Low-temperature electrical resistivity and thermal conductivity of binary magnesium alloys

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Abstract:

The electrical resistivity and thermal conductivity of some Mg-Al, Mg-Zn and Mg-Mn binary magnesium alloys were measured in the temperature range of 2 – 300 K. The electrical resistivity increased with the increasing alloying content in each binary alloy system, while the thermal conductivity exhibited an opposite trend. The low-temperature thermal conductivity was understood using $\kappa = (A/T + BT^2)^{-1} + CT^2$, which is found to be applicable in various binary and/or multi-component alloy systems. The parameters A , B , and C were determined through numerical fitting of the experimental data. Significant differences were found in the effect of three solute atoms on the thermal conductivity of Mg. The reasons for large differences in the thermal conductivity of the three binary magnesium alloy systems are discussed. Variations in the atomic volume and the valence are believed to play an important role on the thermal conductivity of magnesium alloys.

Key words: Electrical resistivity, thermal conductivity, binary magnesium alloys

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1. Introduction

Magnesium alloys, owing to their low density, high specific strength, and excellent damping capacity, are usually used as lightweight structural materials in various applications, such as automobile parts and electrical appliances [1, 2]. From an economic point of view, magnesium alloys play a very important role in reducing the overall weight of the product, as they are much lighter than steel and approximately one-third lighter than aluminium **for a given volume**. Recently, their good ability to conduct and spread the heat has also attracted considerable attention for potential cryogenic and aerospace applications [3, 4].

However, the information concerning thermophysical properties of magnesium alloys such as thermal conductivity is rather limited, especially **at low temperatures**. Even though the interest in the thermal conductivity of magnesium dates back to the late 1930's, most of the work so far has focused on pure magnesium [5, 6] and magnesium alloys above room temperature [7, 8]. Only more recently **has** the behaviour of thermal conductivity at low temperatures attracted attention of the scientific and engineering communities. In particular, Galeazzi et al. [4] measured the thermal conductivity of pure magnesium in the 60 – 150 mK temperature range, and the results indicate **that** magnesium can serve as a lightweight alternative to copper for the fabrication of refrigerator components for space. Lee et al. [9] investigated the thermal conductivity of two Mg-Al-Zn alloys, AZ31 (Al 3wt% and Zn 1wt%) and AZ61 (Al 6wt% and Zn 1wt%), in the temperature range of 150 – 673 K and the results show **that** the thermal conductivity **increase** with temperature in both alloys,

and **that** the experimental data can be useful in thermal design for automobiles and notebook applications. In order to explore the application potential of magnesium alloys at low temperatures, it is essential to analyze the effect of individual alloying **elements** on the thermal conductivity, so as to provide **guidance in** choosing suitable magnesium alloy systems for various applications.

Therefore, in this paper, the thermal conductivity of three most commonly-used binary magnesium alloy systems, Mg-Al, Mg-Zn and Mg-Mn, have been investigated in the temperature range of 2 – 300 K. Because the electrical resistivity is closely related to the electronic part of thermal conductivity, the electrical resistivity measurements were conducted at the same time.

2. Experimental

Three binary magnesium alloys containing Al, Zn and Mn solutes were prepared by permanent mold casting in a CO₂/SF₆ protective atmosphere. The composition of all alloys was analyzed by the AXIOS-PW4400 X-ray fluorescence spectrometer. The nominal and actual compositions of the alloys are listed in Table 1. Overall, the agreement between the nominal and the actual **alloy** concentrations is very good. Samples with dimensions of 0.5 mm × 1.5 mm × 12 mm were cut from the ingots for the low temperature electrical resistivity and thermal conductivity measurements. Low-temperature transport property measurements were carried out over the temperature range of 2 – 300 K. Electrical resistivity and thermal conductivity were determined using a longitudinal steady-state technique in a home-made cryostat.

Thermal gradients were measured by fine Chromel-Au/Fe thermocouples, with a small strain gauge serving as a heater. Electrical resistivity was measured by inputting a current along the length of the sample and collecting the voltage signal using a 2182A Keithley nanovoltmeter. Detailed description of the low-temperature apparatus can be found elsewhere [10, 11]. The low temperature transport properties of pure magnesium were also measured under the same conditions for comparison. The uncertainties of electrical resistivity and thermal conductivity are estimated to be $\pm 3\%$ and $\pm 5\%$, respectively.

