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Heat Transfer During Quenching of Modified and Unmodified Gravity Die-Cast A357 Cylindrical Bars

K.N. Prabhu and P. Hemanna

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Heat transfer during quenching of chill-cast modified and unmodified A357 Al-Si alloy was examined using a computer-aided cooling curve analysis. Water at 60 °C and a vegetable oil (palm oil) were used as quench media. The measured temperatures inside cylindrical probes of the A357 alloy were used as inputs in an inverse heat-conduction model to estimate heat flux transients at the probe/quenchant interface and the surface temperature of the probe in contact with the quench medium. It was observed that modified alloy probes yielded higher cooling rates and heat flux transients. The investigation clearly showed that the heat transfer during quenching depends on the casting history. The increase in the cooling rate and peak heat flux was attributed to the increase in the thermal conductivity of the material on modification melt treatment owing to the change in silicon morphology. Fine and fibrous silicon particles in modified A357 probes increase the conductance of the probe resulting in higher heat transfer rates. This was confirmed by measuring the electrical conductivity of modified samples, which were found to be higher than those of unmodified samples. The ultrasound velocity in the probes decreased on modification.

Keywords electrical conductivity, heat treatment, microstructure, thermal conductivity

1. Introduction

Al-Si-Mg alloy (A357) is one of the most commonly used aluminium alloys, mainly due to its good castability and excellent mechanical properties in the heat-treated condition. The alloy is used extensively in the automobile, aircraft, and defense industries (Ref 1, 2). Mechanical properties like ductility and fracture toughness of the A357 alloy cast component can be significantly enhanced by subjecting the component to T6 heat treatment.

T6 heat treatment involves solution heat treatment, quenching, and age hardening. Quenching is the most critical step in the sequence of heat-treating operations. The highest strengths attainable and the best combinations of strength and toughness are associated with the most rapid quenching rates. Resistances to corrosion and to stress corrosion cracking are other characteristics that are generally improved by maximum rapidity of quenching (Ref 3). The objective of quenching of aluminium alloys is to preserve the solid solution formed at the solution heat-treating temperature, by rapidly cooling through the range of 290-400 °C. The cooling rate varies throughout the quenching process and depends upon the various heat transfer regimes that occur during the quenching process. To avoid the detrimental effects of thermal stresses, aluminum alloy parts of complex shape are commonly quenched in a medium that provides a somewhat slower rate of cooling. This medium may be water at 65-80 °C, boiling water, an aqueous solution of poly alkaline glycol, or some other fluid medium, such as forced air or mist (Ref 4).

K.N. Prabhu and **P. Hemanna**, Department of Metallurgical and Materials Engineering, National Institute of Technology Karnataka, Surathkal, Srinivasnagar 575 025, India. Contact e-mail: prabhu@nitk.ac.in.

Knowledge of the casting/quenchant interfacial heat flow rate and its variation with temperature at the interface is very useful in modeling of the quenching process (Ref 5). The heat flux transients at the metal/quenchant interface are useful in accurately predicting the temperature distribution and the cooling rates inside the part being quenched. The simulation based quench process design would enable the heat treater to judiciously select the quench medium for a specific application. The heat transfer during quenching depends mainly upon the thermophysical properties of the material of the part being quenched, severity of quenching, surface roughness of the part, and agitation of the medium.

Prabhu and Ravishankar (Ref 6) observed during solidification of Al-12%Si alloy that the silicon morphology of the initial solidified shell significantly affects the heat flow from the solidifying casting to the mold. Under normal cooling conditions, Si particles are present as coarse acicular needles. The needles act as crack initiators and lower mechanical properties appreciably. Consequently, small amounts of Na or Sr are added to the melt to chemically modify the morphology of Si particles. The Si particle characteristics can also be altered by subjecting the casting to high-temperature treatment for long periods. Both chemical and thermal modifications are being used in conjunction to produce the desired properties of the casting (Ref 7). The effect of Si morphology of the part being quenched on heat transfer is not yet investigated.

