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Interface Heat Transfer Coefficient between Casting and Round Chilled Moulds during Solidification of Aluminium Alloy Castings

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Abstract: **Interfacial heat transfer coefficient, being an important factor in developing CAD/CAM System, is being estimated for commonly used LM6 Aluminium alloys. To make calculation easy, unidirectional heat flow is considered in a sand mold having a metallic chill bottom. Sand is comparatively insulator with respect to metal. Different thickness metallic chills are used to study the effect of thickness on heat flux. As the study shows the heat flux is across the interface depends upon the thickness of the chill and the time for air gap formation is delayed for higher thickness.**

Keywords— IHTC, Mechanical Properties, Air Gap,Super Heat, Heat Flux, LM 6

1. INTRODUCTION

Metal casting is a process of producing the desired object with pre specified quality. To assure of this, it is most important that we know the thermal behaviour of the liquid metal when poured into moulds.

Aluminium and its alloys are used extensively in automobile, aircraft and other engineering industries. Aluminium alloys have properties like high strength to weight ratios, good corrosion resistance and ascetic beauty. So iron castings are slowly being replaced by aluminium castings. Having smaller freezing range of 10 degree Celsius, LM 6 (11.8 Si) is one of the extensively used Aluminium alloys. In this computer era, it's not necessary to do experimentation to study the thermal behaviour during solidification of poured metal Computer simulation and graphics have opened a new vista to picturise the solidification.

To produce a sound casting it is necessary to control the heat transfer coefficient 'h' to induce directional solidification. To achieve this, many objects are used like incorporating a chill in sand mould, attaching a riser etc. The chill increases the heat transfer and the sand acts like an insulating material.

Pehlke(19) and other investigators have contributed much information on the use of chill. But there is no mathematical model to give direct heat transfer coefficient by knowing the parameters to help us establish a CAD system for the foundry men. In present investigation new method of chill incorporation in sand is being studied. The opposite surface of the chilling surface is being exposed to the atmosphere. So it is a combination of sand-metal-mould having a better heat transfer coefficient than the ordinary sand chill combination. One of the main factors of the chill thickness is being investigated using simple experimental setup. In sand mould varying chills are kept at the bottom varying diameter of cylinder. And opposite side of the chilling material is exposed to the air to make it nearly unidirectional. Data, obtained by recording temperature and time history at different depths of the chill, could be used to evaluate IHTC, to be applied to develop a CAD/CAM system.

2. LITERATURE SURVEY

2.1 Solidification in Moulds

When the liquid metal is poured into the mould, it changes from liquid state to the solid state, the process called solidification. During this span of time, factors like pouring temperature, thermal behaviour of the cast metal, physical, chemical, thermal properties of the mould etc. Come into picture simultaneously to yield the final casting.

To begin with mould plays a significant role in the history of casting solidification. Basically two types of moulds, i.e., sand mould, metallic moulds, impart different historic to the casting because of their different thermal behaviour during solidification. So they represent different freezing patterns.

In case of sand castings, Chvorinov's rule states that the solidification time't' can be expressed as a function of V/SA ratio.

$T = V/ (SA)^2$

Where,
V = volume of casting.
SA = surface area of the casting.
The rule makes the following assumptions.

1. The temperature at the interface between the metal and the mould remains constant throughout the solidification period.
2. The temperature diffusivity of the mould material is sensible independent of temperature.
3. The mould material is homogenous.
4. Semi infinite conditions exist in the mould.

The sand material can be considered to be relatively insulating to the metal.

The perfect contact will be developed between the sand casting and the sand, resulting into only mode of heat conduction between the casting and the mould. The interface temperature can be considered to be constant during the entire period of solidification and also it gets assumed that that the mould can be treated as semi infinite, i.e., the outer surface of the mould can be taken to be at ambient temperature till the completion of solidification (fig. 2.1, 2.2). But the interface temperature at the metallic mould is not constant. During solidification, the cast material shrinks and the mould expands, resulting in the formation of an air gap. Metallic moulds are not considered as semi infinite. Due to higher thermal conductivity of metal, higher solidification rate and temperature gradient are developed. So different thermal behaviour are presented for different thermal materials.