3. Results

3.1. Electrical resistivity

The temperature dependence of the electrical resistivity of pure Mg and binary Mg-Al alloys is shown in Fig. 1. As Fig. 1(a) indicates, no resistance maximum or minimum is found at low temperatures and the electrical resistivity of all four samples is little temperature dependent in the temperature range 2 – 40 K. However, as the temperature increases further, the electrical resistivity increases sharply due to enhanced electron-phonon scattering as indicated by the data in Fig. 1(b). As expected, pure Mg has the lowest value of the electrical resistivity. With the increasing content of Al, the electrical resistivity increases due to stronger alloy scattering even though Al has a much larger electrical conductivity than Mg.

Figure 2 shows the temperature dependence of the electrical resistivity of binary Mg-Zn alloys. In general, the behavior of the electrical resistivity is similar to that of

Mg-Al alloys. However, it is worth noting that the Zn impurity has a much weaker effect on the electrical resistivity than does Al. For instance, the resistivity of Mg-0.5%Zn alloy is only about one-half that of the Mg-0.5%Al alloy and even 5wt% of Zn results in lower resistivity than 1wt% of Al.

In Fig. 3, the temperature-dependent resistivity of binary Mg-Mn alloys is displayed. Unlike the Mg-Al and Mg-Zn alloy systems, Mg-Mn alloys exhibit a resistivity minimum at $T_{\min}$, as is easily discerned at low temperatures in both Figs. 3(a) and 3(b). This phenomenon is related to magnetic scattering often referred to as the Kondo effect [12, 13]. As the concentration of impurity c increases, $T_{\min}$ seems to follow the classical $c^{1/5}$ dependence, as indicated in the inset of Fig. 3 (b).

3.2. Thermal conductivity

Figure 4 shows the temperature dependence of the thermal conductivity of Mg-Al alloys and of pure Mg in the temperature range 2 – 300 K. In pure Mg, the thermal conductivity curve displays a pronounced peak in the range of 20 – 30 K, reaching values greater than 700 W/m-K. This is a characteristic behavior of a pure metallic element. Compared to pure Mg, no obvious peaks are found at low temperatures in binary Mg-Al alloys and the thermal conductivity increases monotonically with temperature. Although thermal conductivity decreases with increasing content of Al, the difference in the magnitude of the thermal conductivity of pure Mg and Mg-Al alloys becomes smaller and smaller as the temperature approaches room temperature.

The temperature dependence of thermal conductivity of Mg-Zn alloys is shown in

Fig. 5. The two lowest content alloys, Mg-0.5%Zn and Mg-1.5%Zn, exhibit a thermal conductivity maximum in the temperature range 30 – 40 K, but the peak is **significantly reduced** at higher Zn concentrations. The presence of the low temperature peak for concentrations of Zn up to 1.5wt% attests to a weaker scattering power of Zn in comparison to Al, just as was the case of the electrical resistivity.

The variation of thermal conductivity with temperature in binary Mg-Mn alloys is shown in Fig. 6. The trend is analogous to that of Mg-Al alloys with no distinct peaks observed at low temperatures, a substantially **monotonic** temperature dependence, and comparable values of thermal conductivity for comparably dilute alloys.

4. Discussion

4.1. Electrical resistivity

According to the Matthiessen's rule [14], the total electrical resistivity ρ of pure metals and alloys consists of two independent parts: the residual resistivity ρ_0 caused by scattering of electrons by impurities and structural imperfections, and the ideal resistivity ρ_i governed by scattering of charge carriers by phonons, i.e.,

$$\rho = \rho_0 + \rho_i \quad (1)$$

The residual resistivity ρ_0 is independent of temperature, and, under most experimental conditions, the electrical resistivity of metals arising from structural imperfections, e.g., dislocations and grain boundaries, is small compared with that produced by phonons and solute atoms [15]. **The ideal resistivity ρ_i is temperature dependent. Temperature coefficients of various samples are listed in Table 2. The**

Matthiessen's rule states that the temperature coefficient is independent of concentration, however, the temperature coefficient of the resistivity obtained in this paper is not a constant. Salkovitz et al. [16] also observed such a deviation from Matthiessen's rule in the work on dilute binary magnesium alloys, including Mg-Al, Mg-Ag and Mg-In. The reason is that ρ_i is, in fact, dependent upon the axes ratio c/a and upon the Brillouin zone overlap [17]. Because the ratio c/a and the degree of zone overlap change with concentration, this imposes the dependence of ρ_i on the concentration.

