Solubility of Fe in Al Rich Region of Al–Mg–Si System at 973 K

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Solubility of Fe in the liquid of Al–Mg–Si alloys was determined at 973 K. The liquid of Al–Mg–Si alloy with Fe concentration of up to 15 wt% was heated at 973 K. After equilibration a part of liquid was sampled and solidified to analyze the chemical compositions by X-ray fluorescence. The solubility of Fe was determined as functions of Mg and Si concentrations in weight percent as follows,

\[ C_{Fe} = -(0.14 \pm 0.00)C_{Mg} + (0.02 \pm 0.01)C_{Si} + (2.74 \pm 0.03) \]

The solid phase coexisting with the Fe saturated liquid was FeAl3 in which Si was dissolved up to 2.4 at%.

KEY WORDS: aluminizing; solubility.

1. Introduction

The production of zinc coated steels for the body of automobile has increased recently because of protection of the steel from environmental corrosion. However, the reserve of Zn is estimated to run out approximately 20 years. Alternative coating materials are required for sustainable supply of surface coated steels. A coating of Al–Mg–Si alloy is proposed as a potential alternative because Al has large amount of reserve and exhibits high corrosion resistance. Magnesium offers sacrificial protection to a coating. Silicon suppresses the growth of Fe–Al intermetallic layer which generates between the coating and Fe substrate. Thinner intermetallic layer is better for the formability of the aluminized steel.

The aluminized steel is expected to be fabricated in continuous coating process. In this process, Fe dissolves from steel to the liquid, and saturation is reached due to continuous immersion of the steel. Solubility of Fe is important to fabricate a coating of the Al alloy, because the microstructure of a coating layer shows the solidified structure of the Fe saturated liquid of Al–Mg–Si alloy. On the other hand, the layers of FeAl3 and Fe2Al5 form on steel during the immersion of steel in the liquid of Al–Mg–Si alloy. This reaction takes place within several seconds. The early stage of reaction may frequently be so fast that the concentrations in the liquid alloy near the reaction interface would be different from those in the bulk. Solubility of Fe in the liquid of Al alloy is influenced by concentrations of the other elements. It is necessary to determine the solubility of iron as functions of concentrations of the other elements.

Phillips reported the Al–Mg–Si–Fe quaternary phase diagram. Figure 1 shows the liquidus at various temperatures in the Al-rich region at 8 wt%Mg. The alloy composition for aluminizing is shown in this figure. It indicates that the solubility of Fe in the liquid of the alloy at 973 K is approximately 2.5 wt%, and FeAl3 is in equilibrium with the liquid of Al alloy. However, Phillips mentioned that the liquidus in the area where FeAl3 is a primary crystal could not link up with the liquidus in his previous report of Al–Si–Fe ternary system. Hence, the solubility of Fe in the liquid of Al–Mg–Si alloy is still in question. This study determines the solubility of Fe in the Al rich region of Al–Mg–Si system at 973 K.

2. Experimental

2.1. Materials

Solubility of Fe in three types of the liquid of Al alloy was investigated. Iron foil (Nilaco Corp., purity of 99.99% and thickness of 0.1 mm) was used as an iron source. Table 1 summarizes the chemical composition of Al–Mg–Si alloys and nominal Fe concentration before each experiment.

![Fig. 1. Liquidus of Al–Si–Fe–8 wt%Mg quaternary system.](image-url)
2.2. Experimental Procedure

Figure 2 shows a schematic illustration of the apparatus. The Al–Mg–Si alloy ingot of 36.3 g and Fe foil correspond to each nominal concentration were put into an MgO crucible and set at the isothermal zone of the furnace. Argon was introduced into the chamber at flowing rate of \(1.7 \times 10^{-6} \text{ m}^3\text{s}^{-1}\). The temperature at the bottom of the crucible was continuously monitored by a K-type thermocouple in an MgO tube. The temperature was increased at heating rate of 0.083 Ks\(^{-1}\). The liquid was frequently agitated by an MgO tube during the heating process.