2.2 Air Gap Formation

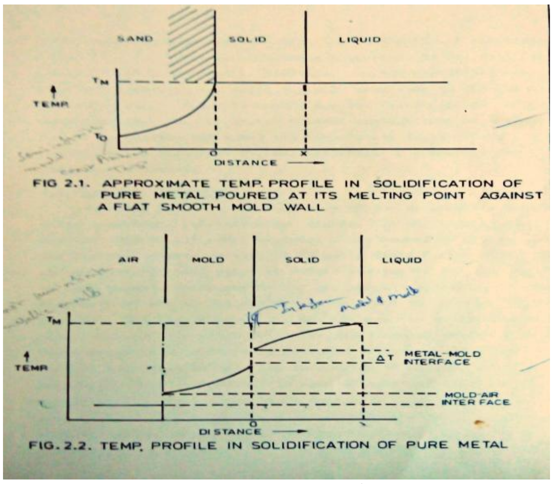

Fig 2. Temperature Profiles

When the liquid is poured into the metallic mould, after the sometime solidification starts at the same time the casting shrinks and the mould expands. This causes an air gap. The air gap formation starts at corners during the early solidification stage and later stage at middle portion of the casting. As this passes the air gap thickness keeps increasing. So the thickness of the air is not uniform at uniform at the surface of the casting at all its sides. The formation of air gap changes the condition of heat transfer from metal to mould, affecting the solidification rate. The air gap reduces the heat transfer due to its lower heat conductivity and with increase in its size. In the beginning only conduction was the mode of heat transfer. As the gap forms all three modes starts operating. Radiation mode is effective at high temperature and emissivity only. And at the low temperature conduction dominates the scene. Conduction depends on the medium and size of the air gap.

There is abundant information regarding the size of the air gap. The accurate modelling of heat transfer across the air gap requires the knowledge of factors affecting the air gap formation, interface temperature etc.

2.3 Factors affecting air gap formation.

Extensive research has been done to understand measure and simulate the air gap formation. The research has yielded important information about the air gap. There are many factors that affect this phenomenon, originating from five sources cast metal, mould material, configuration of casting to be made, interface between metal and mould, external forces acing on the mould as well as cast metal during solidification.

2.3.1 Cast metal

Being the most important factor, it's the thermal history, chemical composition etc affect the air gap formation collectively.

Pouring temperature

Davies (21) et al observed that a reduction in pouring temperature result in reduction in solidification time. (Fig. 2.4). This solidification time in turn is proportional to the heat transfer between solidifying metal and mould are observed by Ho (20) et al, Mallur Srinivasan (9), Davies (4) et al (fig2.4, table2.1)

Chemical Composition

Solidification occurs by two modes, "skin type" and "pasty type" depending upon the metal is pure (of eutectic) or alloy. Directional solidification can be achieved easily in skin type mode having smaller freezing rate or constant solidification temperature. Whereas pasty mode of solidification presents difficulties in directional solidification.

2.3.2 Casting Configuration

This factor has tremendous effect on the heat transfer coefficient. All objects casts are a combination of simple shapes- cylinder, bar, plates sphere. So studies have been concentrated to which simple shapes varies with sizes with a view to derive a formula for combination of fundamental shapes.

Casting Size

Sully (7) confirmed that the casting size has major influence over the time frame in which the changes of interface thermal properties occur. It is observed that thin section castings that freeze in a minute or less, do so with dynamic interface. A constant value of interface coefficient will not be sufficient to describe the freezing behaviour. So dynamic value of interface coefficient has to be incorporated in numeric simulation for solidification. But heavy section can be simulated with fixed value due to higher solidification time.

Casting Shape

Casting shape makes the heat wave either diverge or converge into the mould was depending upon the surface contour. IHTC will be more for divergence rather than convergence and corners provide even higher value.

According to Issac (2) et al, the time of air gap formation at the corners is less than that of middle at any given times.

Sully (7) observed that the geometry of the interface was the most important factor in determination of thermal behaviour of interface. Geometry effect would probably over ride the effect of interface heat transfer.

Srinivasan (8) also observed the higher value of heat transfer coefficient for cylindrical coatings.

