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Study on Evolution of Ti-containing Intermetallic Compounds in Alloy 2618-Ti during Homogenization

Abstract: Dispersive Al_3Ti particles introduced into alloy 2618-Ti are enclosed gradually by ternary $Al_{18}Mg_3Ti_2$ phase during homogenization, which can be described as a "peritectic reaction". This reaction is sensitive to homogenization temperature and time within 24 h but not so sensitive to homogenization time after 24 h because of its special growth pattern. The evolution of the intermetallic compounds during homogenization process of alloy 2618-Ti is further confirmed by means of diffusion couple of (Al-25Mg)/(Al-10Ti). After homogenization, much Al_3Ti particles coexist with $Al_{18}Mg_3Ti_2$ which depends on the composition of Al-Mg-Ti system and only a few single $Al_{18}Mg_3Ti_2$ appear. The occurrence of single $Al_{18}Mg_3Ti_2$ phase, within which Al_3Ti disappears, can be attributed to the local fluctuation of alloy compositions.

Keywords: aluminum alloys, ternary system, phase transitions, phase equilibria, diffusion

DOI 10.1515/htmp-2014-0136
Received August 11, 2014; accepted September 27, 2014;

1 Introduction

Aluminum alloy 2618 (AA2618) is a heat-treatable wrought aluminum alloy with its strength derived from aging precipitation hardening of coherent Guinier-Preston-Bagaryatskii (GPB) zone and semi-coherent S′ (Al_2CuMg) and dispersion hardening of stable Al_9FeNi intermetallic phases [1, 2]. It is widely used for aeronautical application up to 150 °C such as aircraft engine components and cladding of ultrasonic aircrafts, etc. However, strength declines in a long term exposure to elevated temperature which limits its wider application [3]. To further improve its properties at elevated temperature, many researches [2, 4–8] have been carried in recent years.

Aluminum alloys reinforced with aluminide particles (Al_3Ni, Al_3Fe, Al_3Ti, etc.) possess excellent properties both at ambient and elevated temperature [9]. Among these aluminum-rich intermetallic compounds, Al_3Ti is very attractive due to its high melting point, low diffusivity and solubility in aluminum, which result in a low coursing rate at elevated temperature [10]. Because of this reason, Ti is added into alloy 2618 to introduce Al_3Ti particles in the alloy. However, it is very interesting that a new phase forms around Al_3Ti after homogenization, which was found in our research work. So it is necessary to explain the evolution of the intermetallic compounds during the homogenization process of alloy 2618-Ti.

2 Experimental

The alloy 2618-Ti (Al-2.3Cu-1.6Mg-1.1Fe-1.1Ni-1.5Ti, wt.%) was fabricated by solid-liquid mixing and near-liquidus casting [11]. After casting, the ingot was machined into specimens to a size of 10 mm × 10 mm × 8 mm. The specimens were homogenized at the temperatures ranging from 450 °C–500 °C in step of 10 °C for 24 h, respectively. Besides, some specimens were homogenized at 500 °C for 12 h, 24 h, 72 h and 12 days, respectively. After homogenization, all specimens were quenched in water at room temperature. To further confirm the phase formed around Al_3Ti particles in alloy 2618-Ti, a solid-solid diffusion couple of (Al-25wt.%Mg)/(Al-10wt.%Ti) was prepared by heating the Al-Mg alloy over its melting point and then immersing the Al-Ti master alloy into the Al-Mg melt. The diffusion couple was sealed in an evacuated quartz tube, and then annealed at 500 °C for 12 h, followed by water quenching.

The specimens for observation were prepared through conventional metallographic procedures and followed by etching in a standard Keller's reagent. Microstructures of the studied alloys were investigated using Leica DIM 3000 optical microscope (OM), JSM-6510 scanning electron microscope (SEM) equipped with OXFORD energy dispersive spectrometry (EDS). The phase identification of alloy

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2618-Ti and diffusion couple was carried out using D-5000 X-ray diffractometer (XRD) using Cu Kα radiation.