It takes long time to achieve equilibrium state in higher Fe contents than solubility. In the experiments of 3, 5 and 15 wt%Fe, the temperature of the sample was raised to 1023 K for 3.6 ks in order to enhance the dissolution of Fe and the equilibrium state at 973 K was reached from higher Fe concentration. For determination of the composition of the liquid, the liquid was sampled by an MgO tube preheated over the liquid. Then, the temperature was decreased to 973 K and the liquid was agitated to prevent the supercooling. The temperature fluctuation was within ±0.5 K at 973 K. The liquid was sampled three times every 3.6 ks at 973 K. After the sampling of the liquid, the crucible was taken from the furnace and air-cooled.

2.3. Analytical Method

Dimension of the sample taken by an MgO tube was 4 mm in diameter and 20 mm in length. The sample was mounted in epoxy resin and the cross section along its length was prepared. The cross section was ground with abrasive paper of #320–#2000 and finally polished with 2 \(\mu\text{m}\) diamond paste. Concentrations of Al, Mg, Si and Fe were measured by X-ray Fluorescence Spectroscopy (XRF, Shimadzu LAB CENTER XRF-1800). The size of X-ray beam was 3 mm in diameter to get the concentration of large area because the sample exhibited the solidification structure. The area which has shrinkage cavity and Fe based intermetallic compound which was in equilibrium with the liquid is not suitable for XRF analysis to get the Fe concentration in the liquid. Therefore, the microstructure of the cross section of the sample was examined by an optical microscope prior to the XRF analysis. Many points were measured to cover whole area of the cross section of the sample where did not have any shrinkage cavity or the Fe based intermetallic compound.

The air-cooled ingot in crucible was 30 mm in diameter and 25 mm in length. The cross section of the ingot along its length was prepared and polished. Microstructure was observed by an optical microscope. Large grains in the cross section were identified by the composition evaluated by electron probe micro-analyzer (EPMA, Shimadzu EPMA-8705). The size of the electron beam was 1 \(\mu\text{m}\).

3. Results

3.1. Determination of Intermetallic Compound Existed in Liquid at 973 K

Figures 3(a) and 3(b) show the appearance of the cross section of the ingots of Al–8.55 wt%Mg–4.85 wt%Si alloy with 1.05 wt%Fe and 5.04 wt%Fe, respectively. The appearance of the ingot with 1.05 wt%Fe is uniform and no particle is observed in Fig. 3(a). On the other hand, some particles
are observed at bottom part of the ingot with 5.04 wt%Fe in Fig. 3(b). Figure 4 shows the optical micrographs of the cross section of the ingots of Al–8.55 wt%Mg–4.85 wt%Si alloys with various Fe concentrations. The center of a numbered circle is the point analyzed by EPMA with the electron beam of 1 μm in size. The chemical composition determined by EPMA is also shown in Fig. 4. The chemical composition is expressed in atomic percent in order to determine the phase of intermetallic compounds by its composition. Figures 4(a) and 4(b) show the microstructure of Al–8.55 wt%Mg–4.85 wt%Si alloy without Fe and with 1.05 wt%Fe, respectively. The microstructure of the alloy with 1.05 wt%Fe shows fine eutectic structure as same as that without Fe. Small particles of Mg2Si are also observed.

Fig. 4. Optical micrographs and the chemical composition of large phases in the ingot of Al–8.55 wt%Mg–4.85 wt%Si alloy. (a) Without Fe (b) 1.05 wt%Fe, (c) 3.04 wt%Fe, (d) 5.04 wt%Fe, and (e) 15.00 wt%Fe.

Fig. 5. Optical micrographs and the chemical composition of large phases in the ingot of Al–8.1 wt%Mg–2.1 wt%Si alloy. (a) 3.00 wt%Fe, (b) 5.00 wt%Fe.
in Fig. 4(b). On the other hand, the microstructures of 3.04, 5.04 and 15.00 wt%Fe shown in Figs. 4(c) to 4(f) have large phases in the matrix. The EPMA analysis shows the phases are FeAl_3. This fact coincides the reported phase diagram of Al–Si–Fe ternary system, indicating that FeAl_3 is in equilibrium with Fe saturated liquid of Al alloy with Si concentration up to 9.6 wt%Si at 973 K. The Si concentration in FeAl_3 is between 1.6 and 2.4 at% and Mg concentration is negligibly small. The Mg_2Si is also observed in the Figs. 4(b), 4(d) and 4(f). The Mg_2Si crystallized during cooling of the liquid. Because, the chemical composition of Al–Mg–Si alloy shifted from Al–Mg_Si quasi-binary eutectic composi-

