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Al-rich part phase relation in Al-Mg-Sc system at 430 ℃①

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Abstract: Phase relation of the aluminium-magnesium-scandium system in the Al-rich range at 430 ℃ was investigated by means of multiphase diffusion couples along with electron probe microanalysis, X-ray diffraction and electron microscopy techniques. It consists of five single-phase fields, four 2-phase fields and one 3-phase field. The maximum solid solubilities of Mg and Sc in α(Al) solid solution at 430 ℃ are about 15.27% Mg(mole fraction) and 0.33% Sc, respectively. The maximum solid solubilities of Sc in Mg_2Al_3 and $Mg_{17}Al_{12}$ are about 1.08% and 0.03% at the same temperature. The diffusion path at 430 ℃ was constructed and interpreted by means of the Al-Mg-Sc equilibrium phase diagram assuming that local equilibrium is established at the phase boundaries.

Key words: Al-Mg-Sc; diffusion couple; isothermal section; diffusion path
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1 INTRODUCTION

Wrought non-heat-treatable Al-Mg alloys are used widely as structural materials for their good weldability, excellent corrosion resistance and ductility. However, even the most strong alloys of this system containing 5% - 6% Mg do not show adequate strength. Small scandium additions to aluminium alloys are beneficial to improving the specific properties of these light alloys. In the aluminium case, scandium acts as a potential dispersoid strengthener, grain refiner and recrystallisation inhibitor. Additionally, positive effects on weldability and welding properties have been observed. An overview of the current knowledge in this field is given by Refs. [1 - 4]. Furthermore, ternary alloys based on aluminium are potential candidates for aeronautical applications. An Al-Mg-Sc sheet offers advantages because it does not require cladding to provide high corrosion resistance and shows improved weldability. Potential applications for future subsonic aircrafts are suggested to include the fuselage belly of Al-Mg-Sc sheet laser welded to an Al-Mg-Sc integral structure[5].

In order to control process conditions to obtain specific alloy properties, knowledge of the underlying phase diagrams is indispensable. The phase equilibria in the binary Al-Sc[6] and Mg-Sc[7] have been elaborated recently. However, only a few data points are available for the ternary Al-Mg-Sc system. The first report on this system has been published by Turkina et al[8]. They studied the phase relations in the Al-rich part of the diagram up to 26% Mg and 3% Sc (mass fraction). An isothermal section at 430 ℃ as well as two isopleths have been drawn based on DTA measurements and microscopic investigations. Those T-C diagrams show some inconsistencies in comparison with the isothermal section. A second work on this system has been performed by Odinaev et al[9, 10]. They examined the Al-Mg rich side of the diagram by DTA, micrographic and X-ray methods. Based on these measurements, an isothermal section at 400 ℃ has been drawn as well as the partial liquidus surface. Basic features are two broad two-phase regions Al_2Sc-(Mg) and Al_2Sc-γ($Al_{12}Mg_{17}$) and a three-phase field Al_2Sc-γ-β(Al_3Mg_2). Al_2Sc is only in equilibrium with Al and β.

The purpose of this study is the determination of the ternary phase equilibria in the Al-Mg-Sc system. The key experiments are defined and performed. The diffusion couples along with electron probe microanalysis(EPMA), scanning electron microscope(SEM) and X-ray diffraction(XRD) analysis are used to establish the 430 ℃ phase relations of the Al-Mg-Sc system in the Al-rich range and to evaluate the diffusion path of the Al-Mg-Sc interface.

2 EXPERIMENTAL

The specimens used in the present work were prepared from elemental materials as follows: 99.99%(mass fraction) magnesium and Al-1.77% Sc(mass fraction) hardeners. These components were assembled into a diffusion couple after ground and polished. The samples were sealed into quartz capsules under vacuum(10^{-4} Pa) and annealed at 430 ℃ for 720 h in a GK-2B type diffusion furnace. The quartz capsules were hermetically sealed filled with 3×10^4 Pa high-purity argon gas to prevent oxidation

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and volatilization. The temperature was controlled with a thyristor regulator and was found to be within ±1 ℃ as measured with a calibrated Ni-Cr/Ni-Al thermocouple. After the heat treatments these samples were water quenched by breaking the capsules, and then prepared by mechanical polishing using a cloth with chromium oxide parallel to the diffusion direction.