In the present work, the effect of modification on quench heat treatment of gravity die-cast A357 alloy is investigated. It was observed that for permanent mold castings of a modified

Table 1 Chemical composition of the alloy (wt.%)

Si	Mg	Fe	Zn	Ti	Al
6.86	0.53	0.12	0.03	0.14	Balance

A356 alloy, a shorter solution treatment time is sufficient to attain at least 90% of the maximum tensile properties (Ref 8, 9). Water at 60 °C and an environmentally friendly vegetable oil (palm oil) were selected as quench media. Palm oil has a lower iodine number and a better oxidative stability compared with other vegetable oils. The aim is to study the effect of morphology of eutectic silicon in the microstructure of the cast alloy undergoing heat treatment on the cooling rate parameters and heat flux transients at the metal/quenchant interface during quenching operations.

2. Experimental Procedures

About 750 g of the alloy was melted in a resistance-heating furnace using a graphite crucible. The chemical composition of the alloy is given in Table 1. The melt was degassed at about 700 °C using hexachloroethane degassing tablets. After degassing, a predetermined quantity of elemental sodium was added to the molten alloy at 720 °C and the melt was held for about 4-5 min for effective modification. The melt was then poured into a cylindrical copper mold of 50 mm diameter and 120 mm height. Castings were also made without subjecting them to modification melt treatment. Aluminium alloy specimen probes having dimensions 36 mm in diameter and 72 mm in height were prepared from casting sections. The probes were equipped with K-type thermocouples. One thermocouple is located at the geometric center of the probe, and the other is introduced at 2 mm from the outer surface of the probe. The experimental set-up consists of a vertical tubular electric resistance furnace open at both ends. A beaker containing 2 L of quenchant was placed directly underneath the furnace so that the heated probe could be transferred quickly to the quenching medium. The thermocouples were connected to a PC-based data logging system to record the cooling behavior of the probe during quenching.

Figure 1 shows the schematic sketch of the quenching set-up used for lateral quenching. Before quenching, aluminium alloy probes were soaked for 20 min at 540 °C in an electric resistance furnace. The temperature of probes was monitored during solution treatment. After each solution treatment, the samples were quenched in either water at 60 °C or palm oil. The quenched samples were then immediately aged in a resistance furnace at 170 °C for 4 h. After aging, specimens were prepared from heat treated samples for microstructure studies. Keller's reagent was used as the etchant. The microstructures of unmodified and modified samples were examined under a Leica DMILM (Leica Microsystems GmbH, Wetzlar, Germany) inverted microscope to determine the extent of coarsening of eutectic silicon particles. An eddy current-based Technofour 979 digital electrical conductivity meter and Karl Deutsch Echometer were used for measurement of electrical conductivity and ultrasound velocity respectively in unmodified and modified probes.

3. Results and Discussion

Figure 2 shows the typical thermal history at thermocouple locations TC1, TC2, and TC3 during immersion quenching of A357 alloy probes. Table 2 gives the thermal analysis parameters measured during quenching in water and palm oil. The peak cooling rates quenched samples during quenching were found to be influenced by the sample history. The cooling rates of chemically modified specimens were higher compared with unmodified specimens. The effect was significant at locations close to the interface. The peak cooling rate of the probe during quenching increased from 29 to 110 °C/s on modification. For the palm oil quench medium the cooling rate increased from 15 to 30 °C/s.