2.3.3 Moulds

Mould Material

Sufficient and conclusive reports have been published regarding the mould material. They are classified as sand mould, metallic mould (and combination of these two)

The sand material can be considered as relatively insulating compared to metal.

Mould thickness

Roughly moulds are classified into two categories:-

1. Thin walled moulds
2. Massive (thick) walled moulds

1. Thin walled moulds - For thin walled moulds, Venick(1) observed that superheat has little affect on the conduction of the system. Because the ambient medium is constantly renewed and amount of heat absorbed does not change its temperature of the medium being infinite in quantity.

2. Massive moulds - In massive moulds, superheat is accumulated by the moulds so that the solidification process occurs at an elevated temperature thereby increasing the time of solidification and reducing the temperature gradient.

According to Davies (4) the traditional view on air gap formation is creation of air gap between casting and mould at a given time after solidification of the crust of the metal against the wall . It is claimed that this is caused by solidified metal contracting away from the die wall. He argues that this explanation does not seem very reasonable when considering the strength of the aluminum plate of 5 cm wide with solidified shell of 2mm thick wall be deformed and moved against the wall at a pressure less than 0.01 bar(10^3pascal).

There are 3 stages in solidification:

1. Liquid metal in contact with die casting, the heat transfer is very high.
2. Solidification metal in contact with die coating probably some reduction in heat transfer but metal is still in good contact with all unevenness in die coating.
3. The solidified shell contracts along the die and there will no longer be any intimate contact across the uneven interface, because the distance between the two given points in the solidified shell will be shorter than the corresponding distance on the die wall. The heat transfer is reduced drastically.

   The rate of heat transfer will not be influenced by pressure in phase 1 and very little extent in phase2. In phase3, a small pressure is sufficient to press solidified shell against the die wall and given point contact, but a very high pressure is necessary to prevent the solidifying shell pulling itself out of engagement with unevenness on the die wall.

2.4 *Interface Heat Transfer Characteristics*

When the liquid metal is poured into metallic mould, it starts solidifying; rate of solidification is mainly controlled by the resistance developed for heat transfer at metal/mould interface. To adopt CAD/CAM technique, by simulation, the exact nature of the conditions at the interface is to be known for the casting process where the metallic molds are used (Gravity/Pressure die casting, continuous casting, squeeze casting, etc.). Numerical simulation of casting processes is gaining importance. These simulations are used to predict the casting quality. The accuracy of prediction by simulation method depends upon reliable data based on the interface heat transfer under various casting conditions.

After the beginning of solidification of molten metal poured into metallic moulds, air gap initially forms at corners and then slowly spreads to the other parts of casting with increasing its size. Thickness of air gap is time varying and it depends on factors like thermo-physical properties of metal casting, mould material, external pressure, mould coatings, mould constraints, etc. Once the air gap forms, coefficient of heat transfer drops rapidly. Heat transfer mode of conduction changes to all three modes, and radiation is more effective at an elevated temperature, whereas conduction mode again become predominant at lower temperatures.

Heat transfer at the mould/casting is characterized by macroscopic average heat transfer coefficient 'h' given by,

$$h=q/(T2-T1)$$

Commercial castings are complex combinations of fundamental shape like sphere, cylinder, bar, plate etc. So to begin with, it is necessary to study the interface condition for three fundamental shapes. The interface conditions similarly be defined to take into account of the interface variable like air gap, mould coat, geometry, pressure, etc singularly and in combination. then experimental and analytical technique are used to assess the heat transfer coefficient under any particular set of conditions. This coefficient can be used for that particular set of casting conditions. but modeling of interface heat transfer, for simulation demands exact 'estimation of h' based on dynamic condition, so that, CAD/CAM techniques can be adopted.

SCOPE OF THE PRESENT WORK

Literature study on solidification simulation shows that one of the important parameters is mould wall thickness. The extent to which the temperature of mould wall (chill in case of chilled castings) increase, is depending on the thermal property of the mould and massiveness of the mould/chill. This has direct bearing on the physical condition existing at the interface, because the thermal effect controls distortion of the mould as well as the rate of solidification. It has been shown in literature the heat transfer coefficient has been affected by chill dimensions.

