Interdiffusion in $\alpha$ Solid Solution of the Al-Cu-Mg-Ag System

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Keywords: aluminum-copper-magnesium-silver alloy, quaternary diffusion, diffusion couple, thermodynamic interaction

Quaternary and ternary interdiffusion experiments of Al-rich Al-Cu-Mg-Ag alloys have been performed in the temperature range from 793 to 853 K. The concentration profiles indicate that the diffusion distance of Cu is shorter than those of Mg and Ag in the solid solutions. The direct and indirect interdiffusion coefficients are positive in the ternary and quaternary alloys. The ratio of indirect coefficient to direct one suggests that repulsive interactions exist between Cu and Mg atoms in the Al-Cu-Mg-Ag alloys. In addition, the ratio values of converted interdiffusion coefficients in the quaternary alloys suggest that the interactions between Al(solvent) and Cu atoms are attractive in the present alloy.

(Received July 22, 2003; Accepted September 8, 2003)

1. Introduction

Most important and practical alloys are composed of multi-components. In particular, extensive studies about the metallography and materials structure have been carried out in Al-Cu-Mg-Ag alloys, because these alloys originated from duralmin are the promising structural materials. In order to obtain their superior mechanical properties of such aluminum alloys, the alloys are heat-treated for recovering, recrystallization, homogenization, aging, precipitation, etc. Diffusion is a basic and important factor for understanding and discussing the phenomena and the heat treatments. Therefore, it is necessary to obtain the information on the diffusion in such Al-base quaternary alloys.

Many experimental studies of diffusion in Al-base binary alloys have been performed in order to determine the only one interdiffusion coefficient. On the other hand, some investigations of diffusion have been made in Al-base ternary alloys in which the four coefficients were required to represent interdiffusion. Number of studies on diffusion in the ternary Al-Cu-Mg alloys as the practical materials is small in spite of its importance, and the interdiffusion coefficients in the ternary alloys have been reported only by the present authors.

In particular, a study on the diffusion in the quaternary Al-Cu-Mg-Ag alloys has been not investigated yet because the nine interdiffusion coefficients should be evaluated.

The purposes of the present work are (a) to determine the ternary interdiffusion coefficients in the $\alpha$-phase region of the ternary Al-Cu-Mg system in a temperature range from 793 to 853 K, (b) to determine the quaternary interdiffusion coefficients in the quaternary Al-Cu-Mg-Ag system at 813 K, and (c) to discuss the thermodynamic interactions between solute atoms (solvent-solute atoms) in $\alpha$ Al-Cu-Mg-Ag solid solutions.

2. Experimental Procedures

The Al-Cu, Al-Mg, Al-Cu-Mg and Al-Cu-Mg-Ag alloys for diffusion couples were prepared from 99.99 mass%Al, 99.99 mass%Mg, 99.99 mass%Ag, and a Al-39.61 mass%Cu mother alloy by high frequency induction melting in an argon atmosphere. These alloy ingots were annealed at 773 K for 432 ks for homogenization and grain coarsening. These alloys have a single phase of $\alpha$-phase solid solution and the grain diameter more than about 0.7 mm. The alloy ingots were cut into diffusion plates of $10 \times 10 \times 3 \text{mm}^3$ in size. The surfaces of the alloy plates were metallographically polished by SiC paper and 0.3 $\mu$m alumina powder. The polished plates for diffusion couples were hold together by means of stainless steel clamps. The terminal compositions of diffusion couples are listed in Table 1. The terminal compositions of ternary Al-Cu-Mg diffusion couples have been reported in elsewhere.

The assembled diffusion couples were placed in a Pyrex tube with Ti powder enclosed an aluminum foil. They were evacuated, and then sealed. The diffusion couples were annealed in a temperature range from 793 to 853 K for 12.6 to 96.3 ks. After diffusion annealing, the couples were quenched in ice water and then mounted in synthetic resin. The diffusion couples were cut at their center parallel to the diffusion direction in order to expose sections which had no oxidation and evaporation of elements. The exposed section of each couple was metallographically polished.