| Sampling time, t/ks | Concentration, C/wt% |
|--------------------|---------------------|
|                    | Al     | Mg     | Si     | Fe     |
| 3.6                |        |        |        |        |
| 5.04               | 87.50  | 6.27   | 5.77   | 0.98   |
| 5.10               | 87.35  | 6.22   | 5.61   | 0.89   |
| 5.16               | 87.22  | 6.39   | 5.32   | 0.87   |
| 5.22               | 87.46  | 6.82   | 6.71   | 0.81   |
| 5.28               | 87.64  | 6.61   | 6.72   | 0.79   |
|                    | Average|        |        |        |
|                    | 87.54  | 6.61   | 6.54   | 1.04   |
|                    | Standard deviation | 0.25   | 0.18   | 0.13   | 0.05   |

| 7.2                |        |        |        |        |
| 5.04               | 86.64  | 6.82   | 6.62   | 1.04   |
| 5.10               | 86.57  | 6.27   | 6.54   | 1.04   |
| 5.16               | 86.46  | 6.82   | 6.71   | 0.91   |
| 5.22               | 86.74  | 6.71   | 6.48   | 1.06   |
| 5.28               | 86.64  | 6.61   | 6.72   | 1.04   |
|                    | Average|        |        |        |
|                    | 86.81  | 6.61   | 6.54   | 1.04   |
|                    | Standard deviation | 0.25   | 0.18   | 0.13   | 0.03   |

| 10.8               |        |        |        |        |
| 5.04               | 86.67  | 6.82   | 6.62   | 1.04   |
| 5.10               | 86.57  | 6.24   | 6.57   | 1.04   |
| 5.16               | 86.46  | 6.82   | 6.71   | 0.93   |
| 5.22               | 86.74  | 6.94   | 6.36   | 0.69   |
| 5.28               | 86.64  | 6.61   | 6.72   | 1.04   |
|                    | Average|        |        |        |
|                    | 86.19  | 6.77   | 6.03   | 1.01   |
|                    | Standard deviation | 0.70   | 0.30   | 0.43   | 0.08   |
tion to hypereutectic composition due to the consumption of Al for the formation of FeAl3. Figures 5 and 6 show optical micrographs of the cross section of the ingots of Al–8.1 wt%Mg–2.1 wt%Si alloy with 3 and 5 wt%Fe and Al–3.55 wt%Mg–2.00 wt%Si alloy with 5 wt%Fe, respectively. The large phases are identified to be FeAl3 with Si concentration from 0.5 at% to 0.9 at%. The magnesium concentration is negligibly small.

3.2. Fe Concentration in the Liquid

Figure 7 shows the optical micrograph of the cross section of Al–8.55 wt%Mg–4.85 wt%Si alloy with 5.04 wt%Fe after holding at 973 K for 10.8 ks. The fine particles of FeAl3 are observed, whereas there is no large FeAl3 as shown in Fig. 4(d). Figure 8(a) shows the appearance of the cross section of the sample of Al–8.55 wt%Mg–4.85 wt%Si alloy with 5.04 wt%Fe after holding at 973 K for 10.8 ks. The sample has the shrinkage cavity, and this part is not suitable for XRF analysis. The measured points are illustrated with the circles of 3 mm in diameter in Fig. 8(b). All of the measured concentrations are shown in Tables 2 to 8. If FeAl3 particles are included accidentally in the sampling process, the Fe concentration of the part may be much higher than the other part. However, the part with much higher Fe concentration is not observed.

To confirm the equilibrium, the Fe concentration in the sample as a function of holding time is plotted in Figs. 9 to 11.

Table 3. Results of concentration measurement by XRF in Al–8.55 wt%Mg–4.85 wt%Si alloy with 3.04 wt%Fe.