Further, most of the investigators reported in literature have used chills either completely embedded in sand or with cooling of massive chill at one end. Measurement of 'h' under such circumstances cannot be expected to hold good for solidification simulation in metallic dies, when the heating effects of metal wall will be different. Experiments were therefore conducted with external chilled face exposed to air.

The interface conditions have been reported to be sensitive to the orientation of the casting/mould interface. This parameter was also included in the study. One set of casting was made . A vertical cylindrical casting (fig 4.1) with chills of different thickness at the bottom is studied. In this case, the outer surface of the chill was exposed to atmospheric conditions. The chill, thus, could be treated as the wall of the metallic die.

Though the casting was large (125 mm dia - cylinder,), the study was restricted to solidification of first 20 mm from interface. Since in the beginning, thermal diffusivity along the chill is much larger than along mould wall, so the solidification could be treated as one dimensional.

LM6, one of the extensively used aluminum alloys was taken for study.

The experimental results viz. the time-temperature data at critical location in the chill were used to estimate the heat flux across the interface. It was felt that the 'heat flux (q)' value gave a more realistic picture of heat transfer, though the previous investigators had invariably used the interface heat transfer coefficient (h) to characterize the heat transfer phenomena at the interface.

EXPERIMENTAL SET-UP

To study the effect of chill thickness on interfacial heat transfer in sand cast LM6 alloy, one experimental set-up was used, because the effect is studied on vertical cylinder.

4.1 SET-UP:

The set-up was designed to study the effect of chill thickness of vertical cylindrical casting.

Experimental Details:

Alloy examined - Aluminium-11.8% silicon has been studied (LM6).

Chill specification - For the study, commonly used, cheap and easily machined material like cast iron is used. Chills have the following dimensions.

Chill no.	Diameter (mm)	Thickness (mm)
1	75	40
2	75	12

To measure the temperature in the chill at different depths, 2 holes of 2.5mm diameter were put on all chills as shown in fig 4.1. Two thermocouples TC1, TC2 of chromel alumel (22 gauges) were wedged in the holes - TC1 nearer to the interface (A) and TC2 away from interface (B) respectively.

Chill no.	TC1 (A)	TC2 (B)	Thickness(mm)
1	2mm	22mm	40mm
2	2 mm	10 mm	12 mm

Test pattern - A simple wooden cylindrical shape of 75mm diameter 125mm length was used for production of mould cavity. Molding - CO2 sand moulds were prepared using silica sand APS fineness number 65, containing 5% sodium silicate as binder. Circular molding box of 350 mm dia., 100 mm height were used for uniformity. In all the cases, the moulds were gassed. After molding with the chill located as shown in fig 4.1, thermocouples enclosed in a twin bored porcelain sleeve with bare tip were wedged in the provided holes on the exposed surface. Details of sand and sodium silicate are given below.

Constituent	Percent
Silica (SiO_2)	98 min
Alumina	1 max
Iron oxide	1 max
CaO + MgO	1 max
Alkali	0.5 max

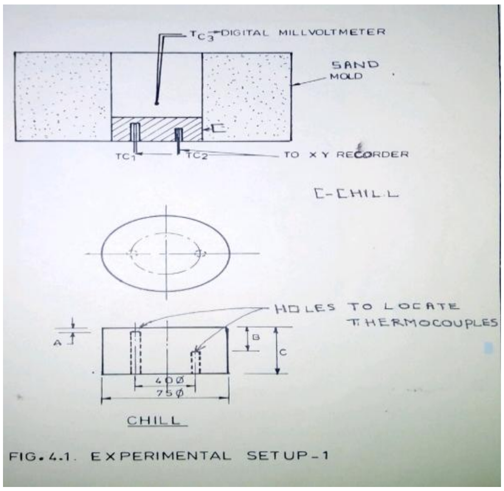

Fig 4.1 Experimental Setup

Fig 4.1B Photograph of Experimental setup

Grain shape - Mostly sub angular to rounded.

