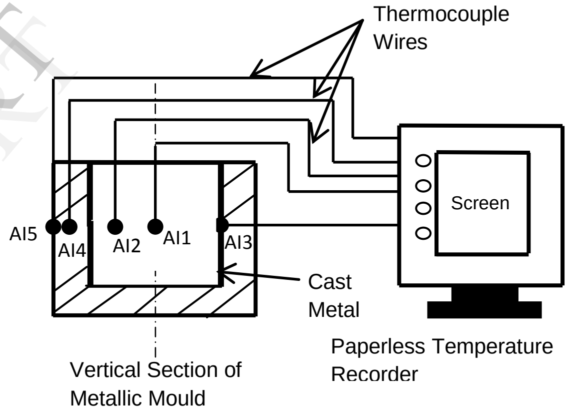

Figure 2. Schematic diagram of experimental setup for rectangular mould

2.3. Measurement and recording of cast and mould temperatures

During the casting process, the temperature distribution in both the cast and the mould were recorded by the use of K-type thermocouples connected to a Paperless Temperature Recorder (RD8900) [14] at the various locations as indicated in Figure 2. The OMEGA® RD8900 Series Paperless Recorder shown in Plate 1 offers real time display of data in a variety of formats (digital, bar, trend, and a mix of all) on a high resolution (VGA) colour TFT display.

Plate 1. RD8900 Paperless Temperature Recorder rear and front view showing six channel displays

The user friendly unit with plug & play cards can easily be set to monitor, record, and evaluate temperature profiles in the casting and the mould. The historical data were stored in a flash ROM (read only memory), compact flash card. Observer 1 software was installed on a PC (personal computer) for assessing and printing of the recorded temperature profiles.

2.4. Mould Thickness and Cast Volume Specification

To investigate the influence of mould thicknesses on the heat flow and solidification time, the moulds thicknesses were varied while the casting (mould cavity) volume remained constant. The various specifications for the rectangular moulds are shown in Table 2.

Table 2. Dimensions of rectangular moulds and cast

Mould wall thickness (mm)	Length of Cast (mm)	Width of Cast (mm)	Depth of Cast (mm)
12.5	100	50	100
25.0	100	50	100
37.5	100	50	100

2.5. Melting and Pouring of Aluminium

The aluminium alloy used for the experiment was obtained from different scrap components of aluminium products. The chemical composition is presented in Table 3.

Table 3. Chemical composition of aluminium alloy in percent

Si	Mn	Ca	Ti	V	Fe	Ni	Al
0.3	3.4	0.1	0.03	0.06	0.1	2.4	94.68

The scrap components of aluminium products were collected and heated in an electric resistance furnace until it melted and reached a pouring temperature of 720ºC. The pouring temperature was monitored by dipping a K- type thermocouple connected to digital multimeter as well as using the temperature indicator of the furnace. Ash from burnt torch batteries as a substitute for a sodium modifier [8] was added during the process of melting. The molten aluminium in the crucible was poured into the mould cavity within 5 seconds. The moulds were kept at an initial temperature of 33.6°C and the molten aluminium poured at 720°C. The solidification time for each thickness was obtained from the plot of graphs from the Paperless Temperature Recorder

3. Results and Discussion

The results obtained from experimentation with aluminium alloy of 94.68% are shown in Figures 3 to 5 and relates to rectangular metallic moulds of thicknesses of 12.5, 25.0, and 37.5mm respectively.

