Determination of Thermal Diffusivity and Thermal Conductivity of Fe-Al Alloys in the Concentration Range 22 to 50 at.% Al

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The thermal diffusivity of Fe-Al alloys in the concentration range 22 to 50 at.% Al was measured within a temperature range of 20 to 600 °C. The thermal diffusivity of the Fe-25 and 28 at.% Al alloys decreases with increasing temperature up to the Curie temperature, and then it increases up to the temperature when the $D0_3 \leftrightarrow B2$ transformation occurs. The thermal diffusivity of Fe-22 at.% Al alloys increases with rising temperature up to the temperature when the $D0_3 \leftrightarrow B2$ transformation occurs, and then it decreases. A further decrease in thermal diffusivity follows up to the Curie temperature. The thermal diffusivity of Fe-34 and Fe-40 at.% Al increases monotonically with the rising temperature. The thermal diffusivity of Fe-50 at.% Al alloys decreases only up to 100 °C, and does not change any further with increasing temperature. Thermal conductivity is the highest for Fe-25 and Fe-50 at.% Al alloys at room temperature. Thermal conductivity rises for all studied alloys with increasing temperature. The smallest increase was registered for Fe-25 at.% Al alloys.

1. Introduction

The Fe-Al system is in its Fe-rich part interesting due to its complex magnetic phase diagram (Fig.1) and to order-disorder transformation concerning the B2 (CsCl-type), $D0_3$ (BiF_3-type), and A2 (disordered random) phases. The alloys near the stoichiometries Fe_3Al and FeAl show B2 and $D0_3$ order over a wide range of compositions and have been the object of considerable research activity in the recent past. A study of relevant literature reveals data on magnetic properties, mechanical properties, electrical resistivity, thermal expansion, and other physical properties. On the other hand, one of the properties that has not been extensively pursued is thermal diffusivity and thermal conductivity [1995Han, 1996Han].

Recently, electrical conductivity of Fe-Al alloys was studied experimentally, *e.g.*, [1960Fed, 1973Cas, 1994Hyd, 1998Lil, 1998Nis]. The dependence of electrical resistivity on composition for homogeneous disordered solid solutions is described satisfactorily by the analytic expression proposed by Nordheim [1931Nor]. Nordheim's relation was confirmed by Johansson and Linde [1936Joh] for the Cu-Au system. The decrease of the electrical resistivity by ordering is obvious from Johansson's results.

The thermal conductivity of metals and alloys consists of two components [1976Ber]: a lattice component and an electronic component. The Wiedemann-Franz law claims that electronic thermal conductivity is inversely proportional to electrical resistivity. Using the Wiedemann-Franz law, Nordheim's relation was converted to thermal conductivity, providing that the Lorenz numbers do not change appreciably for both components and solid solution [1998Ter]. The thermal conductivity of the disordered solid solution λ_{ss} is given by the following relation:

$$\lambda_{ss} = \frac{1}{\dfrac{1-x}{\lambda_A} + \dfrac{x}{\lambda_B} + k'x(1-x)} \qquad \text{(Eq 1)}$$

where λ_A and λ_B are the thermal conductivities of the elements A and B, x is the atomic fraction of the element B, and k' is a positive constant that depends on the alloy system. Thermal conductivity for random solid solutions may be determined by means of this relation. Thermal conductivity shows a minimum at near midcomposition for binary solid solutions. Compound formation or ordering is connected with the peak on the same curve.

It is the purpose of the present paper to determine the thermal diffusivity and the thermal conductivity in a part of the binary Fe-Al system from 22 to 50 at.% Al. The results can be interpreted with respect to the influence of ordering and ferromagnetism on both quantities.

2. Experimental

Measurement of the thermal diffusivity was performed in a temperature range from 20 to 600 °C in an argon atmosphere using the flash method described elsewhere [1991Rud].