The measured temperature data was used as an input to an inverse analysis for estimating the heat flux at the metal/quenchant interface. The method considers the effect of temporal variation of the heat flux on the temperature distribution inside the metal part being quenched. The mathematical details of the inverse analysis are given in Ref 10. Figures 3 and 4 show the effect of modification melt treatment on heat flux transients and the probe surface temperature, respectively, during quenching in hot water. Figures 5 and 6 show the effect of modification during quenching in palm oil. A peak heat flux of

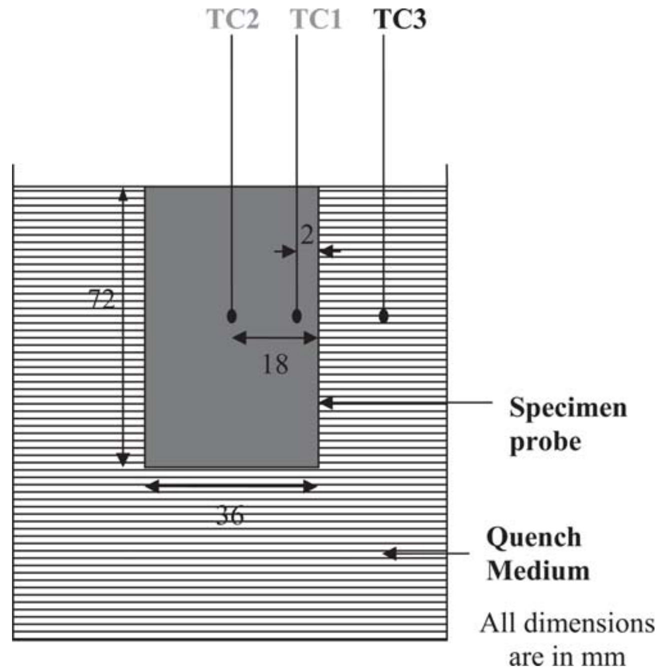

Fig. 1 Schematic sketch of the experimental set-up

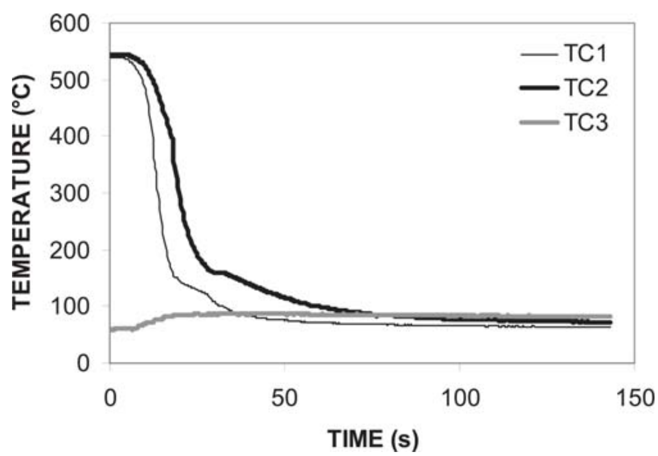

Fig. 2 Typical temperature-versus-time curve quenching

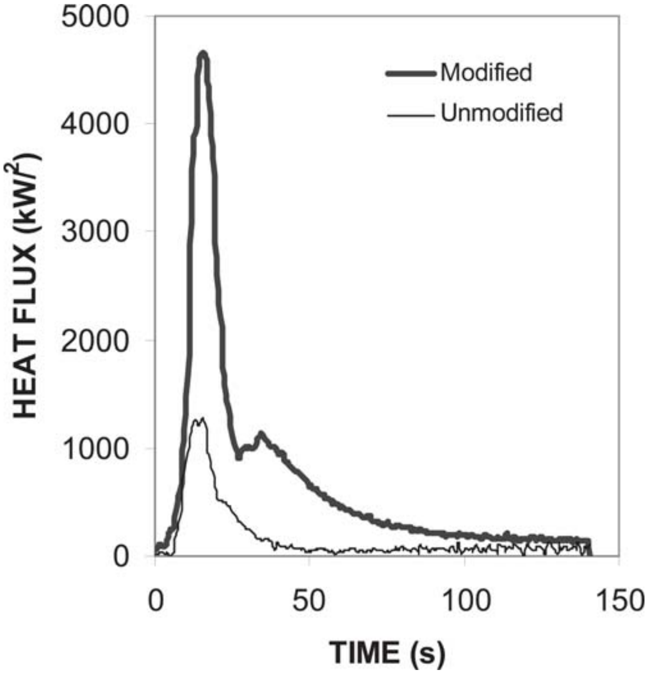

Fig. 3 Effect of modification melt treatment on the estimated heat flux transients during quenching in hot water