| Table 1 Terminal compositions of diffusion couples in Al-Cu-Mg-Ag alloys. |
|---------------------|-----------------|-----------------|
| Couple name | Compositions (at%) | Equivalent concentration |
| J1 | Al-0.42Cu-2.09Mg-1.74Ag/Al-1.88Cu-1.98Mg-1.48Ag | Mg, Ag |
| J2 | Al-1.16Cu-0.95Mg-1.45Ag/Al-1.13Cu-3.12Mg-1.35Ag | Cu, Ag |
| J3 | Al-1.31Cu-2.37Mg-0.42Ag/Al-1.20Cu-1.78Mg-3.25Ag | Cu, Mg |
concentration profiles in these diffusion couples were measured by a JEOL JXA-8900 electron microanalyzer (EPMA). The characteristic X-ray intensities of Cu, Mg and Ag were corrected for atomic number, absorption and fluorescence effects, and were converted into concentration values of Cu, Mg and Ag using the bulk alloy compositions at the ends of the couples as standards.\(^{10,11}\)

The interdiffusion coefficients in the Al-Cu-Mg alloys have been evaluated by using the extended Matano-Kirkaldy method to the ternary alloy system described elsewhere.\(^{12,13}\)

On the other hand, nine interdiffusion coefficients in a 4-components alloy system can be obtained from the diffusion profiles by using the extended Matano-Kirkaldy method to the 4-component alloy system.\(^{12,13}\)

\[
\int_{C_i(-\infty)}^{C_i(+\infty)} x dC_i = -2r \sum_{k=1}^{3} D_{ik} \frac{\partial C_k}{\partial x} \quad (i, 1, 2, 3),
\]

(1)

where \(C_i\) \((i=1, 2, 3)\) is the concentration of solute \(i\), \(C_i(-\infty)\) and \(C_i(+\infty)\): the terminal compositions at the ends of the diffusion couples, \(D_{ji}\) \((j=1, 2, 3)\) are the direct interdiffusion coefficients, \(D_{ik}\): the indirect interdiffusion coefficients, \(r\): the diffusion time, and \(x\): the distance from the Matano interface located at \(x = 0\), which can be determined for diffusion profile from the relation:

\[
\int_{C_i(-\infty)}^{C_i(+\infty)} x dC_i = 0 \quad (i, 1, 2, 3).
\]

(2)

For the 4-component system, three independent diffusion couples are needed, in general, for determination of nine interdiffusion coefficients at one common composition of intersection of the diffusion paths. In other words, the extended Matano-Kirkaldy method for quaternary system requires us to prepare three independent diffusion couples whose diffusion paths intersect at one common composition. It is quite difficult to satisfy this experimental condition.

Recently, an elegant method for the determination of the diffusion coefficients has been presented by Thompson and Morral\(^{14}\) under the assumption of “constant diffusivity” in the reaction zone of the multicomponent alloys. By definition, the diffusivity matrix \([\bar{D}]\) is related to its square root diffusivity matrix \([r]\)

\[
[\bar{D}] = [r][r]^{-1}
\]

(3)

The relation between \(D_{ij}\) and \(r_{ij}\) \((i, j=1, 2, 3)\) in quaternary alloys of this experiments is;

\[
\begin{bmatrix}
D_{11}^i & D_{12}^i & D_{13}^i \\
D_{21}^i & D_{22}^i & D_{23}^i \\
D_{31}^i & D_{32}^i & D_{33}^i
\end{bmatrix} = \begin{bmatrix}
r_{11} & r_{12} & r_{13} \\
r_{21} & r_{22} & r_{23} \\
r_{31} & r_{32} & r_{33}
\end{bmatrix} \begin{bmatrix}
r_{11} & r_{12} & r_{13} \\
r_{21} & r_{22} & r_{23} \\
r_{31} & r_{32} & r_{33}
\end{bmatrix}
\]

(4)

The values of \(r_{11}\) to \(r_{33}\) can be obtained experimentally from the following eqs. (5) and (6).

\[
S_i = -(t/\pi)0.5(r_{11}\Delta C_1 + r_{22}\Delta C_2 + r_{33}\Delta C_3)
\]

(5)

\[
\Delta C_i = C_i(+\infty) - C_i(-\infty) \quad (i = 1, 2, 3)
\]

(6)

The terms, \(S_1, S_2\) and \(S_3\), represent the amounts of solute which have crossed the initial interface, and \(\Delta C_i\) is the difference in the initial concentrations on the right and left sides of the couples.

