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Studies on the Thermal Properties of Hypereutectic Al–Si Alloys by Using Transient Method

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Abstract

The main aim of the paper is to describe the rapid transient method for the determination of thermal properties like thermal diffusivity and thermal conductivity of hypereutectic Al–Si alloys such as Al-13, 14, 15, 17 and 20 Si alloys. The present transient method is based on the application of constant heat flux to the top surface of cylindrical Al-Si specimen that is insulated on all other surfaces. It is observed from the present study that, increase in the percentage of silicon content results in reduction in the values of thermal properties of hypereutectic Al-Si alloys.

Keywords: *Hypereutectic Al-Si alloys, Transient method, Thermal conductivity, Thermal diffusivity.*

Introduction

Aluminium is considered as a kind of metal for sustainable development because of its advantages such as light weight, excellent physical and mechanical characteristics. Among the aluminium alloys, hyper eutectic Al-Si alloys are most widely used in aerospace and transportation due to their excellent mechanical and casting properties. Al-Si alloys that contain more than 12wt % silicon are known as hypereutectic alloys normally consisting of the primary silicon phase in the eutectic matrix. More attention are paid to the hypereutectic Al-Si alloys than conventional materials for automotive applications and piston production because of their attractive combination of low coefficient of thermal expansion, high elastic modulus, high wear resistance, lower density , higher thermal stability, corrosion resistance, good thermal conductivity and Machinability.

The more comprehensive data base can be generated with a more rapid method of measuring thermal properties. The data base of thermal properties of hypereutectic Al-Si alloys can be used to predict the tribological behaviour, Machinability and mechanical properties. Thermal properties of hypereutectic Al-Si alloys can be described by three physical quantities; thermal conductivity (K), thermal diffusivity (α) and specific heat (C). The three quantities are related by the equation.

$$K=\rho\, C\, \alpha \qquad (1)$$

Where, ρ is the density.

The present study aims at describing a transient method of measuring thermal diffusivity and thermal conductivity of hyper-eutectic Al-Si alloys.

Theory

The measurement method involves the application of constant heat flux at the top surface of specimen, which is insulated all around. This ensures 1-D heat conduction through the specimen. The temperature is measured at the base of the specimen, at various times after introduction of the constant heat flux as shown in Fig. 1.

The theory of thermal conduction describing 1-D heat conduction is given by Carslaw and Jaegar (1959, p.112).They consider a slab that is initially at zero temperature, which is insulated all around and has a constant heat flux at top surface. They showed that temperature at a distance x within the specimen and at time t (after the introduction of constant heat flux at x = a) is given by

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (2)$$

The analytical solution to the above governing equation is given by

$$T(x,t) = \frac{F\alpha t}{aK} + \frac{Fa}{K}\left\{\frac{3x^2 - a^2}{6a^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}e^{-\alpha n^2\pi^2 t/a^2}\cos\frac{n\pi x}{a}\right\} \qquad (3)$$

Where α is thermal diffusivity, k is thermal conductivity, and 'a' is the thickness of the slab. If measurement is made at the base of the slab (x = 0), the expression for temperature becomes

$$T(a,t) = F\alpha\, t / aK - Fa / 6K + transient \quad terms \qquad (4)$$

For times large relative to α Π /a, the transient terms are negligible, and the temperature versus time behaviour becomes linear, the intercept t_i on the T=0 axis is;

$$t_i = a^2/6\alpha \qquad (5)$$

Equation 5 can be used to find the thermal diffusivity directly from a series of temperature versus time measurements.

Experimental Method

The proposed experimental method is based on the theory described, and entails a small circular specimens of hyper eutectic Al-Si alloy with constant heat flux at its top surface and other faces thermally insulated as shown in the fig. 2.Temperature is measured at the center of its base, and a 1-D heat flow is assumed.

Sample

A circular rod of approximately Φ10mm x 50mm in vertical dimension is machined from the cast specimens of size Φ12.5mm x 110mm and is lightly polished to achieve flat surfaces. The surfaces other than the top are thermally insulated with low thermal conductivity material (wooden block with Glass wool insulation around the specimen).

Heat Source

Constant heat flux is achieved by using a coiled wire element through which a constant current is passed. Once a constant current is flowing, the wire will radiate with near constant heat flux.