The resistivity increment due to **three** types of solute elements was determined and is shown as a function of composition in Fig. 7. The quantity $\Delta\rho$ is the resistivity increment due to the presence of solute atoms defined as

$$\Delta\rho_0 = \rho_0 (\text{alloy}) - \rho_0 (\text{Mg}) \quad (2)$$

where ρ_0 was determined by the value of the electrical resistivity at 5 K. Figure 7 is a quantitative representation of our earlier statements that Al and Mn impurities in Mg cause a much stronger scattering than Zn. Moreover, the data indicate that the electrical resistivity increases linearly when the concentration of solute atoms is low. 0.5at% Mn, Al and Zn dissolved in pure Mg increase the electrical resistivity by about 22 nΩ-m, 10 nΩ-m, and 5 nΩ-m, respectively.

4.2. Thermal conductivity

In a conductor, the total thermal conductivity κ is generally expressed as [14]:

$$\kappa = \kappa_e + \kappa_L \quad (3)$$

where the electronic component κ_e dominates in the case of pure metals, and the lattice component κ_L becomes relatively more significant in alloys.

As is well known, the electrical conduction and thermal conduction are closely related *via* the Wiedemann-Franz law of the form [14]

$$\kappa_e = L_0 \sigma T \quad (4)$$

where σ is the electrical conductivity and L_0 is the Lorenz constant ($2.45 \times 10^{-8} \text{ W}\Omega\text{K}^{-2}$ for highly degenerate systems such as metals). The Wiedemann-Franz law is essentially always used [18,19] to calculate the electronic part of thermal conductivity from the measured electrical conductivity.

However, the validity of such approach requires two conditions [15]: (1) the electron gas is highly degenerate, which is almost always satisfied in metals and their dilute alloys; and (2) the relaxation time (or, alternatively, the mean-free path) of electrons in electrical and thermal processes is the same, which depends on the nature of the scattering process. If the scattering process is elastic, the relaxation times are identical. However, if the nature of scattering has an inelastic character, the relaxation times can be substantially different between electrical and thermal transport, see, e.g., [14]. The important scattering processes concerning the electrical and thermal conduction by electrons are: (1) the elastic scattering of electrons by static imperfections [20], and (2) scattering of electrons by phonons, a process that has an inelastic character. At the lowest temperatures, impurity scattering dominates and provides a sufficiently large change in electron wave-vector so that it is equally effective in relaxing out-of-equilibrium distributions created by the electric field and

the thermal gradient. Thus the two relaxation times are identical and the Wiedemann-Franz law is obeyed. At temperatures somewhat above the ambient, the dominant phonons have large wave-vectors and **Umklapp processes** are equally capable of restoring equilibrium in systems disturbed by electric fields and thermal gradients, hence, again, the relaxation times for electrical and thermal processes tend to be identical and the Wiedemann-Franz law holds. However, at temperatures somewhat below ambient ($T < \Theta_D$), the phonon wave-vector is not large enough to cause, in a single collision with an electron, a large enough change in the electron wave-vector to give rise to electrical resistance, while it is perfectly capable, in a single collision, to cause thermal resistance merely by lifting an electron from below the Fermi energy to an empty state just above the Fermi energy. In this situation, the relaxation times for electrical and thermal **processes** might differ substantially and this is indicated by a significantly decreasing value of the Lorenz number. In this case, the use of Wiedemann-Franz law is inappropriate and would cause a significant overestimate of the electronic thermal conductivity.

Using the Matthiessen's rule, for temperatures below about $\Theta_D/5$ (the Debye temperature Θ_D of magnesium is 320 K), the electronic thermal conductivity κ_e is usually given by **[21]**

$$1/\kappa_e = A/T + BT^n \tag{5}$$

where the first term on the right side of the equation represents the electron-impurity scattering and the second term comes from the electron-phonon scattering, and $n = 2$ for magnesium **[6]**.