Linear thermal expansion was measured in argon using the Netzsch 402E dilatometer, in a temperature range from 20 to 600 °C. The temperature dependence of the density was calculated from the density measured at 20 °C by weighing the sample in water and in air and from respective values of volume thermal expansion data. The specific heat

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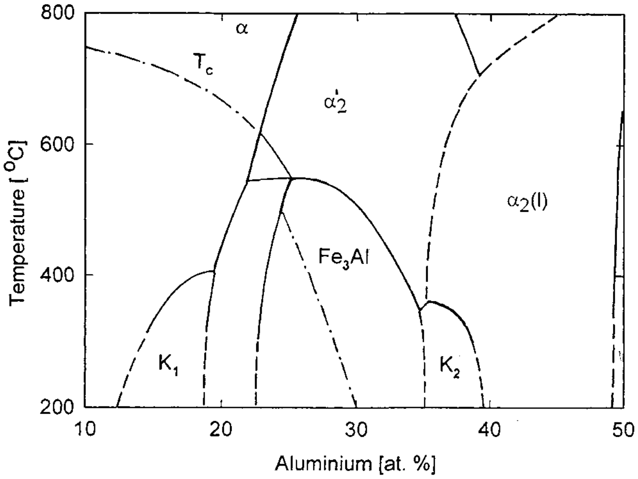

Fig. 1 Phase diagram for FeAl alloys [1982Kub]

Table 1 Chemical composition of FeAl alloys

Notation of alloys	Fe22Al	Fe25Al	Fe28Al	Fe34Al	Fe40Al	Fe50Al
At.% of Al	22.2	24.8	27.7	33.7	40.0	50.1

capacity of alloys was calculated, using the Neumann-Kopp rule, outside the transformation temperature ranges. The thermal conductivity λ was calculated by using the relation $\lambda = a\rho c$, where a is thermal diffusivity, ρ is density, and c is specific heat capacity.

The material for the preparation of samples was obtained by vacuum melting appropriate amounts of Fe 99.8% and Al 99.999%. The chemical analysis was made with an atomic absorption spectrometer (Perkin-Elmer). The results are shown in Table 1. The samples were annealed for 1 h in argon at 800 °C. The rate of the heating and cooling was 5 K/min.

3. Results and Discussion

The dependences of thermal diffusivity on the concentration at different temperatures for Fe22Al, Fe25Al, Fe28Al, Fe34Al, Fe40Al, and Fe50Al alloys are given in Fig. 2. The values of thermal diffusivity are highest for 25 and 50 at.% Al, which correspond to the perfectly ordered structures. The concentration dependences of thermal conductivity are given in Fig. 3 for temperatures of 20, 100, 200, 300, and 600 °C. The dotted curve in this figure corresponds to the thermal conductivity of alloys at room temperature calculated using Eq 1, *i.e.*, for disordered solution (if it were the case) in this concentration range. The constant k' was obtained from relation 1, using the known thermal conductivity of the disordered Fe-34 at.% Al alloy [1998Lil, 1998Nis]. It is obvious in Fig. 3 that an increase in the degree of order increases the thermal conductivity of alloys.

The same results can be presented as the dependence of the same quantities (thermal diffusivity and thermal conductivity) on temperature for different compositions (Fig. 4).