The microstructural investigations were carried out by SEM (JSM-5600LV). XRD was done on an XD-98 diffractometer with unfiltered copper radiation (λ = 1.540 56 Å). The diffraction graphs were calculated using the software of the Peking University XRD system. The composition of each phase in the annealed samples was determined by EPMA (CAMECA-CAMEBAX-SX51) using an accelerating voltage of 15 kV and take off angle 40°.

3 RESULTS AND DISSCUSSION

3.1 Microstructure and composition

Fig. 1 shows the microstructure of the diffusion regions and the schematic phase distribution of the Al-Mg-Sc diffusion couple annealed at 430 ℃ for 720 h. Two layers of the intermetallic compound with clear phase boundary were found. It was identified by EPMA as being Mg_2Al_3, $Mg_{17}Al_{12}$. Table 1 lists some of the experimental tie-lines in the diffusion couple annealed at 430 ℃. These data were made on a CAMEBAX-CAMECA-CX51 set with accelerating voltage of 15 kV and take off angle 40°. The aluminium, magnesium and scandium standards were taken from parts of the corresponding components far away from the diffusion region. The microprobe measurements of each tie-line was taken at a pair of points close to each interfaces.

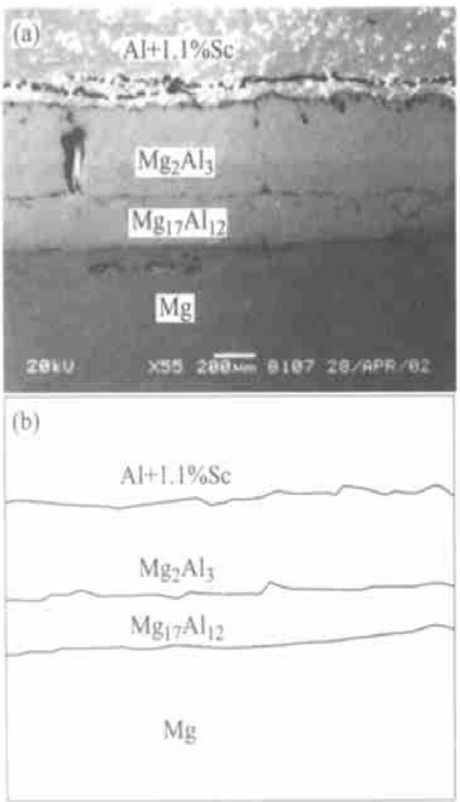

Fig. 1 Phase distribution in Al-Mg-Sc diffusion couple annealed at 430 ℃ for 720 h
(a) —Backscattered electron image (BEI);
(b) —Schematic diagram

Table 1 Electron microprobe measurements of phase equilibria in Al-Mg-Sc diffusion couple annealed at 430 ℃ for 720 h (mass fraction, %)

Al_3Sc			α(Al)		
Sc	Mg	Al	Sc	Mg	Al
27.45	0.03	72.52	0.17	3.92	95.91
27.38	0.04	72.58	0.28	11.76	87.96
27.54	0.05	72.41	0.21	13.51	86.28
27.66	0.10	72.24	0.33	15.27	84.40
Al_3Sc			Mg_2Al_3		
Sc	Mg	Al	Sc	Mg	Al
27.75	0.18	72.07	1.08	37.68	61.24
28.36	0.29	71.35	0.69	39.33	59.98
26.96	0.49	72.55	0.03	41.29	58.68
27.67	2.04	70.29	0.01	42.45	57.74
Mg_2Al_3			$Mg_{17}Al_{12}$		
Sc	Mg	Al	Sc	Mg	Al
0.01	43.01	56.98	0.01	62.98	37.01
0.01	42.70	57.29	0.01	51.10	48.89
0.69	39.33	59.98	0.02	50.53	49.95
1.05	37.74	61.21	0.03	50.90	49.07