| Sampling time, t/ks | Concentration, C/wt% |
|--------------------|----------------------|
|                    | Al      | Mg      | Si      | Fe      |
| 3.6                |         |         |         |         |
| 84.51              | 7.99    | 5.80    | 1.70    |         |
| 84.26              | 8.01    | 5.76    | 1.97    |         |
| 84.57              | 8.03    | 5.70    | 1.71    |         |
| 84.60              | 8.01    | 5.61    | 1.78    |         |
| 84.54              | 7.77    | 5.74    | 1.95    |         |
| 84.41              | 7.77    | 6.08    | 1.74    |         |
| 84.56              | 7.84    | 6.14    | 1.46    |         |
| 84.58              | 7.76    | 6.00    | 1.66    |         |
| 84.32              | 7.98    | 5.99    | 1.71    |         |
| 84.42              | 7.72    | 6.27    | 1.59    |         |
| 84.31              | 7.89    | 6.08    | 1.71    |         |
| 84.60              | 7.88    | 5.93    | 1.59    |         |
| 83.95              | 7.65    | 6.47    | 1.93    |         |
| Average            | 84.43   | 7.87    | 5.97    | 1.73    |
| Standard deviation | 0.18    | 0.12    | 0.24    | 0.14    |

Table 4. Results of concentration measurement by XRF in Al–8.55 wt%Mg–4.85 wt%Si alloy with 5.04 wt%Fe.

| Sampling time, t/ks | Concentrations, C/wt% |
|--------------------|----------------------|
|                    | Al      | Mg      | Si      | Fe      |
| 3.6                |         |         |         |         |
| 83.46              | 8.27    | 6.30    | 1.97    |         |
| 83.91              | 8.09    | 6.07    | 1.94    |         |
| 84.45              | 8.16    | 5.60    | 1.79    |         |
| 84.17              | 8.17    | 5.98    | 1.68    |         |
| 84.28              | 8.06    | 5.88    | 1.78    |         |
| 84.05              | 7.95    | 6.07    | 1.93    |         |
| 84.17              | 8.09    | 6.07    | 1.67    |         |
| 84.01              | 8.02    | 6.13    | 1.84    |         |
| 84.17              | 8.16    | 6.04    | 1.62    |         |
| 84.20              | 8.00    | 6.04    | 1.77    |         |
| 83.96              | 8.20    | 6.05    | 1.79    |         |
| 83.62              | 7.96    | 6.41    | 2.01    |         |
| 83.92              | 8.05    | 6.27    | 1.76    |         |
| 84.38              | 7.68    | 6.11    | 1.84    |         |
| 84.22              | 7.77    | 6.03    | 1.98    |         |
| Average            | 84.09   | 7.99    | 6.13    | 1.79    |
| Standard deviation | 0.23    | 0.16    | 0.21    | 0.13    |

Table 5. Results of concentration measurement by XRF in Al–8.55 wt%Mg–4.85 wt%Si alloy with 7.04 wt%Fe.

| Sampling time, t/ks | Concentrations, C/wt% |
|--------------------|----------------------|
|                    | Al      | Mg      | Si      | Fe      |
| 3.6                |         |         |         |         |
| 84.09              | 7.99    | 6.13    | 1.79    |         |
| Average            | 84.09   | 7.99    | 6.13    | 1.79    |
| Standard deviation | 0.23    | 0.16    | 0.21    | 0.13    |

Table 6. Results of concentration measurement by XRF in Al–8.55 wt%Mg–4.85 wt%Si alloy with 10.84 wt%Fe.

| Sampling time, t/ks | Concentrations, C/wt% |
|--------------------|----------------------|
|                    | Al      | Mg      | Si      | Fe      |
| 10.8               |         |         |         |         |
| 84.87              | 7.98    | 5.98    | 1.17    |         |
| 83.67              | 8.40    | 6.03    | 1.90    |         |
| 84.21              | 8.22    | 5.89    | 1.68    |         |
| 84.18              | 8.20    | 5.99    | 1.63    |         |
| 84.09              | 7.97    | 5.88    | 2.06    |         |
| 84.38              | 7.98    | 5.83    | 1.81    |         |
| 84.32              | 7.95    | 6.06    | 1.67    |         |
| 83.80              | 8.29    | 6.09    | 1.83    |         |
| 84.22              | 7.97    | 6.20    | 1.61    |         |
| 84.08              | 7.97    | 6.00    | 1.95    |         |
| 83.98              | 7.96    | 6.28    | 1.79    |         |
| 84.25              | 7.95    | 6.14    | 1.66    |         |
| Average            | 84.17   | 8.07    | 6.03    | 1.73    |
| Standard deviation | 0.29    | 0.15    | 0.13    | 0.21    |
The average of the Fe concentrations in a sample is defined to be the Fe concentration in the sample, and the values are shown in Tables 2 to 8. The error bar corresponds to the standard deviation of the Fe concentrations. The Fe concentrations in the sample taken at 1 023 K are also plotted in these figures. Figure 9 shows Fe concentrations in samples of Al–8.55 wt%Mg–4.85 wt%Si alloys as a function of holding time. The Fe concentrations are independent of time, indicating the equilibrium state. Fe concentrations in the sample of 1.05 wt%Fe is 1.03 wt%. It indicates that

