Bull. Mater. Sci., Vol. 27, No. 1, February 2004, pp. 69–71. © Indian Academy of Sciences.

Thermal conductivity of Cu–4·5 Ti alloy

S NAGARJUNA
Defence Metallurgical Research Laboratory, Kanchanbagh PO, Hyderabad 500 058, India

MS received 23 October 2003

Abstract. **The thermal conductivity (TC) of peak aged Cu–4·5 wt% Ti alloy was measured at different temperatures and studied its variation with temperature. It was found that TC increased with increasing temperature. Phonon and electronic components of thermal conductivity were computed from the results. The alloy exhibits an electronic thermal conductivity of 46·45 W/m·K at room temperature. The phonon thermal conductivity decreased with increasing temperature from 17·6 at 0 K to 1·75 W/m·K at 298 K, which agrees with literature that the phonon component of thermal conductivity is insignificant at room temperature.**

Keywords. **Cu–4·5 Ti alloy; peak aging; thermal conductivity; temperature; phonon thermal conductivity; electronic thermal conductivity.**

1. Introduction

Cu–Ti alloys are being developed as substitutes for commercial Cu–Be alloys, which are toxic and expensive. Considerable progress has been made in understanding the precipitation hardening mechanisms in relation to their tensile properties and electrical conductivity (Saarivirta and Cannon 1959; Laughlin and Cahn 1975; Datta and Soffa 1976; Nagarjuna *et al* 1995, 1997a, b, 1999). Earlier studies show that a maximum electrical conductivity of 25% international annealed copper standard (IACS) is obtained in Cu–Ti alloys with Ti ranging from 1·5 to 4·5 wt% and 14% IACS in Cu–5·4 wt% Ti alloy (Nagarjuna *et al* 1999). However, little information is available on the thermal conductivity of Cu–Ti alloys. Next to electrical uses, applications involving transfer of heat are the largest consumers of copper and copper base alloys and hence, data on thermal conductivity of Cu–Ti alloys is essential for their use in heat transfer applications.

Heat in metals and alloys is principally carried by electrons and lattice waves or phonons, leading to an overall thermal conductivity, k (Touloukian *et al* 1970)

$$k = k_e + k_g, \quad (1)$$

where k_e is the electronic component and k_g the phonon component. For metals and alloys, k_g is an important component below room temperature (RT), whereas k_e becomes significant at and above RT. The electronic component often parallels electrical conductivity and thermal and electrical conductivity for metals and alloys are related by the Wiedemann–Franz–Lorenz Law

$$k_e = L_0 \cdot s \cdot T, \quad (2)$$

where L_0 is Lorenz number ($2{\cdot}443 \times 10^{-8}$ WΩ/K^2), s the electrical conductivity $(\Omega \cdot \text{m})^{-1}$ and T the absolute temperature (K). On substituting (2) in (1), we get

$$k = k_g + L_0 \cdot s \cdot T. \quad (3)$$

The aim of the present work was to study the temperature dependence of thermal conductivity of Cu–4·5 wt% Ti alloy and examine the phonon and electronic components of TC at 0 K and room temperature (298 K). This paper presents the first measurements of thermal conductivity in terms of phonon and electronic components for this alloy.

2. Experimental

A 30 kg melt of Cu–Ti alloy with aimed Ti content of 4·5 wt% was made in a vacuum induction melting furnace with oxygen-free electronic (OFE) copper and high purity Ti metal as raw materials. The ingot thus cast, was subjected to homogenization treatment at 850°C/24 h and analysed for Ti content. The analysed composition matched with the aimed composition of Ti (4·5 wt%). The ingot was subsequently processed into wrought products of suitable sizes. Samples from the hot rolled rod were solution treated and aged at 450°C for 16 h to obtain maximum strength. Specimens of size 10 mm diameter and 3·0 mm thickness were machined from the peak-aged samples. The thermal conductivity was measured using Laser Flash Thermal Conductivity apparatus (contact type) at temperatures ranging from 20 to 400°C and the average of 5 readings was taken for every measurement.