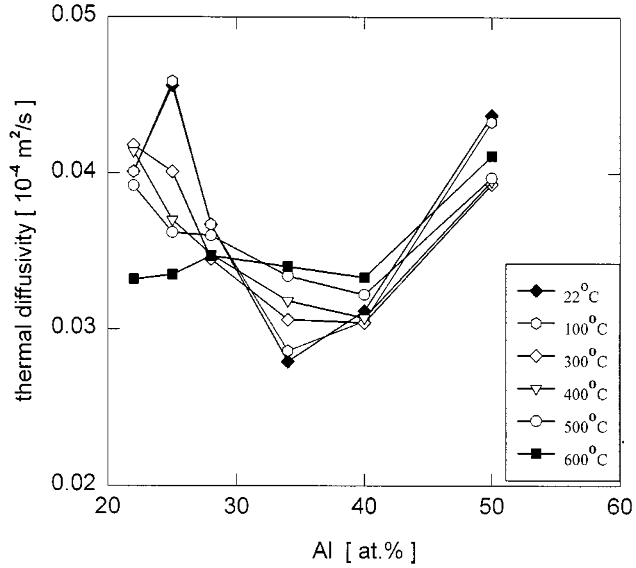

Fig. 2 Concentration dependence of thermal diffusivity

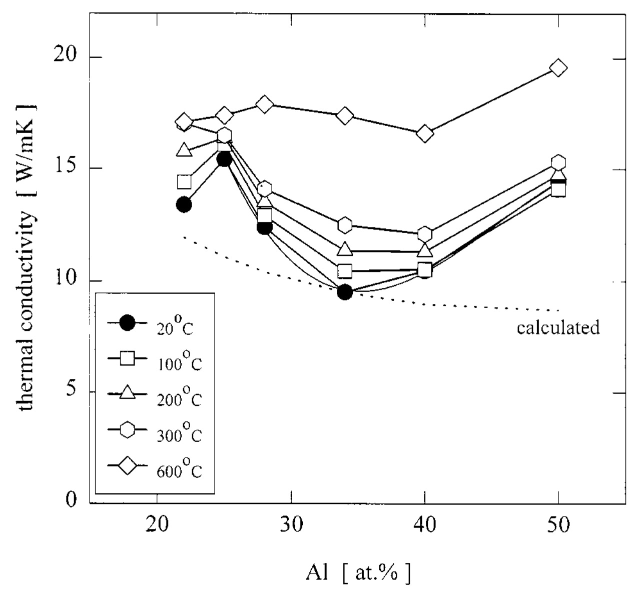

Fig. 3 Concentration dependence of thermal conductivity

The alloys with 22, 25, and 28 at.% Al are ferromagnetic and ordered at low temperatures (upper part of Fig. 4). For nonferromagnetic alloys (34, 40, and 50 at.% Al), see the lower part of Fig. 4. It can be seen from the phase diagram [1982Kub] that, while the ferromagnetic transition precedes the order-disorder transition in alloys with 25 and 28 at.% Al, in the alloy with 22 at.% Al, the opposite is the case.

If a ferromagnetic transition exists in a metal, thermal diffusivity always decreases from room temperature to the Curie temperature and then increases (*e.g.*, [1967Sha] for Armco iron) if the magnetic transition is the first phase transition in an alloy. Such behavior of thermal diffusivity is obvious for the Fe25Al and Fe28Al alloys (Fig. 4a). When these two alloys are further heated, a drop in the thermal diffusivity at about 535 °C is observed. This drop is due to the phase transition $D0_3 \leftrightarrow B2$ in both alloys.