### Table 5. Results of concentration measurement by XRF in Al–8.55 wt%Mg–4.85 wt%Si alloy with 15.00 wt%Fe.

| Sampling time, t/ks | Concentrations, C/wt% | Al  | Mg  | Si  | Fe  |
|---------------------|-----------------------|-----|-----|-----|-----|
| 3.6                 |                       | 82.79 | 9.80 | 5.98 | 1.44|
|                     |                       | 82.72 | 9.82 | 6.04 | 1.43|
|                     |                       | 83.80 | 9.17 | 5.64 | 1.39|
|                     |                       | 83.92 | 8.98 | 5.63 | 1.48|
|                     |                       | 82.82 | 9.78 | 6.07 | 1.34|
|                     |                       | 82.08 | 9.81 | 6.79 | 1.33|
|                     |                       | 81.45 | 9.92 | 7.23 | 1.40|
|                     |                       | 80.20 | 10.58| 7.80 | 1.42|
|                     |                       | 81.16 | 10.05| 7.45 | 1.33|
|                     |                       | 81.50 | 9.56 | 7.35 | 1.59|
|                     |                       | 81.42 | 9.59 | 7.46 | 1.54|
|                     |                       | 81.95 | 9.60 | 6.98 | 1.46|
|                     |                       | 81.38 | 9.96 | 7.27 | 1.39|
|                     |                       | 81.12 | 10.05| 7.33 | 1.50|
| Average             |                       | 82.02 | 9.76 | 6.79 | 1.43|
| Standard deviation  |                       | 1.03  | 0.37 | 0.73 | 0.07|

### Table 6. Results of concentration measurement by XRF in Al–8.1 wt%Mg–2.0 wt%Si alloy with 3.00 wt%Fe.

| Sampling time, t/ks | Concentrations, C/wt% | Al  | Mg  | Si  | Fe  |
|---------------------|-----------------------|-----|-----|-----|-----|
| 7.2                 |                       | 87.28 | 7.68 | 3.20 | 1.84|
|                     |                       | 87.60 | 7.73 | 2.88 | 1.79|
|                     |                       | 87.47 | 7.77 | 2.92 | 1.85|
|                     |                       | 87.58 | 7.98 | 2.93 | 1.51|
|                     |                       | 87.46 | 7.84 | 2.99 | 1.71|
|                     |                       | 87.29 | 8.07 | 2.99 | 1.65|
|                     |                       | 87.40 | 7.98 | 2.97 | 1.65|
|                     |                       | 87.41 | 7.98 | 3.09 | 1.51|
|                     |                       | 87.44 | 7.84 | 2.98 | 1.75|
|                     |                       | 87.54 | 7.95 | 2.96 | 1.55|
|                     |                       | 87.51 | 7.89 | 2.89 | 1.72|
|                     |                       | 87.76 | 7.63 | 2.71 | 1.89|
|                     |                       | 87.52 | 7.82 | 3.04 | 1.63|
|                     |                       | 87.12 | 8.12 | 3.20 | 1.56|
|                     |                       | 87.60 | 7.76 | 2.86 | 1.78|
|                     |                       | 87.45 | 7.80 | 3.03 | 1.72|
|                     |                       | 87.42 | 7.89 | 2.95 | 1.74|
|                     |                       | 87.23 | 8.03 | 3.23 | 1.51|
|                     |                       | 87.58 | 7.63 | 3.00 | 1.79|
|                     |                       | 87.27 | 8.03 | 3.05 | 1.65|
|                     |                       | 87.27 | 8.12 | 3.08 | 1.53|
|                     |                       | 87.60 | 7.66 | 2.95 | 1.79|
| Average             |                       | 87.44 | 7.87 | 3.00 | 1.69|
| Standard deviation  |                       | 0.15  | 0.15 | 0.12 | 0.12|