The lattice thermal conductivity κ_L is mainly limited by phonon-impurity scattering at low temperatures and is given by [22],

$$\kappa_L = CT^2 \quad (6)$$

Thus, combining Eq. 3, Eq. 5, and Eq. 6, the total thermal conductivity κ of magnesium alloys can be expressed as

$$\kappa = (A/T + BT^2)^{-1} + CT^2 \quad (7)$$

where coefficients A , B , and C can be obtained through numerical fitting of the experimental data. Figures 8 – 10 display the fitting results which are in excellent agreement with the experimental data in a wide temperature range of 2 – 100 K. The coefficients A , B , and C are summarized in Table 3. The increasing trend of A for all the alloy systems reflects very well the enhanced electron-impurity scattering as the content of solute increases. The generally decreasing trend of C for all the alloy systems also indicates a stronger phonon-impurity scattering with more defects being introduced.

The parameter B in Eq. 7 is given by Sondheimer [23] as

$$B = DW_\infty N^{2/3} / \Theta_D^2 \quad (8)$$

where D is a constant having a value of 71.7 according to Sondheimer, N is the effective number of free electrons per atom, and W_∞ is the limiting value of the ideal thermal resistivity at high temperatures (using 300 K experimental value). The value of $N^{2/3} = 0.21$ obtained from Eq. 8 for pure Mg is in good agreement with the value of 0.22 obtained in Ref. 6.

In addition, it is **worth noting** that Eq. 7 is not only useful to predict the thermal

conductivity of binary magnesium alloys studied in this paper, but it is also applicable to the low-temperature thermal conductivity of other metal alloy systems, such as the aluminum and copper alloys shown in Fig. 11. The fitting parameters are given in Table 4. The fitting result agrees with the experimental data very well in all binary or multi-component alloys tabulated in Ref. 24.

Clearly, the type of impurity added to Mg does matter. Since the thermal conductivity is sensitive to the microstructure, the lattice distortion caused by different kinds of solute atoms can affect the value of thermal conductivity to a different degree. The lattice distortion may be regarded as the sum of two effects [25]:

- (1) One arising from the difference in atomic volumes of the solute and magnesium, which may lead to local lattice expansion or contraction, depending on whether the impurity has a larger or smaller atomic volume than magnesium.
- (2) The other effect is due to the difference in valence of a solute and magnesium such that the valence of the solute greater than 2 introduces a tendency towards lattice expansion and vice versa. This effect is closely related to the electronic structure of magnesium and the shape of the Brillouin zone [25]. Therefore, we provide some information about atomic volumes and valences of alloying elements in Table 5.

Comparing the atomic volumes of the three alloying elements with that of magnesium, we note that Mn has the most unfavorable size and thermal conductivity of Mg-Mn alloys is, indeed, the lowest, particularly at low temperatures where impurity scattering dominates. The electrical resistivity in Fig. 7 also attests to the fact that Mn creates the greatest distortion in the Mg lattice and the incremental resistivity is the

largest of the three impurities. Although Zn creates a greater **distortion** in the Mg lattice than does Al, its valence is identical to Mg and thus disturbs the band structure to a lesser extent. Adding Zn to Mg does not change the number of electrons per atom and the shape of the Brillouin zone is unchanged. In contrast, Al with its valence of 3 increases the number of electrons and, in fact, **activates the zone overlap and causes lattice distortions and**, hence, lowers the thermal conductivity.

5. Conclusions

The electrical resistivity and thermal conductivity of pure Mg and dilute binary Mg-Al, Mg-Zn and Mg-Mn magnesium alloys were measured over the temperature range 2 – 300 K. The following conclusions can be drawn:

- (1) Electrical resistivity increases with the increasing impurity content in each magnesium alloy system. The electrical resistivity of Mg-Al and Mg-Zn alloys is monotonically increasing while the electrical resistivity of Mg-Mn alloys shows a distinct minimum at low temperatures. Among the three alloying elements, Mn tends to induce the largest increment of residual resistivity, while Zn is the weakest electron scatterer.
- (2) Thermal conductivity of pure Mg, Mg-0.5%Zn and Mg-1.5%Zn alloys exhibited peaks in the temperature range 20 – 40 K, while no obvious peaks were found in Mg-Al and Mg-Mn alloys. The thermal conductivity of Mg-Al and Mg-Mn alloys increased monotonically with temperature.
- (3) Thermal conductivity of pure Mg and binary magnesium alloys was fitted to an

equation of $\kappa = (A/T + BT^2)^{-1} + CT^2$ in the temperature range 2 – 100 K and the parameters A, B, and C were determined. The value of parameters for pure Mg agrees well with the values previously established. The equation is also applicable for predicting the low-temperature thermal conductivity of other alloy systems such as aluminum and copper alloys.