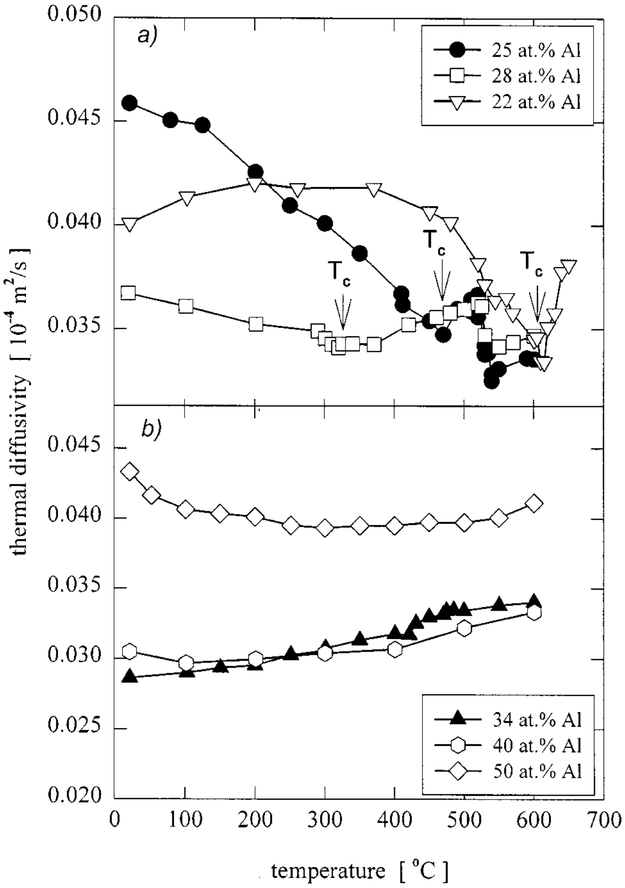

Fig. 4 Temperature dependence of thermal diffusivity

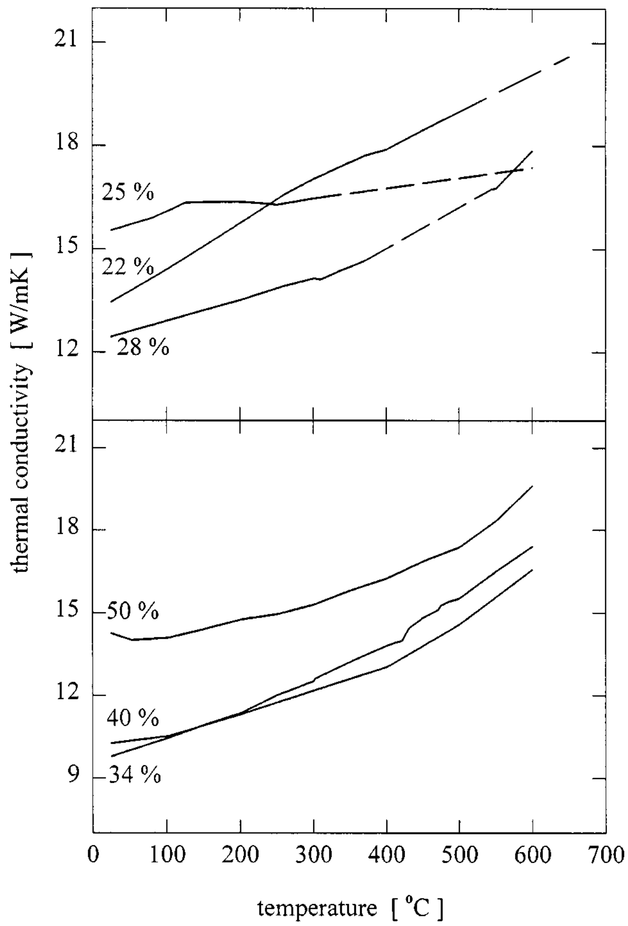

Fig. 5 Temperature dependence of thermal conductivity

For the Fe22Al alloy, the $D0_3 \leftrightarrow B2$ transition occurs above 500 °C and the ferromagnetic phase transition above 600 °C (phase diagram Fig. 1). In this alloy, the order-disorder transition precedes the ferromagnetic transition (sequence of both transitions is opposite in comparison with the Fe25Al and Fe28Al alloys). The thermal diffusivity at first increases during heating from room temperature up to 400 °C. This increase is followed by two characteristic drops of the thermal diffusivity as the $D0_3 \leftrightarrow B2$ transition and ferromagnetic transition occur in an alloy.

The present results are in agreement with the fact that the value of the thermal diffusivity of Fe and the ferromagnetic Fe alloys (Fe-Co [1995Zin], Fe-Cr [1998Kor], and other Fe alloys [1978Tay]) at the Curie temperature is nearly the same, *i.e.*, 0.031 to 0.035 · 10^{-4} m^2/s, and independent of the alloying elements. The thermal diffusivity of Armco iron at the Curie temperature is 0.031 · 10^{-4} m^2/s [1967Sha]. In the Fe-Co system, alloys with 0.8 to 30.8 wt.% Co have a thermal diffusivity at the Curie temperature of about 0.033 · 10^{-4} m^2/s [1995Zin]. The value of 0.031 · 10^{-4} m^2/s was published for Fe-Cr alloys with 1 to 30 wt.% Cr [1998Kor]. For ferromagnetic Fe-Al alloys measured in this work, the values of the thermal diffusivity at the Curie temperature were found to be between 0.033 and 0.034 · 10^{-4} m^2/s (Fig. 4).

Figure 4(b) shows the temperature dependence of the thermal diffusivity for 34, 40, and 50 at.% Al. No phase transition was found in these dependences. No phase transition was found by dilatometry either.

The temperature dependence of thermal conductivity is shown in Fig. 5. Thermal conductivity of all investigated alloys increases with increasing temperature. The smallest increase of thermal conductivity is observed for the alloy of Fe with 25 at.% Al, where the ferromagnetic transition is the first phase transition in the studied temperature range and where the decrease of thermal diffusivity due to ferromagnetism is the highest.

4. Conclusions

- The thermal diffusivity and thermal conductivity of the ordered alloys are higher than those of the disordered solid solution.
- The temperature dependence of thermal diffusivity and the thermal conductivity of Fe-Al alloys are influenced not only by ordering but also by magnetic transition. For increasing temperature, the values of both parameters depend on the sequence in which the ferromagnetic transition and the order-disorder transition occur.
- The value of thermal diffusivity at the Curie temperature is the same for all the investigated alloys, and it is in

agreement with the values published for Fe and other Fe-rich Fe alloys.

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