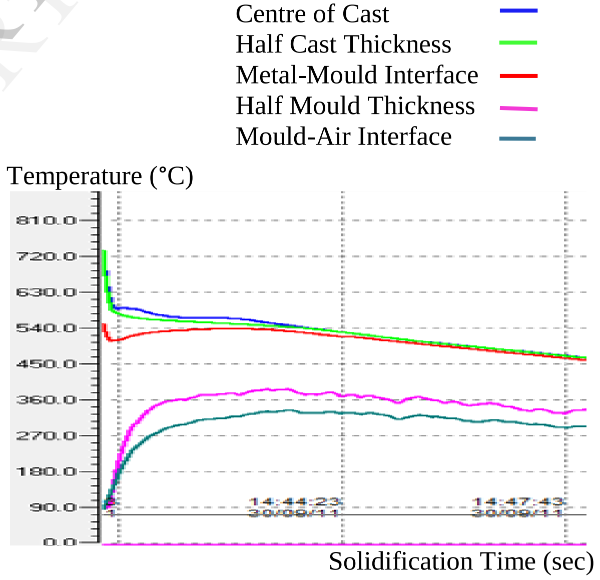

Figure 3. Cooling and heating curves at varying aluminium cast and mould locations for 12.5mm thick rectangular metallic mould for the solidification of aluminium alloy

Temperature (°C)

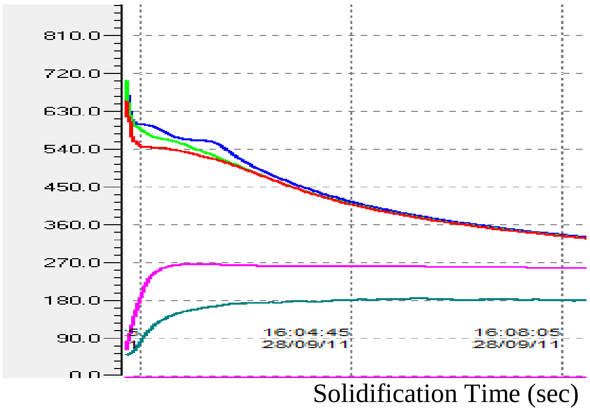

Figure 4. Cooling and heating curves at varying aluminium cast and mould locations for 25.0mm thick rectangular metallic mould for the solidification of aluminium alloy

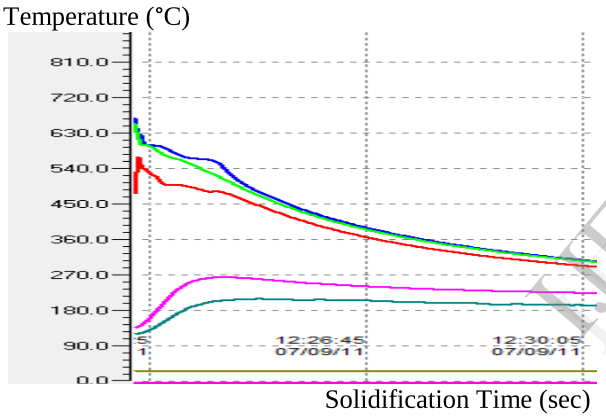

Figure 5. Cooling and heating curves at varying aluminium cast and mould locations for 37.5mm thick rectangular metallic mould for the solidification of aluminium alloy

The solidification times for the aluminium alloy in rectangular moulds of thicknesses of 12.5, 25.0 and 37.5mm are presented in Table 4. In the rectangular mould of 12.5mm thick Figure 3, the solidification time is 123 seconds with a mould maximum temperature of 270°C at a pouring temperature of 720°C. Figure 4 represents the cooling and heating curves of aluminum cast in 25.0mm thick rectangular mould. It is observed that the mould was heated to a maximum temperature of 270°C and solidified at 81 seconds. Figure 5 is for 37.5mm thick rectangular mould, and shows similar trend but has a total solidification of 73 seconds. An undercooling is observed at the metal-mould interface as a result of the high rate of heat extraction at the surface. The mould maximum temperature is a little below 270°C. The longer time for solidification in the 12.5mm mould is attributed to the higher mould initial temperature of 95.5°C and also with a pouring temperature of 720°C as compare to those of 25.0mm and 37.5mm.

Table 4. Variation of solidification time with mould thickness in rectangular mould for aluminium alloy

Mould Temperature (°C)	Pouring Temperature (°C)	Mould Thickness (mm)	Solidification Time (sec)
95.5	720	12.5	123.0
95.5	680	25.0	81.0
95.6	680	37.5	73.0

Conclusion

From the experimental results it is ascertained that the mould thickness has significant influence on the solidification time. Smaller mould thickness had longer solidification time in the rectangular moulds.

Acknowledgements

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