3 Results and discussion

3.1 The optical microstructures of alloys

The microstructures of as-cast alloy 2618 and 2618-Ti are shown in Fig. 1. As shown in Fig. 1(b), a lot of dispersed Al_3Ti particles exist within α-Al matrix and the grain size of alloy 2618-Ti decreases remarkably compared with that of alloy 2618 as shown in Fig. 1(a). The size of rod-shaped Al_3Ti is about 2–15 μm in length and 2–5 μm in width. Fig. 2 shows the microstructures of alloy 2618-Ti homogenized at different temperature for 24 h and the BSE images at 500 °C for different time. After homogenization at temperatures from 460~500 °C for 24 h, Al_3Ti particles are surrounded by a new phase (labeled as X) as shown in Fig. 2(b)–(c). However, this phenomenon is not obvious when the alloy 2618-Ti is homogenized at 450 °C for 24 h as shown in Fig. 2(a). With the increasing of homogenization temperature, the size of Al_3Ti particles decreases and the X phase grows up gradually. The BSE images of alloy 2618-Ti homogenized at 500 °C (the highest homogenization temperature [12]) for different time can be seen in Fig. 2(d)–(f). As the increasing of the homogenization time within 24 h, the size of Al_3Ti particles decreases dramatically (Fig. 2(d)–(e)) and a few Al_3Ti particles disappear completely after long time homogenization as shown in Fig. 2(f).

3.2 The analysis of SEM microstructure

To determine what the X phase is, the distributions of alloying elements around Al_3Ti particles are analyzed as shown in Fig. 3. It can be observed that the distributions of Fe, Ni and Cu in as-cast alloy 2618-Ti are similar to that in homogenized alloy. But the content of Mg becomes rich in the areas around Al_3Ti particles and the peak width of the distribution line of titanium increases, too. Thus, it can be inferred that both Ti and Mg are contained in the X phase formed during homogenization. The results of EDS analysis of X phase are listed in Table 1. The compositions of the phase are very close to that of phase $Al_{18}Mg_3Ti_2$ existed in Al-Mg-Ti system at temperatures of 800−820 K in Ref. [13].

3.3 The microstructure of diffusion couple

To further confirm which the X phase is, a diffusion couple of (Al-25wt.%Mg)/(Al-10wt.%Ti) were investigated. Fig. 4 shows the microstructure of (Al-25wt.%Mg)/(Al-10wt.%Ti) diffusion couple annealed at 500 °C for 12 h, and the XRD patterns of the couple and alloy 2618-Ti before and after homogenization. For the diffusion couple, the X-ray diffraction analysis is conducted near the side of Al-25wt.%Mg alloy and on the cross section perpendicular to the diffuse interface. It can be known from the binary phase diagrams of Al-Ti and Al-Mg that α−Al and Al_3Mg_2 coexist in Al-25wt.%Mg alloy, and α−Al and Al_3Ti coexist in Al-10wt.%Ti alloy. It can be seen in Fig. 4(a) that a new phase forms around Al_3Ti particles in the diffusion zone after annealing at 500 °C for 12 h. The EDS results of the phases in the diffusion zone are listed in Table 1. According to the EDS analysis, the spots from A to D are corresponding to Al_3Mg_2 phase, Mg-rich solid solution of α−Al in Al-Mg alloy, Ti-containing solid solution of α−Al in Al-Ti alloy with little amount of Mg and Al_3Ti phase, respectively. The compositions of spot E are also close to that of the phase $Al_{18}Mg_3Ti_2$ in Ref [13].