From the results of the EPMA, it was established that the maximum solid solubility of magnesium and scandium in α(Al) solid solution at 430 ℃ is about 15.27% Mg and 0.33% Sc (mole fraction), respectively. The maximum solid solubilities of scandium in β(Mg_2Al_3) and γ($Mg_{17}Al_{12}$) at the same temperature are about 1.08% and 0.03% (mole fraction) respectively. The composition range of magnesium in the β(Mg_2Al_3) and γ($Mg_{17}Al_{12}$) phases is about 37.68%–43.01% and 50.90%–62.98% (mole fraction), respectively.

3.2 X-ray diffraction analysis

The annealed Al-Mg-Sc diffusion couple was examined by XRD analysis, the corresponding calculation of the diffraction pattern is listed in Table 2. From the XRD profile, the intermetallic compound β (Mg_2Al_3) has face-centered cubic lattice and its maximal peak is at $2\theta = 37.536°$ with (11 3 3) crystal face indice; the $\gamma(Mg_{17}Al_{12})$ phase has A12 cubic lattice, but its maximal peak is not observed because we use the copper radiation, if the molybdenum radiation ($\lambda = 0.7107$ Å) was used in the experiment, all the diffraction pattern of $\gamma(Mg_{17}Al_{12})$ phase will be observed in the profile. The Al_3Sc phase has $L1_2$ (Cu_3Au) lattice. The data are in good agreement with those in the Al-Sc and Al-Mg phase diagrams reported by Cacciamani[6] and Okamoto[6, 11].

The 430 ℃ phase relation of the Al-Mg-Sc system in the Al-rich range derived from the present investigation carried out by XRD, SEM and EPMA and from the Al-Sc, Al-Mg, Mg-Sc binary phase diagrams[6, 11, 12] is shown in Fig. 2. There coexist three compounds: Al_3Sc, $\beta(Mg_2Al_3)$ and $\gamma(Mg_{17}Al_{12})$ in the Al-Mg-Sc system at 430 ℃. Apart from $\alpha(Al)$, Al_3Sc, β, γ and $\alpha(Mg)$ single-phase fields, four 2-phase fields and one 3-phase fields have been determined to be present in this section and they are $\alpha(Al) + Al_3Sc$, $\alpha(Al) + \beta$, $\beta + \gamma$, $\gamma + \alpha(Mg)$ and $\alpha(Al) + Al_3Sc + \beta$ respectively.

Table 2 Calculation of diffraction pattern in diffusion couple

2θ/(°)	d/Å	(h k l) Al	Mg	Al_3Sc	Mg_2Al_3	$Mg_{17}Al_{12}$
30.916	2.89			(110)		
31.498	2.8379				(771)	
32.94	2.7169				(10 2 2)	
34.358	2.608		(002)			
35.222	2.5459				(11 1 1)	
37.536	2.3941				(11 3 3)	
38.1	2.3599			(111)		
38.477	2.3377	(111)				
38.628	2.3289				(11 5 1)	
39.312	2.29				(12 0 0)	
44.137	2.0502			(200)		
44.730	2.0244	(200)				
63.06	1.473		(103)			
65.108	1.4315	(220)			(14 14 0)	
73.42	1.2886					(321)
77.80	1.2267		(202)		(19 13 1)	
78.247	1.2208	(311)				
78.69	1.2150					(400)