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Table 7. Results of concentration measurement by XRF in Al–8.1 wt%Mg–2.0 wt%Si alloy with 5.00 wt%Fe.

| Sampling time, t/ks | Concentrations, C/wt% |
|---------------------|-----------------------|
|                     | Al       | Mg       | Si       | Fe       |
| 3.6                 |          |          |          |          |
| 3.6                 | 87.16    | 8.28     | 3.03     | 1.53     |
| 87.20               | 8.42     | 2.92     | 1.46     |
| 87.19               | 8.41     | 2.98     | 1.41     |
| 87.48               | 8.02     | 2.96     | 1.54     |
| 87.00               | 8.33     | 3.15     | 1.52     |
| 86.85               | 8.50     | 3.14     | 1.44     |
| 87.03               | 8.25     | 3.17     | 1.54     |
| 87.42               | 7.76     | 3.02     | 1.80     |
| 87.47               | 8.03     | 2.81     | 1.69     |
| 87.38               | 8.27     | 2.81     | 1.55     |
| 87.58               | 8.00     | 2.65     | 1.76     |
| 87.16               | 8.27     | 2.88     | 1.70     |
| 87.42               | 7.76     | 3.02     | 1.80     |
| 87.38               | 8.27     | 2.81     | 1.55     |
| 87.58               | 8.00     | 2.65     | 1.76     |
| 87.16               | 8.27     | 2.88     | 1.70     |
| 87.42               | 7.76     | 3.02     | 1.80     |
| 87.38               | 8.27     | 2.81     | 1.55     |
| 87.58               | 8.00     | 2.65     | 1.76     |
| 87.16               | 8.27     | 2.88     | 1.70     |
| Average             | 87.24    | 8.21     | 2.96     | 1.58     |
| Standard deviation  | 0.21     | 0.16     | 0.12     |

| Sampling time, t/ks | Concentrations, C/wt% |
|---------------------|-----------------------|
| 7.2                 |          |          |          |          |
| 7.2                 | 87.65    | 8.82     | 2.86     | 1.66     |
| 87.74               | 7.68     | 2.86     | 1.73     |
| 87.57               | 8.08     | 2.79     | 1.56     |
| 87.87               | 7.61     | 2.82     | 1.71     |
| 87.71               | 7.72     | 2.86     | 1.72     |
| 87.43               | 8.33     | 2.73     | 1.51     |
| 87.62               | 7.56     | 3.01     | 1.81     |
| 88.09               | 7.33     | 2.73     | 1.85     |
| 87.47               | 8.08     | 2.71     | 1.74     |
| 87.40               | 8.04     | 2.86     | 1.70     |
| Average             | 87.67    | 7.84     | 2.82     | 1.67     |
| Standard deviation  | 0.18     | 0.08     | 0.11     |

Table 8. Results of concentration measurement by XRF in Al–3.55 wt%Mg–2.00 wt%Si alloy with 5.00 wt%Fe.

| Sampling time, t/ks | Concentrations, C/wt% |
|---------------------|-----------------------|
| 10.8                |          |          |          |          |
| 10.8                | 91.31    | 3.30     | 3.06     | 2.33     |
| 91.23               | 3.33     | 3.06     | 2.38     |
| 91.52               | 3.21     | 2.89     | 2.37     |
| 91.53               | 3.26     | 3.01     | 2.20     |
| 91.75               | 3.20     | 2.76     | 2.29     |
| 91.67               | 3.16     | 2.88     | 2.29     |
| 91.34               | 3.13     | 3.10     | 2.43     |
| 91.65               | 2.99     | 2.94     | 2.44     |
| 91.16               | 3.24     | 3.06     | 2.54     |
| 91.49               | 3.11     | 3.02     | 2.39     |
| 91.60               | 3.25     | 2.71     | 2.45     |
| 91.73               | 3.03     | 2.83     | 2.41     |
| 91.75               | 2.88     | 2.95     | 2.43     |
| 91.87               | 3.07     | 2.76     | 2.30     |
| Average             | 91.54    | 3.15     | 2.93     | 2.37     |
| Standard deviation  | 0.21     | 0.12     | 0.12     | 0.08     |
1.05 wt% is lower than the solubility in Al–8.55 wt%Mg–4.85 wt%Si alloy. On the other hand, the Fe concentrations in the sample of 3, 5, and 15 wt%Fe in Al–8.55 wt%Mg–4.85 wt%Si alloy are lower than nominal Fe concentrations. These results show that 3, 5, and 15 wt%Fe are higher than the solubility in this alloy. Figures 10 and 11 show the Fe concentration as a function of holding time in Al–8.1 wt%Mg–2.1 wt%Si alloy and Al–3.5 wt%Mg–2.0 wt%Si alloy, respectively. All of the Fe concentrations are independent of time, indicating the equilibrium.