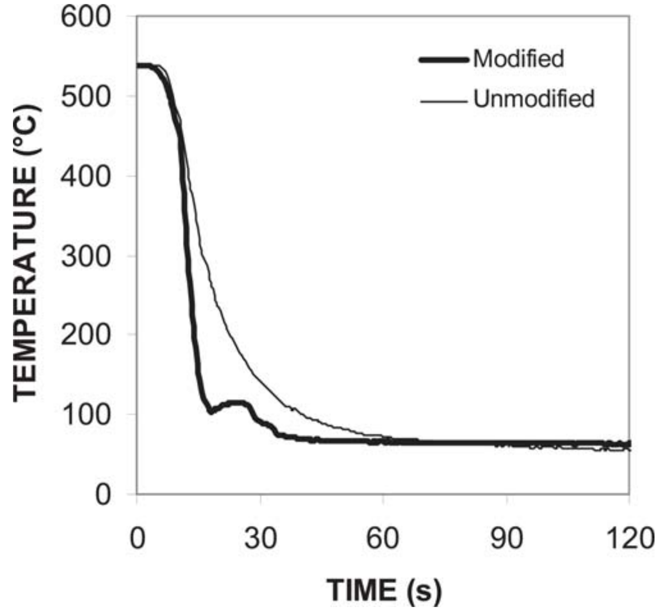

Fig. 4 Effect of modification melt treatment on surface temperature of the probe in contact with hot water quench medium

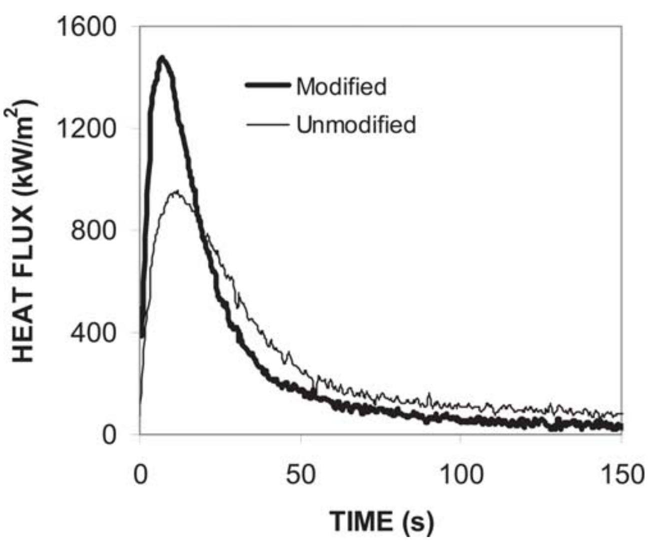

Fig. 5 Effect of modification melt treatment on the estimated heat flux transients during quenching in palm oil