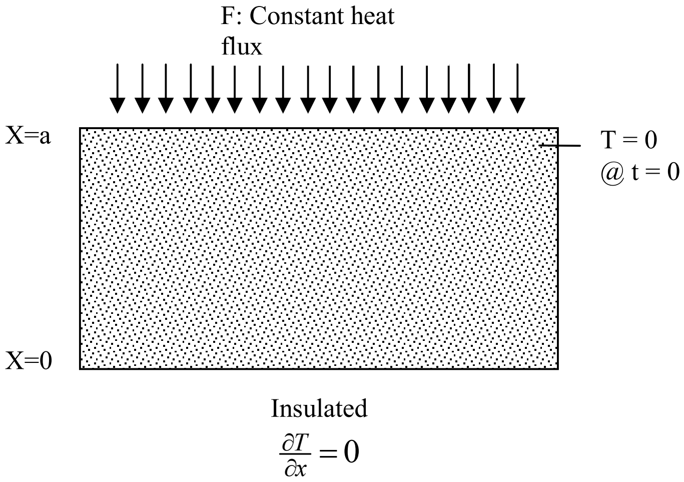


Fig. 1. Constant heat flux 'F' at the top surface of the specimen with base insulated.

The current can be adjusted so as to cause the wire to emit heat without glowing, if required. The heat source (wire coil) is placed about 10mm above the top surface of the sample.

The effect of placing the heating coil just above the surface of the specimen is thermally equivalent to an "oven effect", and a constant heat flux boundary condition is approximately realized. The other advantage of the configuration is that problems of thermal contact resistance are avoided at the top surface, and thus also the necessity to provide a finely polished surface.

Temperature Measurement

The temperature of the specimen is measured using K-type thermocouple having a needle probe of 1.5mm diameter centred at the base of the specimen. The thermocouple has a time constant of 0.2 secs, which means that the true temperature is approximated to about 99.3 percent in one second. Maximum measurement rates are in the order of 1^0C in 10 seconds and the temperature measurement is fairly accurate and the error is typically 1 percent.

The major source of error is the base contact between the sample of hypereutectic Al-Si specimen, the needle probe, and the insulation. A thin leaf of copper foil is placed above the insulation layer to improve the thermal contact and to produce a uniform base temperature. In effect, the copper foil, which is a much better thermal conductor than the sample or insulation, will distribute the base temperature around the temperature probe almost instantaneously.

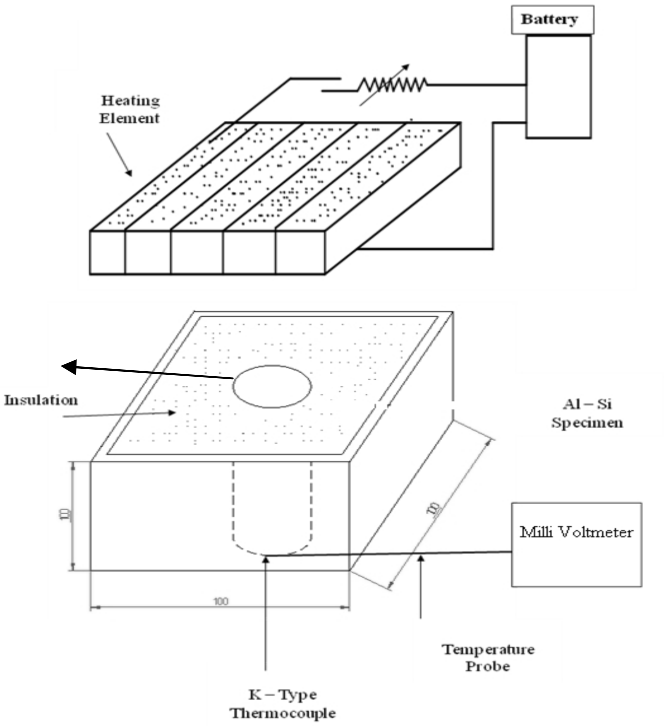


Fig. 2. Schematic of Experimental set up for the measurements of thermal diffusivity.