Sintering temperature - 1685-1710 C

Sodium silicate - IS: 6773-1973

Grade - II

Total soluble silica (SiO_2) 22-36%
Total alkalinity (Na_2O) 10-14%
Molar ratio NA_2O, SiO_2 1:2
Specific gravity 1.5-1.65

Temperature Measurement -

Thermocouples TC1, TC2 were wedged in chill and TC3 was put in mould cavity at 18 mm from bottom as shown in fig 4.1. TC1, TC2 are connected to two X-Y recorders and TC3 is connected to digital mill voltmeter, the voltage is then converted to temperature.

Melting and Pouring -

Alloy was melted in resistance type electric furnace. Before pouring, metal was properly degassed and pouring was done manually.

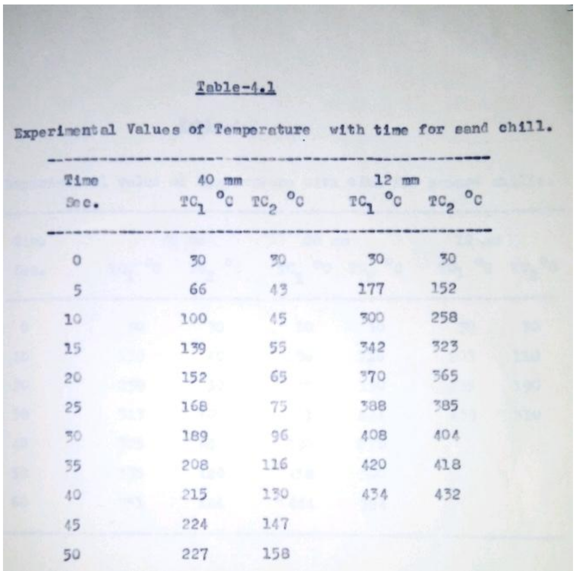

Table-4.1

Experimental Values of Temperature with time for sand chill.

Time Sec.	40 mm TC_1 °C	40 mm TC_2 °C	12 mm TC_1 °C	12 mm TC_2 °C
0	30	30	30	30
5	66	43	177	152
10	100	45	300	258
15	139	55	342	323
20	152	65	370	365
25	168	75	388	385
30	189	96	408	404
35	208	116	420	418
40	215	130	434	432
45	224	147		
50	227	158		

Using the temperature history noted by TC 1 and TC2 with time, heat flux were computed using Becks(14) algorithm. Computed values of heat flux were used to draw graphs of heat flux vs time.