3. Results and Discussion

3.1 Concentration profiles and diffusion paths

Typical concentration profiles of the J1, J2 and J3 couples annealed at 813 K for 86.03 ks are shown in Figs. 1(a), (b) and (c), respectively. The diffusion distance of Cu is shorter than those of Mg and Ag. The concentration profiles indicate that the diffusion rate of Cu is smaller than those of Mg and Ag in the Al-Cu-Mg-Ag alloys. Since the J1, J2 and J3 couples have nearly equal concentrations of the two solute elements in the terminal alloys as listed in Table 1, the concentration distribution of such elements are almost constant over the entire diffusion zone.

Figures 2(a) and (b) show the projections of the diffusion
paths for the quaternary J1, J2 and J3 couples at 813 K onto the C\textsubscript{Mg}-C\textsubscript{Cu} plane and the C\textsubscript{Ag}-C\textsubscript{Cu} plane, respectively.

### 3.2 Concentration dependence of interdiffusion coefficients

By using the extended Matano method to ternary diffusion (Matano-Kirkaldy method), the interdiffusion coefficients of \(D_{\text{AlCuCu}}\) and \(D_{\text{AlMgMg}}\) are evaluated at the intersection compositions of the diffusion paths\(^5\) in the ternary Al-Cu-Mg alloys in the temperature range from 793 to 853 K. These coefficients are shown in Figs. 3(a) and (b). The interdiffusion coefficients are not sensitive to the solute concentrations in the \(\alpha\) Al-Cu-Mg solid solutions.

Table 2(a) lists the values of the nine interdiffusion coefficients in the quaternary Al-Cu-Mg-Ag alloys evaluated from the concentration profiles of the diffusion couples (J1, J2, J3) at 813 K by the Thompson-Morral method. The direct interdiffusion coefficients \(D_{\text{CuCu}}\), \(D_{\text{MgMg}}\) and \(D_{\text{AgAg}}\) are positive, and the other indirect coefficients are positive. The direct interdiffusion coefficient \(D_{\text{CuCu}}\) is the smallest value among the direct ones. Table 2(b) shows the comparison of the values of the interdiffusion coefficients in the binary Al-Cu, Al-Mg, Al-Ag alloys,\(^{15,16}\) the ternary Al-Cu-Mg alloy and the quaternary Al-Cu-Mg-Ag alloy. The direct interdiffusion coefficient \(D_{\text{CuCu}}\) in the quaternary alloy does not almost change in comparison with the values of the binary and ternary alloys, but the direct coefficients \(D_{\text{AgAg}}\) and \(D_{\text{CuCu}}\) increase slightly.

![Fig. 2](https://via.placeholder.com/150)

Fig. 2 Projections of diffusion paths for quaternary diffusion couples J1, J2 and J3 at 813 K for 86.03 ks: (a) projections onto the C\textsubscript{Mg}-C\textsubscript{Cu} plane and (b) projections onto C\textsubscript{Ag}-C\textsubscript{Cu} plane.

![Fig. 3](https://via.placeholder.com/150)

Fig. 3 Concentration dependence of direct interdiffusion coefficients (a) \(D_{\text{AlCuCu}}\) and (b) \(D_{\text{AlMgMg}}\) of ternary Al-Cu-Mg system in a temperature range from 793 to 853 K.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Interdiffusion coefficients of quaternary Al-Cu-Mg-Ag system at 813 K and (b) Comparison of binary, ternary and quaternary interdiffusion coefficients at 813 K.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 813 K</td>
<td>(Thompson-Morral method)</td>
</tr>
<tr>
<td>Units (10^{-8} \text{ m}^2/\text{s})</td>
<td></td>
</tr>
<tr>
<td>(i \ \backslash \ j)</td>
<td>Cu</td>
</tr>
<tr>
<td>(D_{ij})</td>
<td>Cu</td>
</tr>
<tr>
<td>53.8</td>
<td>0.9</td>
</tr>
<tr>
<td>4.7</td>
<td>64.6</td>
</tr>
<tr>
<td>16.4</td>
<td>4.4</td>
</tr>
<tr>
<td>(b) 813 K ((k=\text{Al or 4})) (10^{-14} \text{ m}^2/\text{s})</td>
<td></td>
</tr>
<tr>
<td>(D_{ij})</td>
<td>Cu</td>
</tr>
<tr>
<td>Al-Cu</td>
<td>Al-Mg</td>
</tr>
<tr>
<td>13.3</td>
<td>*</td>
</tr>
<tr>
<td>42.2</td>
<td>*</td>
</tr>
<tr>
<td>27.3</td>
<td>*</td>
</tr>
<tr>
<td>1.8</td>
<td>*</td>
</tr>
<tr>
<td>3.5</td>
<td>*</td>
</tr>
<tr>
<td>0.05</td>
<td>*</td>
</tr>
<tr>
<td>5.6</td>
<td>*</td>
</tr>
</tbody>
</table>
3.3 Thermodynamic interactions among the solute components

