Effect of cerium addition on casting/chill interfacial heat flux and casting surface profile during solidification of Al-14%Si alloy

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Abstract. In the present investigation, Al-14 wt. % Si alloy was solidified against copper, brass and cast iron chills, to study the effect of Ce melt treatment on casting/chill interfacial heat flux transients and casting surface profile. The heat flux across the casting/chill interface was estimated using inverse modelling technique. On addition of 1.5% Ce, the peak heat flux increased by about 38%, 42% and 43% for copper, brass and cast iron chills respectively. The effect of Ce addition on casting surface texture was analyzed using a surface profilometer. The surface profile of the casting and the chill surfaces clearly indicated the formation of an air gap at the periphery of the casting. The arithmetic average value of the profile departure from the mean line (R_α) and arithmetical mean of the absolute departures of the waviness profile from the centre line (W_α) were found to decrease on Ce addition. The interfacial gap width formed for the unmodified and Ce treated casting surfaces at the periphery were found to be about 35µm and 13µm respectively. The enhancement in heat transfer on addition of Ce addition was attributed to the lowering of the surface tension of the liquid melt. The gap width at the interface was used to determine the variation of heat transfer coefficient (HTC) across the chill surface after the formation of stable solid shell. It was found that the HTC decreased along the radial direction for copper and brass chills and increased along radial direction for cast iron chills.

1. Introduction
The simulation of casting solidification is useful for determination of temperature distribution inside the casting, fraction solid, location of defects like shrinkage porosity, hot tear and also for prediction of the microstructure and mechanical properties of the casting. The accuracy and reliability of a simulation model mainly depends on the input parameters like thermo-physical properties of the mold/casting and the boundary interfacial heat transfer coefficient [1,2]. The casting/chill interfacial heat transfer is dependent on factors like alloy, super heat, latent heat of fusion and chill variables like surface roughness, chill size and thermophysical properties of the chill [3,4]. However, the influence of Ce melt treatment on interfacial heat transfer is not yet investigated.

Al-Si alloys with Si content greater than 13 wt. % are categorized as hypereutectic Al-Si alloys. Recently, Ce addition to hypereutectic Al-Si alloys has gained attention due to its ability in refining and modifying primary and eutectic silicon simultaneously [5]. In hypoeutectic Al-Si alloys (Si<12%), the coarse acicular eutectic silicon is transformed into a fine fibrous form by the addition of elements like sodium, salts of sodium and master alloys of strontium. The process is known as ‘modification’. The modification process is known to increase the mechanical and physical properties of the alloy [6].
Prabhu and Ravishankar [7] studied the effect of Na modification on Al-13%Si alloy and found that the modifying of the melt improved the heat transfer from the solidifying casting to the chill material. This was attributed to the increased ability of the liquid metal to wet the chill surface and decreased surface tension of liquid due to the addition of sodium.

The magnitude of interfacial heat transfer depends on the nature of surfaces in contact and the interfacial gap formed during solidification. The effect of varying surface roughness on interfacial heat transfer coefficient was studied by several researchers. Muojekwu et al. [8] studied the effect of chill surface roughness on Al-Si alloys and found that the heat transfer decreased marginally by increasing the roughness of the chill by 500 times. Griffiths and Kayikci [9] found that variation in interfacial heat transfer coefficient with surface roughness was negligible. They found that the sum roughness parameter \( R_z = (R_z^{chill} + R_z^{casting})^{1/2} \) remained constant for all chill surface roughnesses and the negligible variation in interfacial heat transfer coefficient was attributed to unchanged sum roughness parameter. They also reported a curvature formation on the surface of the casting. The casting surfaces were seen to deform convexly soon after pouring, indicating that the transfer of heat is preferentially at the centre of the casting where the two surfaces are in contact.

In the present investigation, the influence of Ce addition on heat transfer at the casting/chill interface was assessed during solidification of Al-14%Si alloy against copper, brass and cast iron chills. The study also aimed to measure the variation of casting surface roughness, surface profile and correlate it with the interfacial heat transfer.

![Figure 1. Schematic sketch of the solidification set up.](image)