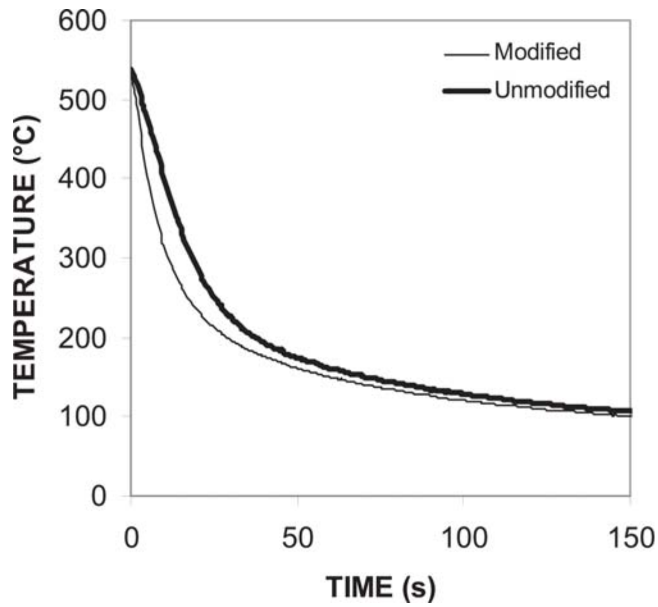

Fig. 6 Effect of modification melt treatment on surface temperature of the probe in contact with the palm oil quench medium

Table 2 Thermal analysis parameters determined from computer-aided cooling curve analysis

	Water at 60 °C		Palm oil	
Thermal analysis parameters	**Modified**	**Unmodified**	**Modified**	**Unmodified**
Peak cooling rate, °C/s	110	29	30	15
Temperature at peak cooling rate, °C	377	415	500	479
Cooling rate at 450 °C, °C/s	47	27	16.6	17
Cooling rate at 200 °C, °C/s	30	10	3.33	3
Time to reach 450 °C, s	11.1	12	6.6	7.8
Time to reach 200 °C, s	16.2	23.7	31.5	39.6
Leidenfrost temperature, °C	537	537	535	539