Kirkaldy et al.\textsuperscript{17)} have approximately derived the relation between $D_{ij}^3/D_{ii}^3$ and Wagner’s interaction parameter, $\epsilon_i^{(1)}$ for very dilute solutions in the ternary alloy systems.

$$D_{ij}^3/D_{ii}^3 = [1 + \epsilon_i^{(1)}]N_i, \quad (i, j = 1, 2)$$  \hspace{1cm} (7)

The similar equation can be derived in the quaternary alloys derived by Kirkaldy et al.\textsuperscript{17)} From the phenomenological theory and Fick’s 2nd law, the diffusion flux of component $i$ is given by the following equations, \textsuperscript{19)} respectively,

$$J_i = \sum_{j=1}^{3} L_{ij}X_j$$  \hspace{1cm} (8)

$$J_i = - \sum_{j=1}^{3} D_{ij} \frac{\partial C_j}{\partial x} \quad (i, j = 1, 2, 3).$$  \hspace{1cm} (9)

where $L_{ij}$ are the phenomenological coefficients, $X_i$ are the driving force (thermodynamic force). The driving force $X_j$ are given by:

$$X_j = - \sum_{i=1}^{3} (\delta_{ij} + V_iC_j/V_iC_i) \mu_j/\partial x$$  \hspace{1cm} (10)

where $\delta_{ij}$ is the Kronecker symbol, 0 when $i \neq j$, 1 when $i=j$, $V_i$ is the partial molar volume of component $i$, and $\mu_j$ the chemical potential of component $i$. For example, the chemical potential $\mu_1$ of component 1 is expressed by

$$\mu_1 = \mu_1^0 + RT\ln N_1 + \gamma_1^0 + N_1\epsilon_1^{(1)} + N_2\epsilon_1^{(2)} + N_3\epsilon_1^{(3)}$$  \hspace{1cm} (11)

where $N_1$ is the mole fraction of component 1, $\gamma_1^0$ is the activity coefficient at infinite dilute solution. In eq. (8), we assume $L_{ij} = 0$ (i $\neq$ j) for very dilute solutions in the ternary alloy systems.\textsuperscript{13)} Substituting $X_j$ [eq. (10)] in eq. (8), and comparing factors of $\partial C_j/\partial x$ in eq. (8) and eq. (9), we obtain eq. (12) relating to the quaternary system. For solute atoms 1 and 2 (i = 1, j = 2),

$$D_{12}^4/D_{11}^4 = [N_1(N_1 + N_2)\epsilon_1^{(2)} + N_1(1 + N_2)\epsilon_2^{(2)}]/\{[(N_1 + N_2)(1 + N_1\epsilon_1^{(1)} + N_2\epsilon_2^{1(2)} + N_1N_2\epsilon_3^{(1)}).$$  \hspace{1cm} (12)

If eq. (12) is rearranged with eq. (13); in dilute solution $N_i = 0$ (i=1,2,3),

$$N_1N_2 = 0, \quad N_1N_3 = 0, \quad N_2N_3 = 0, \quad N_4 = 1.$$  \hspace{1cm} (13)

it becomes the following equation;

$$D_{12}^4/D_{11}^4 = [1 + \epsilon_1^{(2)}]N_1/[1 + (1 + \epsilon_1^{(1)})N_1].$$  \hspace{1cm} (14)

In particular, for highly dilute solution, it reduces the relation,\textsuperscript{17)}

$$D_{12}^4/D_{11}^4 = [1 + \epsilon_1^{(2)}]N_1.$$  \hspace{1cm} (15)

The equation in the quaternary alloys is the same equation as eq. (7) in ternary alloys derived by Kirkaldy et al.\textsuperscript{17)}