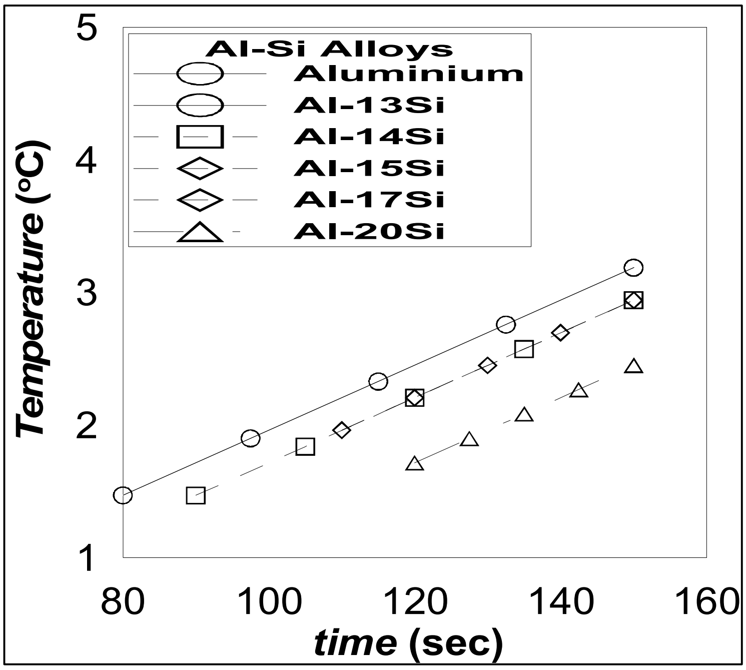


Fig.3. Temperature versus time for pure aluminium (CPAL) and hyper eutectic Al-Si alloys.

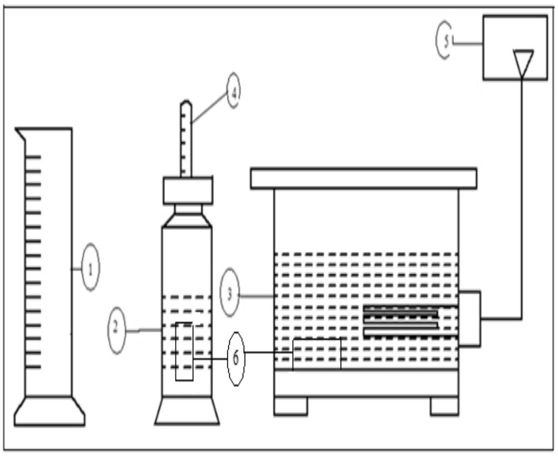
Experimental Procedure

The experiment is carried out by rapidly exposing the top surface of the specimen to the heat source. Temperature is measured at the base of the specimen for a time period of 150 sec, which is sufficient to obtain the linear behaviour. The measured temperatures are reduced by subtracting the initial ambient temperature, effectively making the measurements relative to zero initial temperature. This reduced temperature is plotted against time, and the linear segment and intercept time t_i are then identified from Fig 3. The thermal diffusivity is determined from the intercept t_i by rearranging equation (5)

$$\alpha = a^2/6t_i \qquad (6)$$

Specific heat measurement procedure

The specific heat of a substance is defined as the amount of heat that enters or leaves a unit mass of the substance when it experiences 1°C change in temperature. Specific heat of a substance is a function of temperature. For solids and liquids, value of specific heat varies with temperature and does not differ much for different processes.



1. Measuring flask 2. Thermo flask
3. Heater coil arrangement 4. Thermo meter
5. Power supply 6. Specimen

Fig.4.Schematic layout of experimental set up for the measurements of specific heat.

Figure 4 shows the experimental arrangement for determining specific heat of hyper eutectic Al-Si alloys. 100 ml of water is taken into a thermo flask, the temperature of water is recorded and it is termed as T_{w1}. The specimen is dipped in a hot water bath, and the temperature of specimen is noted down after steady state is achieved and is termed as T_{s1}. The specimen is now dipped into the thermo-flask. The temperature of water and specimen is noted down after attaining the steady state condition and is termed as T_{w2} and T_{s2} respectively.

$$m_w C_{pw} \left(T_{w2} - T_{w1}\right) = m_s C_{ps} \left(T_{s1} - T_{s2}\right) \qquad (7)$$

Where,

m_w– Mass of water ; m_s – Mass of specimen
C_{pw} – Specific heat of water (4.178 J/kg K)
C_{ps} – Specific heat of specimen
T_{w1} – Initial temperature of water
T_{s1} – Initial temperature of specimen
T_{w2} – Final temperature of water
T_{s2} – Final temperature of specimen

Thermal Conductivity Estimation

"A thermal conductivity is the amount of heat conducted per unit time across unit area and through unit thickness, when a temperature difference of 1 degree is maintained across the bounding surface."