2. Experimental

In the present investigation, heat transfer studies were carried out by using copper, brass and cast iron chills. Chills having varying thermal conductivities were selected to obtain different cooling rates. Surface roughnesses of chills before and after casting were measured using a surface profilometer (Form Talysurf Series 50mm Intra). The chill roughness before experiment was set at 0.5±0.05µm. A schematic sketch of the experimental setup is shown in Figure 1. A stainless steel tube of 50 mm outer diameter with a wall thickness of 1 mm was attached at the top of the chill. Stainless steel was selected as it has a low thermal conductivity of 16 W/mK. Two holes of 1 mm diameter and 25 mm depth were drilled into the cylindrical surface of the chill at distances of 2 mm (TC1) and 26 mm (TC2) respectively. Two mineral insulated thermocouples (K-type) were inserted into the drilled holes and
were connected to a PC through a data acquisition system (NI USB 9162). A preheated crucible containing about 400g of Al-14%Si alloy was heated to about 750°C in an electric furnace. The melt was then maintained at that temperature for about 30 minutes. The molten alloy was degassed by introducing about 5g of hexachloroethane tablet into the melt. Cerium was added to the melt in varying quantities (0.5wt. %, 1wt. %, 1.5wt. % and 2wt. %), thirty minutes prior to the start of thermal analysis experiments. The liquid metal was quickly poured into the stainless steel tube with a chill at the bottom. The thermal history at thermocouple locations was recorded using a computerized data acquisition system. The measured temperatures at TC1 and TC2 were used as input to inverse heat conduction model TmmFE Inverse solver (Thermet solutions Private Ltd, Bangalore) to determine the heat flux across the casting/chill interface and the chill.

3. Results and discussion

Figures 2 (a) and (b) show the measured temperature inside the copper chill at two locations (TC1 and TC2) without Ce and doped with 1.5% Ce respectively. TC1 and TC2 show temperature at locations 5 and 26 mm from the casting/chill interface, respectively. It is evident from the figures that the Ce addition results in increases in temperatures inside the chill. The temperatures at TC1 showed a peak value of 265 °C at about 4-5s after pouring the alloy without any Ce. With Ce addition, the peak at TC1 increased to 300°C. The chill surface temperatures and the heat flux across the chill/casting interface were estimated by solving the inverse heat conduction problem. The surface temperature of the chill at the interface corresponding to the peak temperature at TC1 for the alloy without addition was 270.4 °C. Similar temperature profiles were obtained for brass and cast iron chills during solidification. The peak surface temperature for brass and cast iron chills for solidification of alloy without Ce were found to be 388.8 °C and 445 °C respectively.

The heat flux transients estimated using the inverse solver is shown in figure 3(a). The interfacial heat flux shows a steep increase and reaches a peak value. The actual contact between chill surface asperities and the casting is an important factor that determines the rate of interfacial heat transfer. As the solidification proceeds, the interfacial heat flux decreases to a lower value due to the formation of a gap/ non-conforming contact at the interface. The peak heat flux for copper, brass and cast iron chilled alloys without Ce were found to be 6909, 4790 and 3348 kW/m² respectively. The addition of Ce to the alloy increased the heat transfer to the chill in all cases. The increase in peak heat flux with Ce addition is shown in figure 3 (b). For example, the peak heat flux during solidification of 1.5%Ce alloy against the copper chill was 9541 kW/m², showing 38 percent increase in the heat flux. The corresponding increases in peak heat flux for brass and cast iron chills were 42% and 43%, respectively.

Figure 2. Temperature-time curves at different locations from interface in the copper chill (a) without addition (b) with 1.5 wt. % of Ce.
The improvement in heat transfer due to Ce addition was mainly due to two factors: (i) improved contact between melt and the chill surfaces due to low surface tension of the melt, and (ii) higher thermal conductance of the solid shell formed due to the transformation of silicon morphology from acicular to fibrous [7]. Since the atomic radius ratio of Ce to Al alloy is greater than 15%, the solid solution of Ce in aluminum is difficult. Moreover, Ce is a surface active element which tends to get concentrated at the surface. According to the Gibbs Adsorption equation,

\[ \tau = -\frac{C}{RT} \frac{d\sigma}{dc} \]  

where, \( C \) is solute concentration, \( R \) is Boltzmann constant, \( T \) is temperature, \( \tau \) is the mass fraction of the enriched solutes per unit area on the surface of the molten metal, \( \sigma \) is the surface tension of the molten alloy. \( \tau \) is positive for a surface active element and for \( dc > 0 \), and the change in surface tension \( (d\sigma) \) becomes negative [10]. This implies that the surface active element decreases the surface tension of molten alloy.

Ce is known to simultaneously modify and refine both eutectic and primary silicon in hypereutectic Al-Si alloys [11]. Previous studies show that Si modification in Al-Si alloys improved the mechanical properties as well as the physical properties [12]. It has been reported that the addition of Ce to Al-0.3Si-Mg alloy significantly increased in the electrical conductivity of the alloy. The presence of 0.3%Ce in the alloy increased the %IACS from 52.1 to 56.3 respectively [13]. Chang et al. suggested that the Ce addition modifies the solid-liquid interfacial energy for silicon modification [14]. Yet in another study it was reported that the Ce addition decreased the surface tension of molten Mg-9Al alloy [15]. Hence, the increase in heat flux is due to the combined effect of decreased surface tension and improved conductivity of the alloy.