Also, Tanaka et al.\textsuperscript{20,21)} have derived a method for evaluation of interaction parameter in dilute liquid alloy in a ternary A-B-C alloy on the basis of the free volume theory by Shimoji and Niwa\textsuperscript{22)}

$$\epsilon_B^{(C)} = ([\partial G^{ex}/\partial C_B]_{T=0,K=0}/kT = (\eta_B^{(C)} - T\sigma_B^{(C)})/kT$$  \hspace{1cm} (16)

where $G^{ex}$ is the excess Gibbs free energy, k the Boltzmann constant, $\eta_B^{(C)}$ and $\sigma_B^{(C)}$ are the enthalpy and entropy interaction parameters, respectively.\textsuperscript{20)} The values of $\eta_B^{(C)}$ can be calculated by using Miedema’s enthalpy\textsuperscript{23)} of solution at infinite dilution relating the constituent elements. In addition, the values of $\eta_B^{(C)}$ can be evaluated on the basis of molar volume\textsuperscript{21,24)} of the constituent elements, the melting point, and the coefficient ($\beta$)\textsuperscript{25)} to transfer the solid state frequency to that in the liquid at the melting point.

In accordance with eq. (7), the relation between $D_{AlCuMg}^{AlCuMg}/D_{AlCuMg}^{AlCuMg}$ and Mg concentration in the Al-Cu-Mg system at 753, 793 and 813 K is plotted in Figs. 4(a). This figure also includes the ratio of $D_{AlCuMg}^{AlCuMg}/D_{AlCuMg}^{AlCuMg}$ at 813 K in the quaternary Al-Cu-Mg-Ag alloy. Figure 4(b) shows the relation between $D_{MgCu}^{MgCu}/D_{MgCu}^{MgCu}$ and Cu concentration at 813 K and also shows the similar ratio values at 813 and 832 K in the quaternary Al-Cu-Mg-Alloy. In addition, the ratios of $D_{MgCu}^{MgCu}/D_{MgCu}^{MgCu}$ at 813 K in the ternary Al-Cu-Zn alloy\textsuperscript{7)} are plotted by the closed circles in Fig. 4(b). The broken lines are drawn by eq. (7) with the values of $\epsilon_{Mg}^{(Cu)}$.
and \( \varepsilon_{\text{Cu}}^{(\text{Mg})} = +9 \) in Al-Cu-Mg alloys, respectively. The experimental values of \( D_{\text{MgCu}}^{\text{Al}} / D_{\text{MgMg}}^{\text{Al}} \) and \( D_{\text{CuMg}}^{\text{Al}} / D_{\text{CuCu}}^{\text{Al}} \) increase with the Mg and Cu concentration in the Al-Cu-Mg alloys, although they scatter around the line of \( \varepsilon_{\text{Cu}}^{(\text{Mg})} = +9 \). The (ratio) values of \( D_{\text{MgCu}}^{\text{Al}} / D_{\text{MgMg}}^{\text{Al}} \) and \( D_{\text{CuMg}}^{\text{Al}} / D_{\text{CuCu}}^{\text{Al}} \) in the quaternary Al-Cu-Mg-Ag alloy exhibit the positive values.

While eq. (16) is applied for the calculation of interaction parameters, one has \( \varepsilon_{\text{Mg}}^{(\text{Cu})} = +2.2 \) and \( \varepsilon_{\text{Cu}}^{(\text{Zn})} = +1.5 \) in the \( \alpha \) solid solution of Al-Cu-Mg and Al-Cu-Zn alloys, respectively. These positive values of \( \varepsilon_{\text{Mg}}^{(\text{Cu})} \) and \( \varepsilon_{\text{Cu}}^{(\text{Zn})} \) indicate that repulsive interactions exist between Cu and Mg atoms. Similarly, the positive sign of \( \varepsilon_{\text{Mg}}^{(\text{Cu})} \) in eq. (7) is in agreement with that of value obtained by eq. (16) (\( \varepsilon_{\text{Mg}}^{(\text{Cu})} = 2.2 \)). It is evident that the repulsive interactions between Mg and Cu atoms exist in the ternary system. In the quaternary system, the \( D_{\text{MgCu}}^{\text{Al}} / D_{\text{MgMg}}^{\text{Al}} \) and \( D_{\text{CuMg}}^{\text{Al}} / D_{\text{CuCu}}^{\text{Al}} \) have large positive values. These facts indicate that the interactions between Mg and Cu atoms have a repulsive force in the quaternary alloys as well as ternary ones, and that the silver element has a small influence on the interaction between Cu and Mg elements.

