Thermal Properties of Lead and Graphite Dispersed Rheocast Aluminium-Silicon Alloys by Laser Flash Technique

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Aluminium-Silicon alloys have high wear resistance and are being used for bearings and pistons. Lead and graphite have been introduced into these alloys in the present work through the rheocasting technique and thermal properties of these alloys have been measured. Microstructural details of the rheocast alloys have also been incorporated. It has been demonstrated that the thermal conductivity and specific heat of rheocast Al-Si alloys increase with temperature unlike the other metallic alloy systems which show decreasing conductivity.

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I. Introduction

Earlier work at the authors' Laboratory⁽¹⁾⁽²⁾ has shown that rheocast (stircast) hypereutectic aluminium-silicon commercial alloys containing lead dispersions exhibited improved wear resistance and reduced thermal expansion behaviour. Data on thermal diffusivity, specific heat and thermal conductivity of these alloys as a function of temperature are, however, lacking in the literature.

Standard reference books provide the thermal properties data of only pure metals and certain special alloys at different temperatures. There is thus a complete lack of information on reliable thermal conductivity data of the commercial alloys which are actually multi-component systems.

There is also a renewed interest in developing new methods of determining specific heat, diffusivity and thermal conductivity in metals and alloys due to stringent specification required. The conventional methods of determining thermo-physical properties have limitations due to the fact that at elevated temperatures the accurate measurement become difficult and data are not reliable.

Laser Flash Technique (also called Pulse Technique) is a new technique and is recognised as a useful method⁽³⁾⁻⁽⁶⁾ for the determination of thermo-physical properties at elevated temperatures. This is a comparatively simpler method and enables the simultaneous determination of thermal properties of solid materials.

A TC 7000 H Thermal Constant Measuring Unit (Fig. 1) has been employed in the present investigation. The details of this unit are given in the text. In this paper specific heat (C_p), thermal diffusivity (α) and thermal conductivity (K) of the rheocast Aluminium-Silicon alloys have been determined using the above equipment and the microstructures of the alloys have also been discussed.

The instrument and principle

Laser Flash TC 7000 H

Figure 1 shows the Laser Flash Thermal Constant Measuring Equipment Model TC 7000H from Sinku Riko, Japan. The salient features of the unit are given below:

Temp. range	: Room temp. to 1500°C
Atmosphere	: Vacuum 0.0133 Pa
Sample size	: 10 mm dia $\times$ 1-3 mm thick
Thermal cond. range	: 0.1-400 W/m $\cdot$ K
Laser	: Normal oscillation type Ruby laser ($\lambda = 0.69 \mu\text{m}$)
Reproducibility	: $C_p \pm 7\%$ $\alpha \pm 3\%$ $K \pm 10\%$

Fig. 1 TC 7000H thermal constant measuring unit.

II. Principle and Operation

Figure 2 shows the principle of Laser Flash Method.

Fig. 2 Principles of Laser Flash Method.

Disc shaped samples of 10 mm in diameter and 1–3 mm in thickness are irradiated across its entire surface by laser pulse generated from a ruby crystal. The temperature variation of the other side of disc is measured with the help of Pt/Pt-13Rh thermocouple spot welded on to the specimen. The specimen is blackened on the front side with the help of graphite spray to enable uniformity of temperature at the irradiated surface. The instantaneous temperature rise taking place on the back side of the specimen as a result of the laser flash is monitored and stored in the transient memory of the thermal conductivity unit. The data is deciphered onto the video monitor of the computer interfaced with the unit. The computer enables display directly of specific heat and thermal diffusivity and calculates the thermal conductivity values based on the following equations:

$$C_p = \frac{Q}{L \times \Delta T_{\max}} \quad \text{J/gK} \quad (1)$$

$$\alpha = 1.37 \times \frac{L^2}{\pi t_{1/2}} \quad \text{cm}^2/\text{s} \quad (2)$$

$$K = \alpha \cdot C_p \cdot \rho \quad \text{W/(m} \cdot \text{K)} \quad (3)$$

where

C_p = Specific heat

α = Thermal diffusivity

K = Thermal conductivity

L = Thickness of sample (cm)

ρ = Density (Mg/m^3)

Q = Absorbed energy

$\Delta T_{\max}$ = Maximum temperature rise on the backside of the sample due to irradiation.

$t_{1/2}$ = Time to reach half of $\Delta T_{\max}$

III. Experimental

One kg of Al-Si alloys of 6, 12 and 18% Si (commercial grade alloys) containing 5 and 10 mass% Pb and 5 wt% graphite (Table 1) were prepared in an electric resistance furnace following the rheocasting method⁽²⁾. This involved melting the aluminium first and introducing the required amount of alloying additions at 900°C, fluxing with intermittent stirrings and cleaning the surface. The cleaned and homogeneous melt was agitated vigorously at 1440 rpm using a specially designed graphite stirrer attached to an electric motor when the melt has started crystallization and in a slurry state.