(4) In binary magnesium alloys, different alloying elements exert different influence on the thermal conductivity. This is due to different volumes and different valences of solute and Mg atoms.

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References

- [1] Kulekci KM. Int J Adv Manuf Technol 2008;39:851.
- [2] Mordik BL, Ebert T. Mater Sci Eng A 2001;302:37.
- [3] Ostrovsky I, Henn Y. International Conference "NEW CHALLENGES IN AERONAUTICS" ASTEC'07, August 19-22, Moscow, (2007).

- [4] Galeazzi M, Bogorin DF, Prasai K, Uprety Y, McCammon D. Rev Sci Instrum 2010;81:076105.
- [5] Ho CY, Powell RW, Liley PE. J Phys Chem Ref 1972;1:279.
- [6] Kemp WRG, Sreedhar AK, White GK. Proc Phys Soc A 1953;66:1077.
- [7] Yamasaki M, Kawamura Y. Scripta Mater 2009;60:264
- [8] Rudajevová A, Buch FV, Mordike BL. J Alloys Compd 1999;292:27-30.
- [9] Lee S, Ham HJ, Kwon SY, Kim SW, Suh CM. Int J Thermophys 2013;34(12): 2343.
- [10] Chi H, Chen C, Phillips JD, Uher C. Appl Phys Lett 2013;103:042108.
- [11] Chi H, Liu W, Sun K, Su X, Wang G, Lošťák , Kucek V, Drašar Č, Uher C. Phys Rev B 2013;88:045202.
- [12] Kondo J. Prog. Theor Phys 1964;32:1.
- [13] Hedgcock FT, Rizzuto C. Phys Rev 1967;163:517.
- [14] Berman B. *Thermal conduction in solids*, Oxford: Clarendon Press; 1976.
- [15] Kumar GS, Prasad G, Pohl RO. J Mater Sci 1993;28:4261
- [16] Salkovitz EI, Schindler AI, Kammer EW. Phys Rev 1957;105:887
- [17] Schindler AI, Salkovitz EI. Phys Rev 1953;91:1320
- [18] Berman B, MacDonald DKC. Proc R Soc Lond A 1952;211:122.
- [19] White GK. Aust J Phys 1953;6:397.
- [20] Uher C. Thermal conductivity of metals, in: Tritt TM (Eds.). Thermal conductivity-Theory, Properties and Applications. New York: Kluwer Academic /Plenum Publishers; 2004.

- [21] White GK, Woods SB. Can J Phys 1954;33:58.
- [22] Powell RL, Roder HM, Rogers WM. J Appl Phys 1957;28:1282
- [23] Sondheimer EH. Proc Roy Soc A 1950;203:75.
- [24] Touloukian YS, Powell RW, Ho CY, Klemens PG. Thermophysical Properties of Matter, Vol. 1, New York: Plenum; 1970.
- [25] Raynor GV. *The Physical Metallurgy of Magnesium and Its Alloys*, London: Pergamon Press; 1959.

Table 1 The nominal and actual compositions of the binary magnesium alloys

Nominal composition of alloy (wt%)	Actual chemical composition (wt%)	Actual chemical composition (at%)
Mg-0.5%Al	0.58	0.52
Mg-1.0%Al	1.25	1.11
Mg-1.5%Al	1.88	1.67
Mg-0.5%Zn	0.51	0.19
Mg-1.5%Zn	1.49	0.55
Mg-2.5%Zn	2.59	0.97
Mg-4.0%Zn	4.05	1.50
Mg-5.0%Zn	5.20	1.92
Mg-0.5%Mn	0.49	0.22
Mg-1.0%Mn	0.93	0.41
Mg-1.5%Mn	1.47	0.65

Table 2 Temperature coefficient of electrical resistivity for binary magnesium alloys