The magnitude of thermal conductivity tells us how well a material transports energy by conduction. The thermal conductivity of a material is essentially depends on the material structure (chemical composition, physical state and texture), moisture content and density of the material and the operating conditions, pressure and temperature. The thermal conductivity is always higher in the purest form of

Metal. The alloying of metals and presence of other impurities cause an appreciable decrease in thermal conductivity. The thermal conductivity is essentially a coefficient of static heat transfer. By the calculated values of thermal diffusivity and specific heat thermal conductivity is estimated by equitation 1.

Results and Discussion:

Table 1 Thermal Properties of Al-Si alloys

Specimen	**Specific heat J/Kg.k**	**Thermal diffusivity m^2/sec**	**Thermal conductivity W/m.k**
ALUMINIUM(CPAL)	933.35	75.83×10^{-6}	187.5
Al-13Si	920	69.7×10^{-6}	173.8
Al-14Si	897.63	68.9×10^{-6}	158.9
Al-15Si	885.83	66.83×10^{-6}	158.2
Al-17Si	874.58	65.39×10^{-6}	157.2
Al-20Si	832.16	63.33×10^{-6}	143.5

The values of thermal properties of as cast alloys are depicted in table 1.

Table 1 and Fig. 5 show the variation of specific heat with various percentage of Silicon in Aluminium. It is observed that specific heat decreases with increase in percentage of silicon in Aluminium, it may be due to increase in the concentration of silicon ions,it is known that specific heat of silicon (710 J/kg K) is much lower than that of Aluminium (933 J/kg K) hence increase in percentage of silicon leads to decrease in specific heat. It may also due to induced porosity.

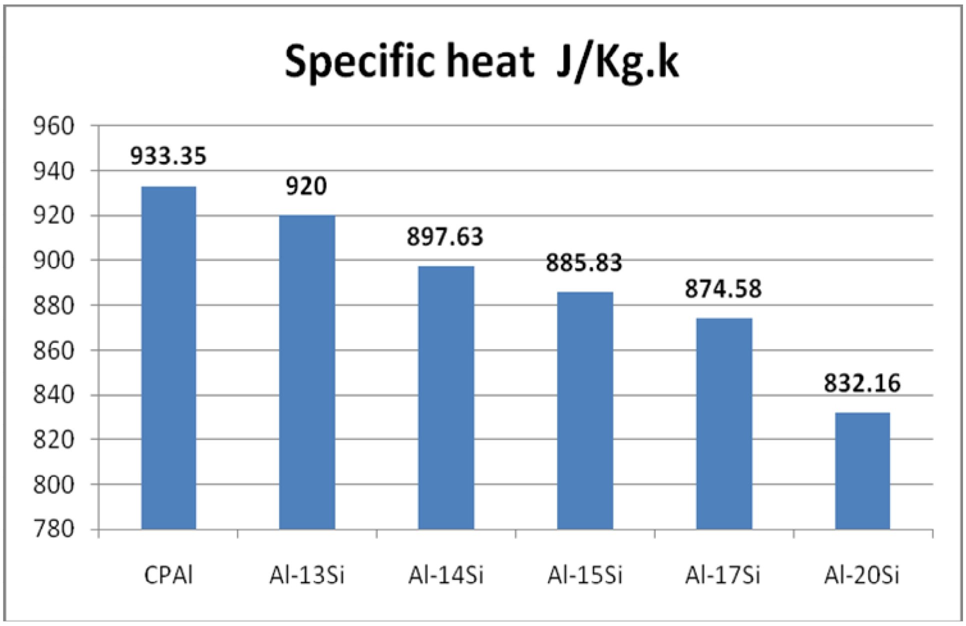


Fig. 5 Variation of Specific heat for varying Alloy Composition.

Table 1 and Fig. 6 & 7 shows the results obtained for the variation of thermal diffusivity and thermal conductivity with various percentage of Silicon in Aluminium. It is observed that the thermal diffusivity and thermal conductivity of hyper-eutectic Al-Si alloys decreases with increase in the percentage of silicon. It is known that thermal conductivity and thermal diffusivity of silicon are 149 W/m.k and 88×10^{-6} m^2/sec respectively and these values are much lower than that of aluminium 237 W/m.k and 97 m^2/sec. Hence increase in percentage of silicon leads to decrease in thermal diffusivity and thermal conductivity. It may also due to induced porosity.