4. Discussion

4.1. Solubility of Fe in Al–Mg–Si System

The phase rule of Gibbs under constant temperature and pressure is expressed as

$$F = C - P$$

where $F$ is the degree of freedom, $C$ is the number of components, and $P$ is the number of phases. As explained earlier, only FeAl$_3$ is determined to be in equilibrium with liquid Fe.
at 973 K. The number of components is four, and the number of phases is two in this study. Hence, the degree of freedom is two. It means that the solubility of Fe is affected by concentration of the other two elements. The Eq. (2) is applied to represent the solubility of Fe as functions of concentrations of Mg and Si.

\[
C_{Fe} = p C_{Mg} + q C_{Si} + r
\]

where \( C \) is the concentration in weight percent, and subscripts are the elements. The \( p, q, \) and \( r \) are the coefficients in the equation. The calculation of the coefficients in the equation follows the least square method, and the equation is derived as follows.

\[
C_{Fe} = -(0.14 \pm 0.00)C_{Mg} + (0.02 \pm 0.01)C_{Si} + (2.74 \pm 0.03)
\]

Figure 12 shows Fe concentrations as functions of Mg and Si concentration. The plane which is expressed as the Eq. (3) is also drawn in Fig. 12. The value of intercept at the \( C_{Fe} \) axis is 2.74, indicating the solubility of Fe in Al at 973 K. This value is consistent with the literature value of 2.60.

4.2. Solidified Microstructure at the Reaction Interface

Figure 13 schematically illustrates the aluminizing process and the possible concentration distribution of each element in the liquid of Al–Mg–Si alloy. The layer of FeAl\(_3\) forms on the top of steel and the layer of Fe\(_2\)Al\(_5\) grows between the steel and FeAl\(_3\). Figure 4 shows that the Si concentration in FeAl\(_3\) which coexisted with the liquid was 2 at% and the Mg concentration was negligibly small. The Al is consumed for the growth of FeAl\(_3\) and the Si dissolved into FeAl\(_3\), but the Mg remains near the reaction interface. The concentrations at the reaction interface are expected to be different from those in the bulk as shown in Fig. 13. The concentration of Al in the liquid is so large that the supply of Al to reaction interface is sufficient and the decrease of Al concentration would be very small. The concentration of Si in liquid at the interface is smaller and that of Mg is larger than the bulk composition. The Eq. (3) shows that the decrease of Si concentration and the increase of Mg concentration decrease the solubility of Fe in the liquid of the alloy. It enhances the formation of FeAl\(_3\) near the reaction interface. The microstructure of coating layer close to the layer of FeAl\(_3\) would have more FeAl\(_3\) precipitates than the solidified structure of the liquid of the bulk.

4.3. Estimation of the Si Concentration in the Liquid at the Reaction Interface

The thickness of intermetallic layer affects the formability of the aluminized steel. The Si is added to Al in order to suppress the growth of Fe–Al intermetallic layer. The effect of Si concentration on the growth rate of FeAl\(_3\) is an interesting issue. In the continuous aluminizing process, the Si concentration at the reaction interface would be lower than that of the bulk liquid as shown in Fig. 13. It is important to know the Si concentrations in the liquid at the reaction interface. Figure 14 shows the Si concentration in the liquid as a function of the Si concentration in FeAl\(_3\).
5. Conclusion

Solubility of Fe in three kinds of Al–Mg–Si alloy at 973 K was investigated. The Fe saturated liquid was in equilibrium with FeAl\(_3\) containing Si. The solubility of Fe is expressed as functions of Mg and Si concentrations as follows,

\[
C_{\text{Fe}} = -(0.14 \pm 0.00)C_{\text{Mg}} + (0.02 \pm 0.01)C_{\text{Si}} + (2.74 \pm 0.03)
\]

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