Materials	Temperature coefficient ($\mu\Omega\text{-m/K}$)
Pure Mg	1.63
Mg-0.5% Al	1.99
Mg-1.0% Al	1.92
Mg-1.5% Al	1.98
Mg-0.5% Zn	1.84
Mg-1.5% Zn	2.33
Mg-2.5% Zn	1.67
Mg-4.0% Zn	1.56
Mg-5.0% Zn	1.89
Mg-0.5% Mn	1.98
Mg-1.0% Mn	1.60
Mg-1.5% Mn	1.64

Table 3 Summary of the coefficients of A , B , and C for binary magnesium alloys

Materials	A (m-K ² /W)	B (10 ⁻⁶ m/W-K)	C (10 ⁻³ W/m-K ³)
Pure Mg	0.020	0.96	-
Mg-0.5%Al	0.351	1.71	5.86
Mg-1.0%Al	0.593	2.92	5.38
Mg-1.5%Al	0.912	2.93	4.08
Mg-0.5%Zn	0.124	1.50	7.76
Mg-1.5%Zn	0.181	1.77	6.92
Mg-2.5%Zn	0.324	2.12	6.47
Mg-4.0%Zn	0.451	2.49	5.86
Mg-5.0%Zn	0.569	2.84	5.42
Mg-0.5%Mn	0.390	1.57	5.50
Mg-1.0%Mn	0.887	2.33	3.94
Mg-1.5%Mn	1.112	2.66	3.97

Table 4 Summary of the coefficients of A , B , and C for aluminum and copper alloys

Materials	A (m-K ² /W)	B (10 ⁻⁷ m/W-K)	C (10 ⁻³ W/m-K ³)
5052 Al alloy	0.890	6.84	2.51
5154 Al alloy	0.965	0.89	1.13
Cu-As alloy	0.605	29.9	7.84
Cu-Be alloy	2.081	39.3	2.75
Al-Cu-Mg alloy	0.627	5.59	0.15
Al-Fe-Si alloy	0.086	5.77	7.22
6063 Al alloy	0.116	6.14	7.36
5052-O Al alloy	0.839	11.8	3.62
5154-O Al alloy	0.967	15.2	3.80
5083-O Al alloy	1.296	18.0	2.89
3003-F Al alloy	0.364	8.59	5.84
7075 Al alloy	1.092	1.52	3.53

Table 5 Some basic information of various alloying elements in magnesium

Alloying element	Valence	$\Delta V / V_{Mg}^*$ (%)
Al	3	-28.4
Zn	2	-34.5
Mn	2 (7)	-47.1

* Atomic volume relative to magnesium

Figure 1: Temperature dependent electrical resistivity of Mg-Al alloys and of pure Mg in the temperature range of (a) 2 – 70 K and (b) 2 – 300 K.

Figure 2: Temperature dependent electrical resistivity of Mg-Zn alloys in the temperature range of (a) 2 – 70 K and (b) 2 – 300 K.

Figure 3: Temperature dependent electrical resistivity of Mg-Mn alloys in the temperature range of (a) 2 – 100 K and (b) 2 – 300 K. **Inset: $T_{\min}$ versus $c^{1/5}$ of Mg-Mn alloys.** Note a distinct minimum in the electrical resistivity curves that shifts to higher temperatures with increasing content of solute.

Figure 4: Temperature dependent thermal conductivity of Mg-Al alloys and of pure Mg.

Figure 5: Temperature dependent thermal conductivity of Mg-Zn alloys.

Figure 6: Temperature dependent thermal conductivity of Mg-Mn alloys.

Figure 7: Concentration dependence of residual resistivity of magnesium with Al, Zn and Mn impurities at 5K.

Figure 8: Comparison of fitting results with experimental data of thermal conductivity in pure Mg and Mg-Al alloys. Fitting coefficients are provided in Table 3.

Figure 9: Comparison of fitting results with experimental data of thermal conductivity in Mg-Zn alloys. Fitting parameters are provided in Table 3.

Figure 10: Comparison of fitting results with experimental data of thermal conductivity in Mg-Mn alloys. Fitting parameters are given in Table 3.

Figure 11: Comparison of fitting results with experimental data of thermal conductivity in (a) binary aluminum and copper alloys and (b) multi-component aluminum alloys. (All experimental data and compositions are from Ref. 23) **Fitting parameters are provided in Table 4.**