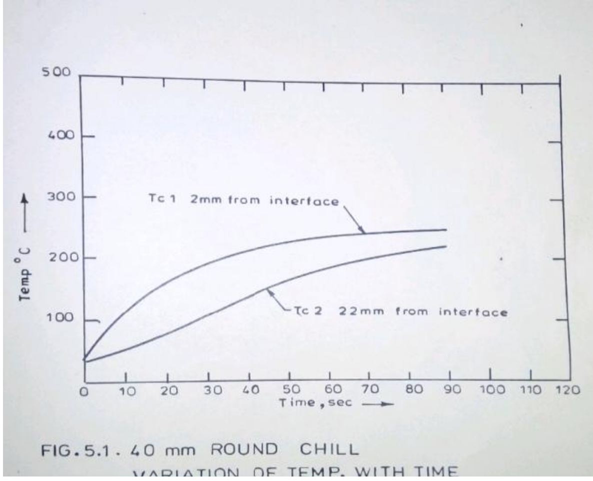

Fig 5.1 40 mm Round Chill Variation of Temp with Time

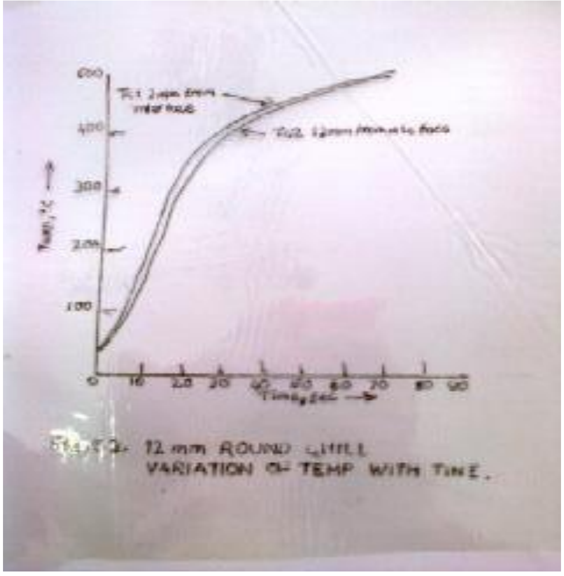

Fig 5.2 12 mm round chill variation of temp with time

RESULTS AND DISCUSSION

The observations were made in the case of round chills. The thinner chill (12mm) achieved peak heat flux (17.87 cal/cm^2 sec ◦c) at heat flux dropped at higher rate. In case of thicker chill (40mm) heat flux reached maximum value (10.92cal/cm^2 sec ◦c) after 20 seconds and dropped slowly. The higher heat flux at the initial stages in case thin chill was observed. in beginning because of its low volumetric heat capacity one chill gets heated up , the further heat extraction becomes reduced. This is reflected in the lower heat flux at the later stage. On the other hand a thicker chill heated up slowly as indicated in the graphs (fig 5.1, 5.2).

A thin chill extracts heat faster in the beginning, but at a later stage, due to the initial heating effect of the chill to higher temperature. The chilling capacity is reduced. In other words, heat flux reduces. A thicker chill however is slower in the heat extraction in the beginning resulting in the heating of the chill at lower temperature. Hence, even at later stage, the thicker chill continues to extract heat at faster rate than the thin chill. This explains why the thicker chills have high overall heat extraction rate.

The peak in the heat flux occurs, at progressively lower times, for thinner chills. The peak in the curve could be attributed to the formation of thin layer of solids, which effectively reduces the heat flux by creating an imperfect contact at the interface. Since the thinner chills, have higher heat extraction in the beginning, an air gap forms earlier during solidification.

TABLE- 5.1
Variation of heat flux with time for round chill

TIME SEC	HEAT FLUX 40mm	Cal/cm^2 sec 12mm
0	7.8	9.39
5	9.4	13.32
10	10.6	17.87
15	11.10	16.91
20	11.30	13.65
25	11.0	8.39
30	10.4	6.10
35	9.6	3.4
40	9.2	2.29

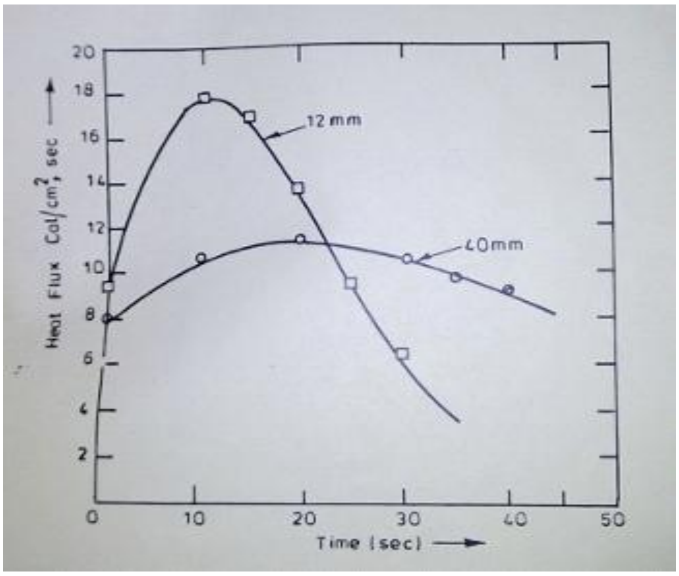

Fig 5.3 Variation of Heat flux vs. Time for round chill

CONCLUSION

Analysis of heat flux across the interface of LM6 alloy of vertical cylinder, cast against iron Chills of different thickness with external side exposed to air, indicates the following

1) The heat flux across interface depends on the thickness of the chill.
2) The initial heat flux in case of the thinner chill is more than in case of thicker chill.
3) The heat flux curve show a maximum which can be attributed to the formation of skin of solidifying metal, i.e. to the time of the air gap formation.
4) The time of the air gap formation is successively larger for the thicker chill.
5) Once the skin had formed the heat flux drops rapidly and at later stages heat flux is more in the case of thicker chills.

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