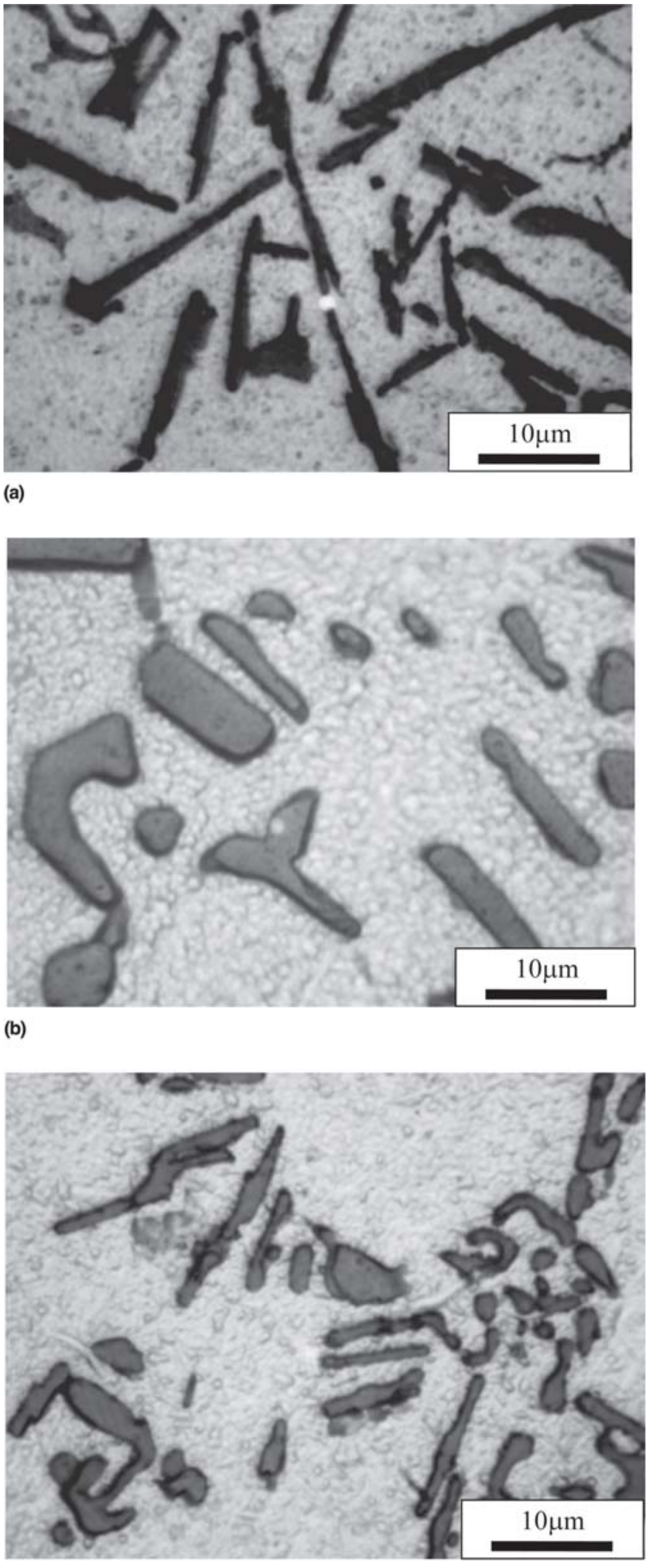

Fig. 7 Microstructures of unmodified samples: (a) as cast, (b) after quenching in water at 60 °C and aging, and (c) after quenching in palm oil and aging

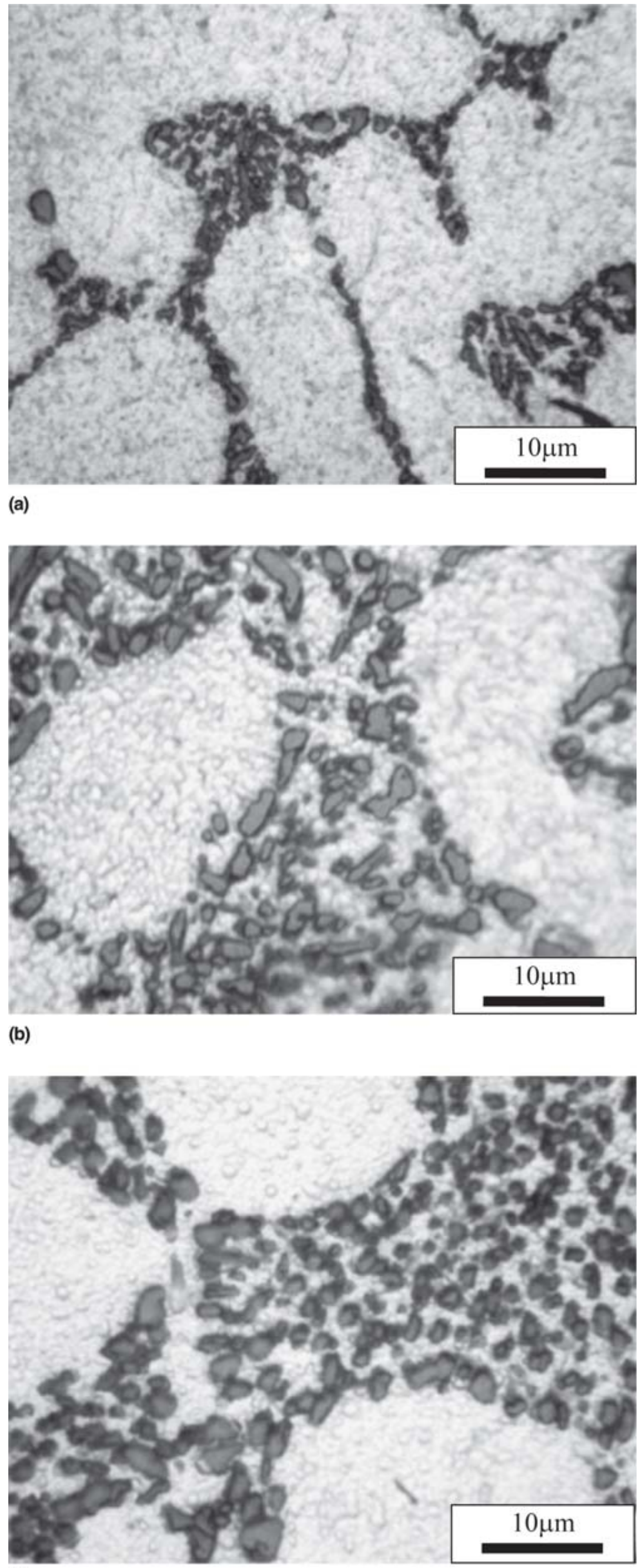

Fig. 8 Microstructures of modified samples: (a) as cast, (b) after quenching in water at 60 °C and aging, and (c) after quenching in palm oil and aging

