Effects of Alloying Additions on Thermal Conductivity of Ferritic Iron

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1. Introduction

Thermal conductivity is one of the most important properties for iron-base heat-resisting alloys. For the alloys with low thermal conductivity, the temperature is not readily homogenized over long distances and thus the alloys will be locally heated. Such local heating may cause degradation of the heat resistance owing to local melting, local oxidation, etc. Thus, in order to avoid the degradation due to the local heating, high thermal conductivity is indispensable for the heat-resisting alloys.

Alloying elements usually improve the mechanical and chemical properties of iron, but may degrade the thermal conductivity. Consequently, information on the thermal conductivity is needed for determination of the alloying elements and their concentrations of the alloys. Unfortunately, such information is very limited even in binary Fe–X systems so far. In the present study, the thermal conductivity has been experimentally determined for various iron-base binary alloys.

2. Experimental

Various binary Fe–X alloys were prepared as button ingots by argon arc melting from pure metals with the highest purity readily available. Here, the term X indicates alloying elements of Al, Si, Ti, V, Cr, Mn, Co, Ni, Cu, Ga, Ge, As, Mo, Ru, Rh, Pd, Sn, Sb, Re, Os, Ir and Pt. The melting was repeated at least five times for each ingot to improve the homogeneity. The weight reduction after the repeated melting was less than 0.1% for all the ingots.

Each ingot was encapsulated in an evacuated quartz tube and then homogenized at an appropriate temperature, followed by water quenching with breaking the quartz tube. The temperature and time for the homogenization are 1123 K and 72 h, respectively, for X=Al, Si, Ti, V, Cr, Co, Cu, Ga, Ge, As, Mo, Sn, Sb and Re, whereas they are 973 K and 504 h for X=Mn, Ni, Ru, Rh, Pd, Os, Ir and Pt. Such homogenization conditions were adopted to realize an Fe-rich single phase microstructure with body-centered cubic (bcc) on the basis of recent binary phase diagrams.

Disk specimens with a diameter of 10 mm and a thickness of 2 mm were cut from the homogenized ingot and then used to determine the thermal conductivity by a laser-flash technique. In this technique, a circular surface of the disk specimen was laser flashed using a ruby laser with a wave length of about 700 nm and a beam radius of 10 mm. The transient temperature on the other circular surface was measured with an infrared detector and a thermocouple. The thermal conductivity was evaluated from the time dependence of the transient temperature. The evaluation method was described in detail in previous articles.

3. Results and Discussion

3.1. Composition Dependence of Thermal Conductivity

The composition dependence of the thermal conductivity λ for the Fe-rich solid solution (α) phase was determined at 300 K. The results of the binary Fe–Al, Fe–Co and Fe–Cr systems are shown as open rhombuses, squares and triangles, respectively, in Fig. 1. Here, Al is a b-subgroup element, Co is a typical transition element, and Cr is a principal substitutional alloying element of ferritic steels.

An open circle in Fig. 1 shows a value of λ=82.8 W m⁻¹ K⁻¹ obtained for pure Fe. This value is close to those reported by Touloukian et al. and Ho et al. The thermal conductivity λ monotonically decreases with increasing concentration x of alloying element in all the three binary systems.

Such a composition dependency of λ is the most remarkable in the Fe–Al system. The addition of Al with only 3 at% reduces the value of λ by half. The reduction rate of λ gradually decreases with increasing concentration x. On the other hand, in the case of the Fe–Cr system, a concentration of x=10 at% is needed to reduce the value of λ by half.

![Fig. 1. The thermal conductivity λ of the α phase versus the concentration x of alloying element in at% for the binary Fe–Al, Fe–Cr and Fe–Co systems at 300 K. The experimental results by Williams et al. are also shown as solid symbols.](image)
alloying element X on the thermal conductivity.

Such reduction of $\lambda$ cannot be realized in the Fe–Co system. In this binary system, $\lambda$ decreases by less than 20% at $x=5$ at% and the reduction rate of $\lambda$ is fairly small at $x>5$ at%. In Fig. 1, the results of the Fe–Al and Fe–Cr systems reported by Williams et al.\textsuperscript{14,15} are shown as solid rhombuses and triangles, respectively. As can be seen, their results coincide well with those in the present study.

### 3.2. Thermal Conductivity in Various Binary Systems

As mentioned in Sec. 3.1, the thermal conductivity $\lambda$ of the $\alpha$ phase monotonically decreases with increasing concentration $x$ of alloying element in the binary Fe–Al, Fe–Cr and Fe–Co systems. In these binary systems, the reduction rate of $\lambda$ is large at lower values of $x$, while it is small at higher values of $x$. Thus, in order to examine the effect of alloying element $X$ on the thermal conductivity $\lambda$, we focus on the value of $\lambda$ at $x=2$ at% in this section. This value of $\lambda$ is hereafter designated $\lambda_2$.