The converted equations relating to the ternary interdiffusion coefficients have been reported by Sabatier and Vignes.\(^{26}\) Their equations can be extended to the quaternary alloy system. When the component of ‘solvent’ is 4 (=Al), for example, the diffusion flux of component 1 is expressed by the following equation,

\[
J_1 = -D_{11}^{\text{Al}} \partial C_1 / \partial x - D_{12}^{\text{Al}} \partial C_2 / \partial x - D_{13}^{\text{Al}} \partial C_3 / \partial x. \tag{17}
\]

In addition, the component 2 (=Mg) is considered as the solvent;

\[
J_1 = -D_{11}^{\text{Al}} \partial C_1 / \partial x - D_{13}^{\text{Al}} \partial C_3 / \partial x - D_{14}^{\text{Al}} \partial C_4 / \partial x. \tag{18}
\]

\[
\sum_{i=1}^{4} C_i V_i = 1 \tag{19}
\]

On the assumption that the partial molar volumes \( V_i \) of 1, 2, 3 and 4 are constant, eq. (19) is differentiated with respect to \( x \), and then is substituted in eqs. (17) and (18). When both equations are compared in the diffusion coefficient terms, the quaternary converted equations similar to the ternary system can be obtained as follows

\[
D_{11}^{\text{Al}} = D_{11}^{\text{Al}} - (V_1 / V_2) D_{12}^{\text{Al}}, \tag{20}
\]

\[
D_{13}^{\text{Al}} = D_{13}^{\text{Al}} - (V_3 / V_4) D_{12}^{\text{Al}}, \tag{21}
\]

and

\[
D_{14}^{\text{Al}} = -(V_4 / V_2) D_{12}^{\text{Al}} \tag{22}
\]

For instance, by using the equation \( D_{14}^{\text{Al}} / D_{11}^{\text{Al}} = 1 + \varepsilon_{\text{Cu}}^{(\text{Al})} \), the effect of 4 (=Al) on 1 (=Cu) can be considered. The interaction parameter \( \varepsilon_{\text{Cu}}^{(\text{Al})} \) is found from the calculation to be \(-2.0\) by using the quaternary interdiffusion coefficients in Table 2(a). The values of \( V_1 (1=\text{Cu}), V_2 (2=\text{Mg}), V_3 (3=\text{Ag}) \) and \( V_4 (4=\text{Al}) \) calculated from the data of the lattice parameters are 7.1, 14.0, 10.3 and 10.0 \((\times 10^{-6} \text{ m}^3 \text{ mol}^{-1})\). From the value of \( \varepsilon_{\text{Cu}}^{(\text{Al})} \), it is thought that the interactions between Al and Cu atoms have attractive force in the quaternary alloys. If the component 1 (=Cu) and 3(=Ag) are considered as the solvent, the equations similar to eqs. (20) through (22) are derived, and the interactions between Al and Mg (or Ag) can be discussed.\(^{27}\) However, the discussion is beyond the scope of this paper.

4. Summary

Quaternary and ternary interdiffusion experiments of Al-rich \( \alpha \) Al-Cu-Mg-Ag alloys have been performed in the temperature range from 793 to 853 K. The results are summarized as follows.

1. The direct and indirect interdiffusion coefficients are positive in the quaternary alloys. The direct coefficient \( D_{\text{CuCu}}^{\text{Al}} \) is the smallest value among the direct ones. The direct coefficient \( D_{\text{MgMg}}^{\text{Al}} \) in the quaternary alloy does not almost change in comparison with the values of the binary and ternary alloys, but the direct coefficients \( D_{\text{AgAg}}^{\text{Al}} \) and \( D_{\text{CuCu}}^{\text{Al}} \) increase slightly.

2. From the ratio values of indirect coefficient to direct one, it is suggested that repulsive interactions of Cu-Mg atoms exist in the Al-Zn-Mg-Cu alloys. In addition, from the converted equations relating to the interdiffusion coefficients in the quaternary alloys, it is thought that the interactions between Al and Cu atoms have attractive force in the present alloy.

Acknowledgments

This work was financially supported by the Light Metal Educational Inc., Osaka 541-0056, Japan. The authors are deeply indebted to the support. Chemical analysis of the aluminum alloys was performed by Showa Aluminum Co., Ltd., Oyama 323. The authors would like to thank Mr. Satoshi Hozumi of the company for his assistance of the chemical analysis.

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