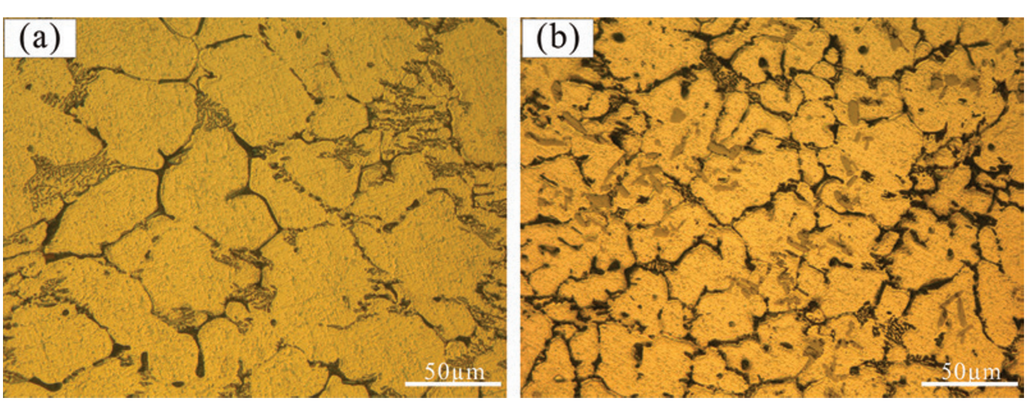

Fig. 1: Microstructures of as-cast alloys: (a) alloy 2618, (b) alloy 2618-Ti.