The results in the various binary systems are shown in Fig. 2, where open circles, triangles and squares indicate the values of $\lambda_2$ for the alloying elements of the first, second and third long periods, respectively. As can be seen in Fig. 2, $\lambda_2$ takes the maximum value at $X=Fe$. Here, $X=Fe$ means that the $\alpha$ phase is pure Fe. Therefore, it is concluded that the addition of alloying element always reduces the thermal conductivity $\lambda$.

In the first long period, $\lambda_2$ monotonically decreases as the horizontal distance of the alloying element $X$ from Fe increases, when $X$ is positioned at the right-hand side of Fe in the periodic table. Such a trend of $\lambda_2$ is recognized also for the alloying elements of the second long period. On the other hand, for the alloying elements located on the left-hand side of Fe, the changing manner of $\lambda_2$ is slightly complicated and a monotonic trend is not observed. It is worth noting that $\lambda_2$ at $X=Al$ and Si are slightly larger than $\lambda_2$ at $X=Ga$ and Ge, respectively. The effect on the reduction of $\lambda$ is more remarkable for the elements positioned in the lower part of the periodic table.

### 3.3. Temperature Dependence of Thermal Conductivity

#### 3.3.1. Fe–Al System

The thermal conductivity $\lambda$ of the $\alpha$ phase in the Fe–Al system is shown as a function of the absolute temperature for various compositions in Fig. 3. In this figure, the results for $x=0$–20 at% are indicated as solid and open symbols, whereas the Curie temperature is shown as a dashed curve. The regions on the left-hand and right-hand sides of the dashed curve correspond to the ferromagnetic and paramagnetic states, respectively.

As can be seen in Fig. 3, the thermal conductivity $\lambda$ at $x=0$ at% monotonically decreases with increasing temperature, and then reaches to 38 W m$^{-1}$ K$^{-1}$ at 1100 K. Such a monotonic dependency of the thermal conductivity $\lambda$ on the temperature is also observed at $x \leq 2$ at%. On the contrary, $\lambda$ is rather insensitive to the variation of the temperature at $x \geq 5$ at%. The difference between the values of $\lambda$ at $x=0$ and 20 at% decreases with increasing temperature. For each solid curve connecting the corresponding experimental points in Fig. 3, there should exist an inflection point at the Curie temperature. The existence of inflection point at a Curie temperature is a general characteristic feature for the temperature dependence of the thermal conductivity. Such a characteristic feature is also observed in the Fe–Ti, Fe–V and Fe–W systems by Kobayashi et al.\textsuperscript{51} and in the Ni–Al system by the present authors.\textsuperscript{51}

#### 3.3.2. Fe–Cr System

The experimental results for the temperature dependence of the thermal conductivity in the Fe–Cr system are shown as solid and open symbols in Fig. 4. In this figure, a dashed curve indicates the Curie temperature, whereas a dashed-and-dotted curve shows the result for $x=0$ at% in Fig. 3. In
this binary system, the single-phase microstructure of the \( \alpha \) phase is realized for \( x \leq 2 \) at\% at all the experimental temperatures, whereas the two-phase microstructure consisting of the \( \alpha \) phase and the \( \sigma \) or Cr-rich solid solution phase is obtained for \( x > 5 \) at\% at certain experimental temperatures.\(^7,8\) For the single-phase microstructure, the thermal conductivity \( \lambda \) monotonically decreases with increasing temperature. Such a tendency is also recognized for the Fe–Cr system.\(^7\) The experimental results for commercial ferritic steels of AISI 405, 409, 430, 434 and 446 obtained by Madelung and White\(^7\) and by Kaye and Laby.\(^7\)

4. Conclusions

The thermal conductivity \( \lambda \) of the Fe–rich solid solution (\( \alpha \)) phase with body-centered cubic (bcc) structure was experimentally determined in various binary Fe–X systems. The determination was carried out for X=Al, Si, Ti, V, Cr, Mn, Co, Ni, Cu, Ga, Ge, As, Mo, Ru, Rh, Pd, Sn, Sb, Re, Os, Ir and Pt. According to the experimental results, the addition of X always reduces the value of \( \lambda \). For the elements of the first and second long periods, \( \lambda \) monotonically decreases as the horizontal distance of the alloying element X from Fe increases, when X is positioned at the right-hand side of Fe in the periodic table. On the other hand, the changing manner of \( \lambda \) is rather complicated, if X is located on the left-hand side of Fe. In the Fe–Al system, \( \lambda \) monotonically decreases with increasing temperature at Al concentrations of 0–2 at\%, whereas it is rather insensitive to the variation of the temperature at those of 5–20 at\%. A similar temperature dependency of the thermal conductivity is also observed in the Fe–Cr system.

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