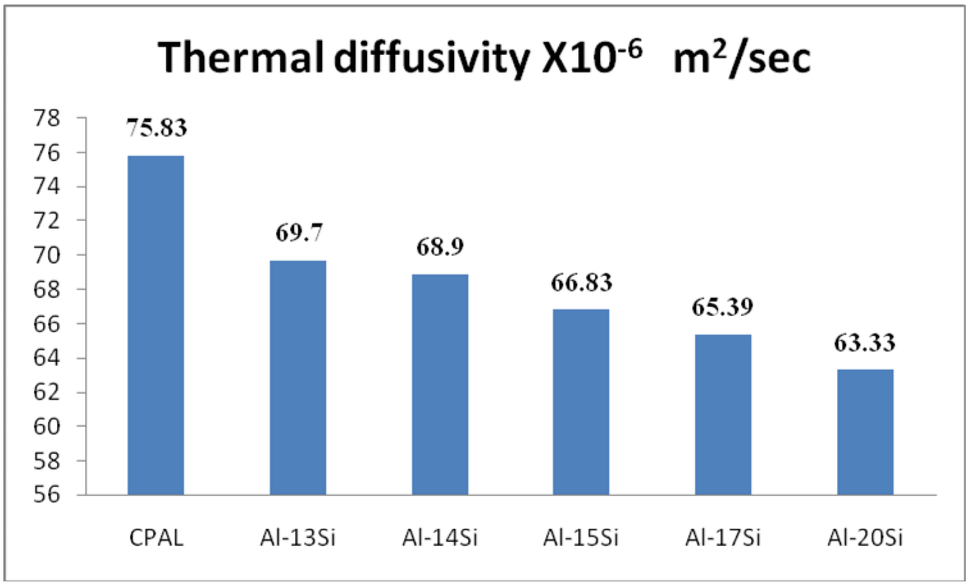


Fig. 6 Variation of Thermal Diffusivity for varying Alloy Composition.

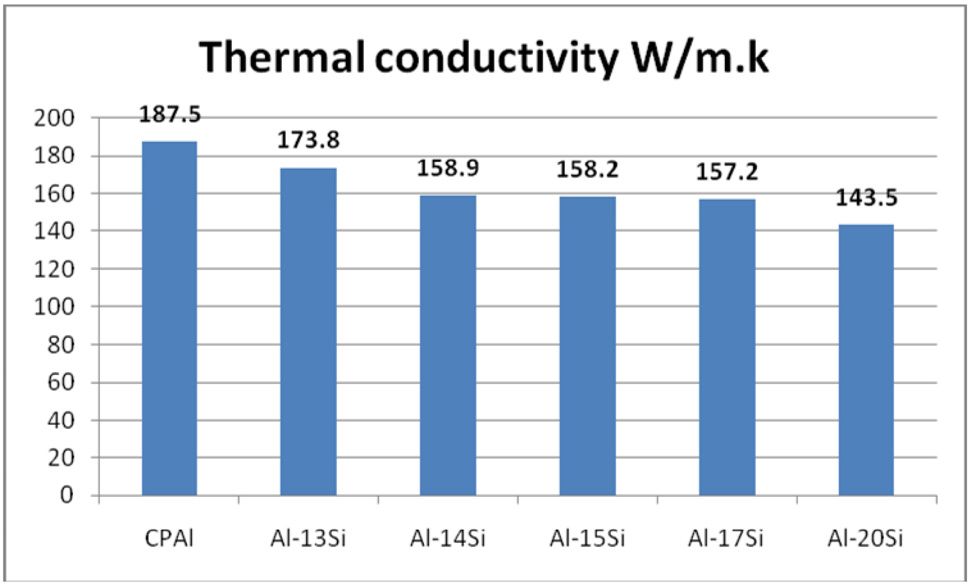


Fig. 7 Variation of Thermal conductivity for varying Alloy Composition.

Conclusion.

Transient method of determining Thermal properties is discussed in the present study. The following are the conclusions that can be drawn from the results obtained.

1. The transient method of determining the thermal properties can be applied to alloys, composites, monolithic metals and non metals.
2. It is observed in the present study that, increase in percentage of silicon in Aluminium leads to decrease in the value of thermal properties like thermal diffusivity, thermal conductivity and specific heat. This could be due to that values of thermal diffusivity, thermal conductivity and specific heat of silicon are much lower than that of Aluminium.
3. The method adopted is cost effective, and best suited for determining the thermal properties.

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