4666 kW/m^2 was obtained when the chemically modified probe was quenched in water. The corresponding heat flux for the unmodified probe was substantially lower at about 1287 kW/m^2. During quenching in palm oil, a peak heat flux of 1475 kW/m^2 was obtained for the modified probe. The peak flux for the unmodified probe was only 959 kW/m^2. The results are significant from the point of simulation of quench heat treatment of Al-Si alloy castings as heat-transfer boundary conditions depend not only on quenching parameters but also on modification melt treatment of the alloy. Acicular eutectic silicon morphology in unmodified probes scatters electrons and reduces the thermal conductivity of the probe. The reduction in the thermal conductance of unmodified probes results in lower heat-transfer rates. The temperature of the quench medium increased significantly, particularly during quenching in vegetable oil. For the water quench medium, the temperature increased from 60 to 85 °C during cooling of the probe from 540 to 100 °C. However, for the oil quench medium, the temperature increased significantly from 30 to 145 °C during cooling of the probe for the same temperature drop, showing an increase in temperature by about 400%. This is due to the lower specific heat of vegetable oil (1.67 kJ/kg K) compared with water (4.19 kJ/kg K).

Figure 7(a) shows the microstructure of the unmodified A357 alloy in the as-cast condition. The effects of quenching with water and palm oil and aging on microstructure are shown in Fig. 7(b) and (c), respectively. Figure 8(a) shows the microstructure of the modified A357 alloy in the as-cast condition. The effect of heat treatment on the microstructure of the modified alloy is shown in Fig. 8(b) when water was used as the quench medium. The corresponding microstructure for palm oil quench medium is shown in Fig. 8(c). In the as-cast copper-chilled unmodified samples, silicon particles were present as coarse acicular needles. The silicon morphology changes after solution treatment. In the as-cast structure, acicular silicon flakes are seen as clusters. After heat treatment, they are found to be dispersed. The interparticle spacing increased from 4 to 6 μm and from 3 to 5 μm when quenching was carried with water and palm oil, respectively. Modified samples showed fine fibrous silicon particles. After aging, samples revealed spheroidized eutectic silicon crystals in the matrix of aluminum. The spheroidization was found to be almost was identical in modified samples irrespective of the quench medium.

The electrical conductivity of modified samples (36.8% IACS) was higher than that of unmodified samples (33.6% IACS). In the unmodified alloys, acicular silicon eutectic hinders the flow of electrons. The melt treatment transforms the acicular silicon morphology into fine fibrous nature reducing the resistance to the flow of electrons. For similar reasons, the ultrasound velocity measured in unmodified alloy is higher compared with that in modified state. For the same thickness of the sample, the time-of-flight decreases due to early reflection of ultrasound waves by acicular silicon particles present in unmodified samples. This results in the increase in ultrasound velocity. The ultrasound velocities in modified and unmodified samples were found to be 6375 and 6455 m/s, respectively.

4. Conclusions

Chemically modified quench probes always yielded higher cooling rates compared with unmodified probes. The increase in cooling rate of the chemically modified A357 alloy probe was attributed to the fibrous nature of eutectic silicon in the modified alloy resulting in the increase in the thermal conductivity of the probe. The electrical conductivities of modified samples were higher than those of unmodified samples. The ultrasound velocity in modified quench probes was lower compared with unmodified probes.

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