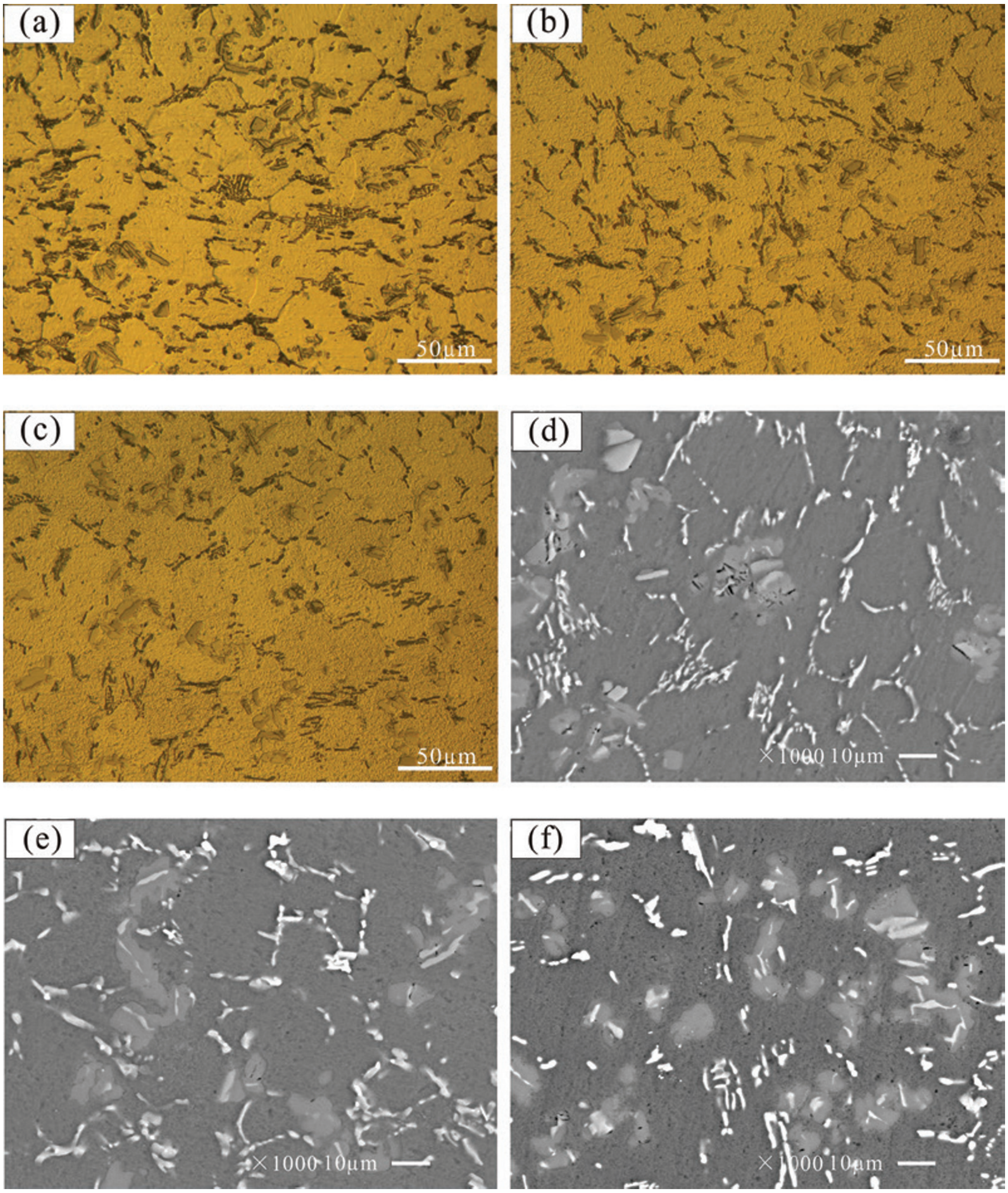

Fig. 2: OM microstructures of alloy 2618-Ti homogenized at different temperature for 24 h: (a) 450 °C, (b) 460 °C, (c) 500 °C; and BSE images at 500 °C for different time: (d) 12 h, (e) 24 h, (f) 12 d.

3.4 XRD pattern analyses

Fig. 4(b) displays the XRD patterns of the diffusion couple and the alloy 2618-Ti before and after homogenization. As is known to all, the intensity of diffraction peaks corresponding to some phase mainly depends on phase amounts and its inherent nature. Thus, some phases existed in alloy 2618-Ti such as Al_9FeNi etc. cannot be detected because of their limited amount. On the contrary, the peaks in XRD patterns could determine the existence of certain phase. From the XRD results, it can be concluded that as-cast alloy 2618-Ti is mainly composed of α-Al and Al_3Ti. $Al_{18}Mg_3Ti_2$ forms in both the diffusion couple and the homogenized alloy 2618-Ti, which is well consistent with the former line-scan and EDS results. So, both the new phase X existed in alloy 2618-Ti and the spot E in diffusion couple can be identified as the ternary $Al_{18}Mg_3Ti_2$ phase.

3.5 Theoretical explanation to the formation of $Al_{18}Mg_3Ti_2$

Similar to the "peritectic theory" proposed to hypothesize the mechanism of grain refinement of Ti, the formation

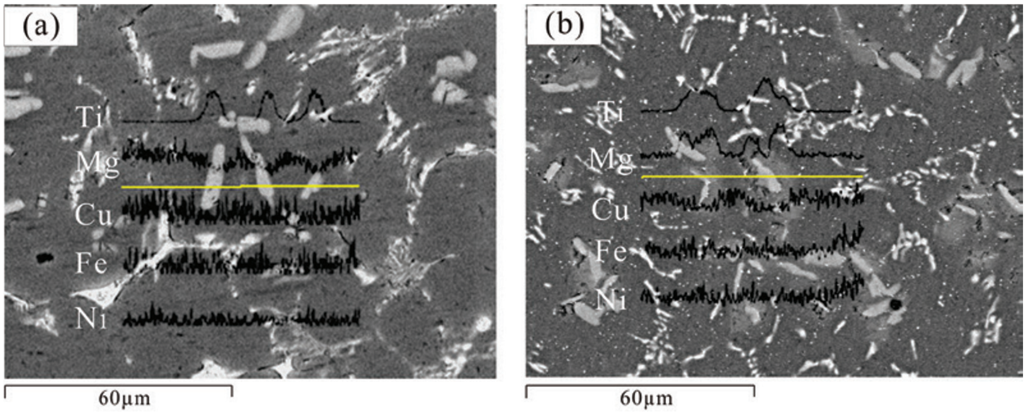

Fig. 3: Elements distribution around Al_3Ti in (a) as-cast and (b) homogenized alloy 2618-Ti.