Table 1 Nominal composition of the Al-Si alloys investigated.

		mass%			
	Si	Cu	Mg	Ni	Al
1	6	—	—	—	balance
2	12	0.1	0.1	0.1	balance
3	18	1	1	1	balance

While the melt forms a vortex due to stirring, lead/graphite was added and stirred and cast into graphite mould. The schematic presentation of the set up is shown in Fig. 3.

Specimen preparation

Specimens of size 10 mm dia $\times$ 2–3 mm thick were machined out from the samples. It was made sure that both the sides of the specimens are polished and parallel. The side of the specimen receiving the laser flash was coated with graphite spray and on the temperature monitoring side Pt/Pt-13 Rh fine thermocouple was spot welded with about 2–3 mm gap.

IV. Metallographic Examination

Metallographic examination was carried out of the samples of hypo, eutectic and hyper eutectic Al-Si alloys with and without Pb and graphite addition through rheocasting after polishing and etching with 0.5% HF.

V. Thermal Property Measurement

Thermal conductivity unit (TC 7000H)

First, absorbed energy was measured by using sapphire

Fig. 3 Schematic of rheocasting setup.

as standard sample with known specific heat and attaching a light receptor (glassy carbon) to it. This is the correction value to be used in obtaining heat capacity at room temperature. The absolute specific heat of the unknown sample was obtained by using the absorbed energy corrected with a sapphire sample. The same glassy carbon sample was used in this case also. Now, after removing the glassy carbon and cleaning the sample, back-side of the sample was coated with graphite spray. Specific heat and diffusivity at elevated temperatures were measured. The computer directly displays the

graphs and values of the thermal constants. The TC unit was calibrated with a standard sample of pure Ni supplied by the Principal.

VI. Results and Discussion

Figure 4(a) and (b) show optical microstructures of Al-6Si and Al-6Si-5 g respectively revealing uniform distribution of graphite in (b) obtained by rheocasting technique. Figure 5(a) shows optical microstructure of conventionally cast Al-12Si alloy showing the typical

Fig. 4 Microstructures of Al-6%Si alloy. (a) without graphite; (b) with 5% graphite and conventionally cast. ($\times 320 \times \frac{4}{5}$)

Fig. 5 Microstructures of Al-12%Si alloy. (a) without Pb/graphite conventionally cast ($\times 320 \times \frac{4}{5}$); (b) with 5% graphite rheocast; (c) with 5% lead rheocast; (d) with 10% lead rheocast.

Fig. 6 Microstructures of Al-18Si-1Cu-1Ni-1Mg. (a) graphite dispersed and rheocast; (b) Conventionally cast. ($\times 320 \times \frac{1}{5}$)

Fig. 7 Variation of thermal properties of rheocast Al-12Si containing 5%Pb with temperature.

Fig. 9 Variation of thermal properties of rheocast Al-12Si with 5% graphite with temperature.

Fig. 8 Variation of thermal properties of rheocast Al-12Si with 10%Pb.

eutectic structure and Fig. 5(b) and (c) show the microstructures of these alloys dispersed with 5% Pb and 5%g respectively produced by rheocasting technique depicting uniform distribution of the dispersoids. Figure 5(d) shows another microstructure of the alloy with 10% Pb dispersed with rheocasting technique. Figure 6(a) and (b) show the optical microstructures of hyper alloy of conventionally cast and rheocast with introduction of graphite. It has been observed that the graphite and Pb are uniformly distributed by the rheocasting process. Commercial casting of these alloys with graphite or lead

would have caused rejection of these immiscible elements due to wide density difference. Figure 7 shows the variation of thermal conductivity of rheocast Al-12Si + 5% Pb alloy with rising temperature upto 350°C. Conductivity values vary from 155 W/(m·K) at 28°C to 203 W/(m·K) at 350°C. Figure 8 shows variation of thermal conductivity of rheocast Al-12Si with 10%Pb with rising temperature upto 350°C. The thermal conductivity values vary from 220 W/(m·K) at 27°C to 270 W/(m·K) at 350°C. It has been observed that the values of “K” are higher with higher lead content in Al-12Si at any temperature. Figure 9 shows variation of rheocast Al-12Si with 5%g with rising temperature. The values of “K” varies from 167 W/(m·K) at 28°C to 243 W/(m·K) at 310°C. The increasing trend of “K” with temperature in the graphite dispersed alloy is similar to that containing lead. Figure 10 shows comparative variation of thermal conductivity of rheocast and conventional hypo and hyper Al-Si alloy with rising temperature. The rheocast samples exhibit higher “K” values as compared to the conventionally cast alloys of similar composition.

Silicon has decreasing thermal conductivity as the temperature is raised, as in the case of many metals, aluminium does not show any appreciable thermal conductivity change with temperature (Table 2). The Al-Si alloys, however, show an increasing trend of thermal con-

Fig. 10 Variation of thermal conductivity of rheocast and conventionally cast Al-Si alloys with temperature.