3. Results and discussion

Figure 1 shows the thermal conductivity of Cu–4·5 Ti alloy as a function of temperature. The straight line is a least-square fit and is extrapolated to meet the thermal conductivity axis at zero temperature. This shows that the thermal conductivity, k, of the Cu–4·5 Ti alloy in the temperature range 0–673 K can be written as

$$k = A + B \cdot T, \quad (4)$$

where A indicates the thermal conductivity of the alloy at zero temperature, B the slope of the straight line and T the absolute temperature. From figure 1, the values of A and B were found to be 17·6 W/m·K and 0·103 W/m·K^2, respectively. The expression (4) is similar to (3). Therefore, 'A' in (4) could be identified as the phonon component (k_g) and $B \cdot T$ as the electronic component (k_e) of the thermal conductivity of Cu–4·5 Ti alloy. Harms *et al* (2002) reported similar identification for metallic glasses. This might suggest that phonon component (k_g) is independent of temperature, which is not so. It in fact, decreases with increasing temperature and the same is illustrated in the next paragraph. Therefore, Cu–4·5 Ti alloy exhibits a phonon thermal conductivity of 17·6 W/m·K and electronic conductivity of 0 W/m·K at 0 K.

The Widemann–Franz–Lorenz Law (2) has been used to decompose the total thermal conductivity of Cu–4·5 Ti alloy measured at room temperature (298 K), into electronic and phonon components. The electrical conductivity of the alloy determined separately at room temperature by Nagarjuna *et al* (1995, 1999) is 11% IACS, a resistivity of 15·67 μΩ·cm or 6·38 × 10^6 (Ω·m)$^{-1}$. The electronic component of thermal conductivity of Cu–4·5 Ti alloy at room temperature (298 K) was computed using (2) as given below

$$k_e = L_0 \cdot s \cdot T$$
$$= 2 \cdot 443 \times 10^{-8} \times 6 \cdot 38 \times 10^{6} \times 298 = 46 \cdot 45 \text{ W/m·K}.$$

The thermal conductivity of Cu–4·5 Ti alloy measured experimentally at room temperature is 48·2 W/m·K. From this value, the phonon component of thermal conductivity of the alloy ($k_g = k - k_g$) at room temperature is found to be 1·75 W/m·K, which is less by 90% than that at 0 K (17·6 W/m·K from figure 1). This indicates that the phonon component of thermal conductivity of Cu–4·5 Ti alloy decreased with increasing temperature from 17·6 W/m·K at 0 K to 1·75 W/m·K at 298 K, which is in agreement with the literature (Touloukian *et al* 1970). This could be explained by the fact that thermal conduction by electrons is predominant in metals and alloys at and above room temperature and that by phonons is significant below room temperature (Touloukian *et al* 1970). Therefore, the calculated phonon component of thermal conductivity of Cu–4·5 Ti alloy at room temperature is reasonable.

The phonon component of thermal conductivity of Cu–4·5 wt% Ti alloy is compared with thermal conductivity at 4·2 K of other commercial materials (American Institute of Physics Handbook 1972) in table 1. It is observed that the phonon component of thermal conductivity of Cu–4·5 wt% Ti alloy is comparable with thermal conductivity of commercial pure iron at 4·2 K. It is interesting to note that it is greater than the thermal conductivity at 4·2 K of copper alloys and Al alloy 3003 listed in table 1, which is attributed to the concentration and different types of solutes and imperfections present in the alloys at low temperature.

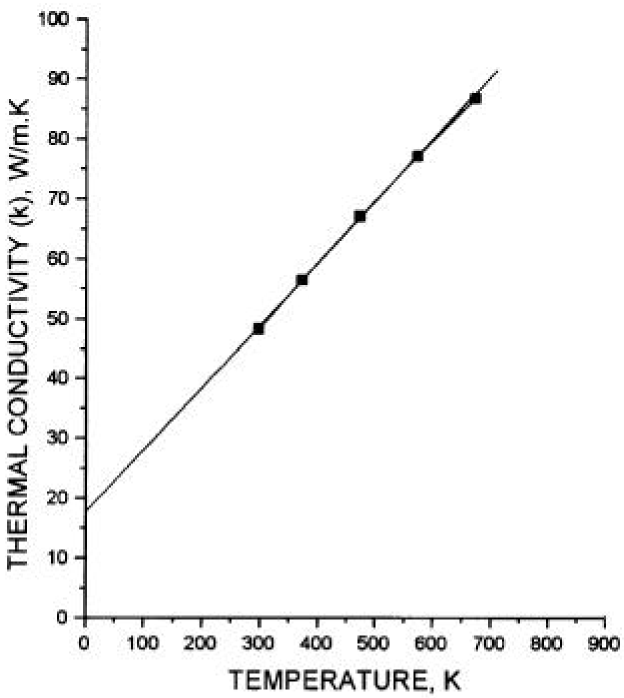

Figure 1. Variation of thermal conductivity of Cu–4·5 Ti alloy with temperature.