3.3 Observed diffusion path at 430 ℃

Heat treatment at 430 ℃ for 720 h resulted in the isothermal diffusion of scandium, magnesium and aluminium atoms. Two layers were formed in the bond zone of (Al+ Sc)-Mg range in the diffusion couple. These phase were identified metallographically and analyzed using electron microprobe analysis (see Table 1). Fig. 1 shows the backscattered electron image (BEI) of the (Al+ Sc)-Mg bond interface. In the first layer which is close to the aluminium side, the magnesium content ranges from 37.68% to 43.01% (mole fraction) and the scandium content ranges from 1.08% to 0.01%. Consequently, this layer should be $\beta(Mg_2Al_3)$. In the next layer the magnesium content ranges from 50.53% to 62.98% and the scandium content ranges from 0.03% to 0.01%. So it is $\gamma(Mg_{17}Al_{12})$ phase. According to the SEI micrograph in Fig. 1 and the compositions range of each phase, the diffusion path of scandium which goes through the $\alpha(Al)$, $\beta(Mg_2Al_3)$, $\gamma(Mg_{17}Al_{12})$ and $\alpha(Mg)$ phases' regions is plotted in Fig. 2 (dashed line). At 430 ℃ the composition of $\alpha(Al)$ with 1.1% Sc is in the two-phase field of $\alpha(Al) + Al_3Sc$, but the equilibrium scandium concentration of $\alpha(Al)$ is 0.33%. Annealing causes the scandium activity to decrease monotonically in the $\alpha(Al)$ phase region. When the scandium activity is equal at the phase boundary of α-β, local equilibrium is established at the phase boundary. The path then covers across the β phase and the scandium activity gradient is established inside the β phase. As the time

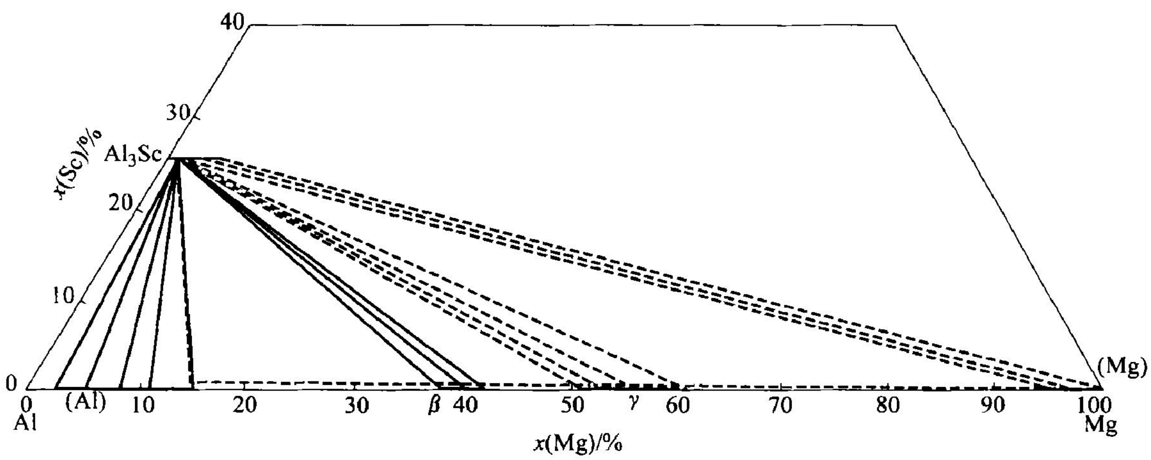

Fig. 2 Isothermal section of Al-Mg-Sc system and diffusion path at 430 ℃

increases, the scandium activity decreases from γ to magnesium side in the bond zone and the scandium activity decreases to zero in the 100% Mg composition point.

4 CONCLUSIONS

1) The phase relation of the Al-Mg-Sc system in the Al-rich range at 430 ℃ was experimentally constructed by EPMA, XRD and EMS. The section consists of five single-phase fields, four 2-phase fields and one 3-phase fields. The maximum solid solubilities of scandium in β(Mg_2Al_3) and γ($Mg_{17}Al_{12}$) phases are about 1.05% and 0.03% at 430 ℃, whilst the maximum solid solubilities of scandium and magnesium in α(Al) solid solution are about 0.33% Sc, 15.27% Mg, respectively.

2) The diffusion path of scandium atoms at 430 ℃ in the Al-Mg-Sc system are analyzed. The diffusion path is governed by the local equilibrium established at the phase boundaries. The diffusion path of scandium which goes through the α(Al), β(Mg_2Al_3), γ($Mg_{17}Al_{12}$), α(Mg) phase regions in the bond zone of (Al+ 1.1% Sc)-Mg range in the diffusion couple at 430 ℃ was constructed.

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