Table 2 Thermal conductivity data of Al, Si and Al-Si alloys.

$W \cdot (m \cdot K)^{-1}$

Temp. (°C)	Al (Super- pure)	99.6%Al	Si	Al-13Si	Lo Ex1	Al-20Si	Lo Ex2
27	237	231 ⁽¹²⁾	148	163.2 ⁽¹⁰⁾	151 ⁽¹³⁾	—	107 ⁽¹³⁾
77	240	—	119	171.5 ⁽⁸⁾	—	—	—
100	—	—	—	175.7 ⁽⁹⁾	—	168.6 ⁽¹¹⁾	—
120	—	—	—	177.8 ⁽⁹⁾	—	—	—
				170.3 ⁽¹⁰⁾	—	—	—
127	240	231 ⁽¹²⁾	98.9	—	—	—	—
150	—	—	—	175.7 ⁽⁸⁾	—	—	—
				182 ⁽⁹⁾	—	—	—
165	—	233 ⁽¹²⁾	—	—	—	—	—
200	—	—	—	175.7 ⁽⁸⁾	—	174.5 ⁽¹¹⁾	—
227	237	—	76.2	—	—	—	—
250	—	—	—	175.7 ⁽⁸⁾	—	—	—
300	—	—	—	179.9 ⁽⁸⁾	—	—	—
327	232	—	61.9	—	—	—	—

Note: Lo Ex1 Al-12%Si-1%Cu-1%Mg-1%Ni
Lo Ex2 Al-23%Si-1%Cu-1%Mg-1%Ni

ductivity with temperature and has been reported by many earlier Worker's in the field⁽⁷⁾⁻⁽¹¹⁾ (Table 2). The values for the alloys, however, showed to be different by the different researchers, perhaps this is due to the different approaches adopted. Such a trend for Al-Si in particular can be traced to the fundamentals of thermal conductivity. It is well known⁽¹²⁾⁽¹³⁾ that electron scattering and phonons contribute to the thermal conductivity in metals.

Silicon being a good phonon conductor is reported to increase the thermal conductivity of Al-Si alloy⁽¹³⁾. It is also known that silicon is almost insoluble in aluminium

in solid state and whole of it get precipitated out during solidification as free silicon or eutectic silicon from the whole range of Al-Si alloys. These precipitated silicon particles contribute to increased phonon activity and thus enhance the thermal conductivity. It may be pointed out that this property of Al-Si alloy is very helpful for bearing applications. The microstructures of the rheocast Al-Si alloys has the further advantage of producing fine silicon phase in the matrix of a refined Al/Al-Si eutectic. This structure enhances the thermal conductivity and makes the alloy more suitable for bearings and pistons. The increased thermal conductivity could also be contributed to denser packing of the silicon phase in rheocast alloys.

VII. Conclusions

Thermal conductivity (K) of rheocast graphite dispersed Al-Si alloys are roughly twice than that of conventionally cast alloys.

Increasing the Pb content from 5 to 10 mass% in rheocast Al-12Si alloy improves the thermal conductivity.

Introducing graphite affects the thermal conductivity in a different fashion, the rise in conductivity is more steep than Pb containing alloys upto 300°C.

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REFERENCES

- (1) C. S. Sivaramakrishnan, R. K. Mahanti and R. Kumar: *Wear*, **96** (1984), 121.
- (2) C. S. Sivaramakrishnan, R. K. Mahanti and R. Kumar: *Trans. Indian Institute of Metals*, **39** (1986), 643.
- (3) W. J. Parker, R. J. Jenkins, C. P. Butter and Abbott: *J. Appl. Phys.*, **32** (1961), 1679.
- (4) R. D. Cowan: *J. Appl. Phys.*, **34** (1963), 926.
- (5) R. D. Cowan: *J. Appl. Phys.*, **32** (1961), 1363.
- (6) P. G. Klemens and R. K. Williams: *Int. Met. Rev.*, **31** (1986), 197.
- (7) R. W. Powell, C. Y. Ho and P. G. Klemens: *Thermal Conductivity: Thermo Physical Properties of Matter TPRC data series*, Vol. 1, ed. by Y. S. Touloukian, Plenum Press, N.Y., (1970).
- (8) E. Griffiths and F. H. Schofield: *J. Inst. Metals*, **39** (1928), 337.
- (9) C. Grard and J. Villey: *Compt. Rend.*, **185** (1927), 856.
- (10) J. Czochralski: *Z. Metallk.*, **13** (1921), 507.
- (11) W. Mannchen: *Z. Metallk.*, **23** (1936), 1931.
- (12) E. Griffiths: *Proc. Royal Soc. (Lond.)*, A115, (1927), p. 236.
- (13) C. J. Smithells: *Metals Reference Book*, 5th Ed., Butterworths (London), (1976), 951.