To analyze the influence of Ce addition on contacting surfaces, the surface roughness values (Ra) and waviness (Wa) values of castings were measured. Dimensionless parameters based on surface roughness and waviness were defined as \( \frac{Ra_{\text{casting}}}{Ra_{\text{chill}}} \) and \( \frac{Wa_{\text{casting}}}{Wa_{\text{chill}}} \) respectively. The variation of these dimensionless parameters with Ce addition is shown in figure 4(a) and 4(b). The results indicate that the roughness ratio \( \frac{Ra_{\text{casting}}}{Ra_{\text{chill}}} \) decreased with Ce addition for casting solidified against copper and brass chills and it increased with Ce additions for castings solidified against the cast iron chill. The waviness ratio \( \frac{Wa_{\text{casting}}}{Wa_{\text{chill}}} \) remained more or less constant for copper and brass chilled castings, but it increased significantly for alloys solidified on cast iron. The surfaces of cast iron chilled castings showed higher waviness (Wa) values up to 38 \( \mu \)m for 1.5 wt. % Ce compared with copper and brass chills. Due to the lower thermal conductivity of the cast iron chill, during solidification of Ce added alloys the surface temperature attained at the casting/chill interface...
was well above the eutectic temperature. For example, the surface temperature of the cast iron chill was found to be 590 °C for 1.5 wt. % Ce additions. The exposure of the casting surface to such a high temperature would have resulted in re-melting of the solid shell formed, thus affecting the casting surface roughness and profile.

Figure 4. Effect of varying cerium content on (a) roughness factor (b) waviness factor.

Figure 5. (a) Selected surface profiles across the chill and casting for different chill solidification (b) Schematic sketch of the gap width measurement using waviness of casting and chill surfaces.

The waviness profiles taken across the casting surfaces showed a curvature and were found to vary significantly with chill material. The profile was convex towards copper and brass chill, whereas, the profile was concave towards cast iron chill. The examples of these profiles are shown in figure 5(a). The waviness profile of copper and brass chills indicates that the heat transfer would have occurred at the centre of the profile interface. The gap between the casting and the chill increased in the radial direction. Assuming that the heat transfer across the casting/chill interface would be maximum at central contact point and the gap formed in the radial direction will be filled by atmospheric air, the gap width across the radial direction was determined. Figure 5(b) shows a schematic sketch showing the measurement of gap width using surface profiles for copper and brass castings. Since the cast iron castings are concave towards the chill, it is probable that casting and chill are in perfect contact in circumferential region and a gas gap was formed at the centre.

The gap width data was used to determine the heat transfer coefficient (HTC) using the equation

$$h = \frac{k_a}{\delta}$$

where, $k_a$ is the thermal conductivity of the air at the casting/chill interface, $\delta$ is the gap width at the chill and casting interface. Figure 6 shows the spatial distribution of heat transfer coefficient estimated by measuring the gap width along the radial direction. The results show that for copper and brass
chilled castings the HTC values decrease with increase in radial distance from the centre due to the increase in gap width.

![Figure 6](image_url)

**Figure 6.** Spatially dependent heat transfer coefficient values along the radial direction for (a) copper (b) brass (c) cast iron.

The HTC increased in radial distance from centre for cast iron chilled castings. The minimum HTC was at the centre of the contacting surfaces. The Ce added alloys showed higher HTC values than the alloys without any addition. For casting surfaces solidified on the copper chill, the widths of the gap at the circumference region for alloys without Ce and with 1.0 wt. % Ce were found to be 35 µm and 13 µm respectively. On Ce treatment the gap width was reduced by about 62%. The reduction in the gap width between casting and chill surfaces results in the increase in heat flux across the interface. The casting solidified against the cast iron chill also showed an increase in the spatially dependent HTC with Ce addition. This was due to the improved contact of the chill and casting surfaces in the circumferential region.

### 4. Conclusions
- The melt treatment of Al-14%Si alloy using Ce resulted in higher interfacial heat flux for all chilling conditions. On 1.5% Ce addition, the peak heat flux increased by 38%, 42% and 43% for solidification against copper, brass and cast iron chills, respectively.
- The surface profile analysis revealed that the Ce addition resulted in smoother casting surfaces in the case of copper and brass chills and a rougher surface in the case of the cast iron chilled alloys. Dimensionless ratios for roughness \( \frac{R_{acasting}}{R_{achill}} \) and waviness \( \frac{W_{acasting}}{W_{achill}} \) decreased with Ce addition for copper and brass chills and increased with cast iron chilled alloys.
- The casting surface profile was convex towards the copper and brass chill surfaces and concave towards the cast iron chill surface. The opposite trend observed in cast iron chilled alloys was due to the formation of rough surface caused by re-melting of the solidified shell formed.
The spatially dependent gap width was measured and was used to calculate the HTC along the radial direction. The HTC values were found to be lower in the circumferential region and higher at the centre for copper and brass chills. An opposite trend was observed in the cast iron chills with HTC at the centre. The spatially dependent HTC increased with Ce addition for all castings due to the reduction in the gap formed between the contacting surfaces.

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