Table 1. Comparison of phonon thermal conductivity of Cu–4·5 Ti alloy with that of other commercial materials (American Institute of Physics Handbook 1972).

Material	Phonon thermal conductivity* (W/m·K)	Reference
Cu–4·5 wt% Ti	17·6	Present work
Copper (ETP)	330·0	AIP Handbook (1972)
Copper (PD)	7·5	-do-
Cu–2·0 Be	2·0	-do-
Leaded brass	2·3	-do-
German Silver	0·75	-do-
Pure iron	15·0	-do-
Al alloy 3003	11·0	-do-

*At 0 K for Cu–4·5 Ti and for other materials, at 4·2 K. (ETP, electrolytic tough pitch; PD, phosphorous deoxidized)

Table 2. Comparison of thermal conductivity of Cu–4·5 Ti alloy with that of Cu base alloys (West 1982).

Material (BS ref.)	Thermal conductivity at 20°C (W/m·K)	Reference
Cu–4·5 Ti	48·2	Present work
Pure copper	399	West (1982)
Cu–Be (CB 101)	83–145	-do-
Brasses (CZ 110–101)	100–230	-do-
Bronzes (PB 104–101)	45–145	-do-

The thermal conductivity of Cu–4·5 wt% Ti measured at room temperature is compared with that of copper and other copper base alloys (West 1982) in table 2. It is evident from this table that the thermal conductivity of Cu–4·5 Ti alloy (48·2 W/m·K) at room temperature is less than that of pure copper (399 W/m·K), which is explained on the basis of flow of electrons and atomic vibration. The free electrons that conduct electricity by moving through the metal also carry over one-half the energy for thermal conduction. The remaining energy is transmitted by atomic vibration; any impurities or alloying additions to copper impede the flow of electrons and atomic vibration, thus resulting in lowered thermal conductivity (Mendenhall 1977). In the present study, Ti added to copper indeed impeded the flow of electrons and vibration of atoms, which resulted in lowered thermal conductivity for Cu–4·5 Ti alloy. The thermal conductivity of Cu–4·5 Ti alloy is also less than that of brasses or Cu–Be alloys, but comparable with that of phosphor bronzes.

4. Conclusions

(I) Cu–4·5 Ti alloy exhibits a thermal conductivity of 48·2 W/m·K at room temperature.
(II) Thermal conductivity of Cu–4·5 Ti alloy increases with temperature.
(III) The alloy exhibits a phonon thermal conductivity of 17·6 W/m·k at 0 K.
(IV) The experimentally measured thermal conductivity of Cu–4·5 Ti alloy at room temperature was decomposed into electronic and phonon components of 46·45 and 1·75 W/m·K, respectively, which indicates that the phonon component is insignificant at room temperature.

Acknowledgements

The financial support of the Defence R&D Organization is gratefully acknowledged. The author is indebted to Prof. P Ramachandra Rao, Vice-Chancellor, BHU, Varanasi, for helpful discussions.

References

American Institute of Physics Handbook 1972 (ed.) Dwight E Gray (New York: McGraw Hill Book & Co.) 3rd ed. pp 4–146, 148 and 4–155

Datta A and Soffa W A 1976 *Acta Metall*. **24** 987

Harms U, Shen T D and Schwarz R B 2002 *Scr. Mater*. **47** 411

Laughlin D E and Cahn J W 1975 *Acta Metall*. **23** 329

Mendenhall J H 1977 *Understanding Cu alloys* (New York: John Wiley & Sons) p. 89

Nagarjuna S, Balasubramanian K and Sarma D S 1995 *Mater. Trans. JIM* **36** 1058

Nagarjuna S, Balasubramanian K and Sarma D S 1997a *J. Mater. Sci*. **32** 3375

Nagarjuna S, Balasubramanian K and Sarma D S 1997b *Mater. Sci. Engg*. **A225** 118

Nagarjuna S, Balasubramanian K and Sarma D S 1999 *J. Mater. Sci*. **34** 2929

Saarivirta M J and Cannon H S 1959 *Met. Prog*. **76** 81

Touloukian Y S, Powell R W, Ho C Y and Klemens P G 1970 *Thermophysical properties of matter, Thermal conductivity of metallic elements and alloys* (New York: IFI/Plenum) Vol. 1, p. 3a

West E G 1982 *Copper and its alloys* (Chichester, UK: Ellis Horwood Limited) p. 136