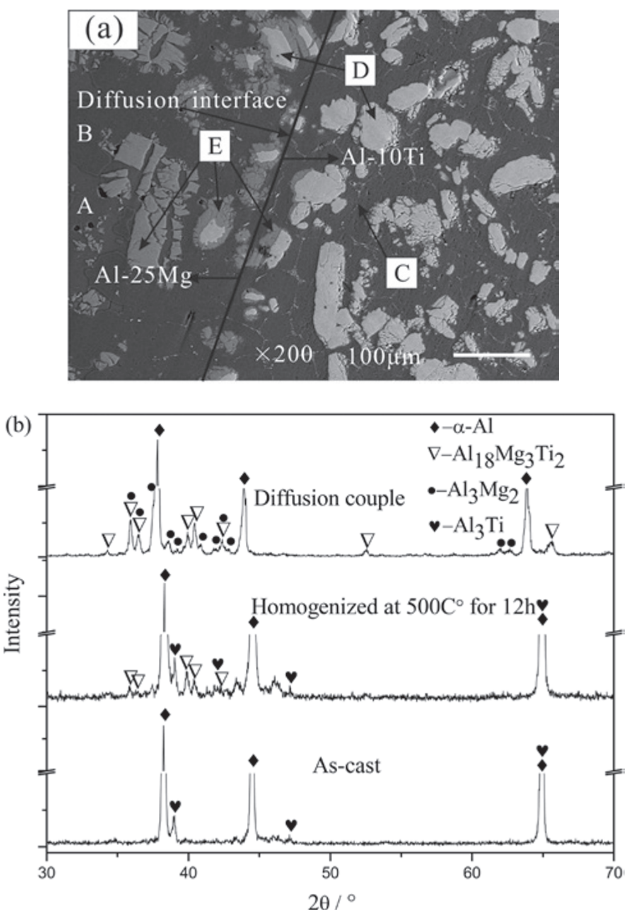

Fig. 4: (a) Microstructure of (Al-25wt.%Mg)/(Al-10wt.%Ti) diffusion couple annealed at 500 °C for 12 h and (b) XRD patterns of the couple and alloy 2618-Ti.

of $Al_{18}Mg_3Ti_2$ around the phase Al_3Ti can also be regarded as a result of "peritectic reaction", $Al_3Ti + \alpha\text{-}Al(Mg) \rightarrow Al_{18}Mg_3Ti_2$. $Al_{18}Mg_3Ti_2$ phase grows surrounding Al_3Ti particles and makes them apart from the matrix. Once the phase $Al_{18}Mg_3Ti_2$ forms, Ti in Al_3Ti and Mg in the matrix

Table 1: Compositions of phases found in this work and $Al_{18}Mg_3Ti_2$ in Al-Mg-Ti system (at.%)

Phase	Al	Mg	Ti	Sources
$Al_{18}Mg_3Ti_2$	79.8–80.2	11.1–11.9	7.9–9.1	[13]
X	79.0	11.5	9.5	Homogenized alloy 2618-Ti
A	59.9	40.1	–	
B	84.6	15.4	–	
C	97.6	2.3	0.1	Diffusion couple
D	73.8	–	26.2	
E	76.4	14.8	8.8	

should diffuse through the phase. Thus, direct diffusion of Ti and Mg atoms between Al_3Ti phase and the matrix α–Al (Mg) is prevented, which leads to the incompleteness of the "peritectic reaction". This incompleteness depends largely on the diffusion rate of atoms in $Al_{18}Mg_3Ti_2$ phase.

As we know, if one reaction can occur, it depends on two factors: thermodynamic and kinetic conditions. Thermodynamic analyses by Kerimov [14] and Gao [15] etc. indicate that this "peritectic reaction" could occur in the investigated temperature range. However, at lower temperature, the diffusion rate of atoms is very slow in terms of Arrhenius equation: $D = D_0 \exp(-Q/RT)$, where D_0 is the diffusion constant, R the mole gas constant, Q the diffusion activation energy and T is the absolute temperature. The diffusion rate of atoms increases with the increase of temperature exponentially, which results in its strong sensitivity to temperature. As mentioned in Fig. 2, the phase $Al_{18}Mg_3Ti_2$ could be observed until the homogenization temperature is up to 460 °C. With the increasing of homogenization temperature, the amount $Al_{18}Mg_3Ti_2$ increases obviously. The results are in good consistence with above kinetic analysis. But the "peritectic theory" is not so sensitivity to homogenization time after 24 h. Even though the homogenization time increases to 12 days, only a few single $Al_{18}Mg_3Ti_2$ particles within which there is no Al_3Ti phase exist in alloy 2618-Ti as shown in Fig. 2(f). The occurrence of single $Al_{18}Mg_3Ti_2$ phase can be attributed to the local fluctuating of compositions, which makes the tri-phase equilibrium of Al_3Ti, $Al_{18}Mg_3Ti_2$ and α-Al depended on the composition of Al-Mg-Ti system change into bi-phase equilibrium of $Al_{18}Mg_3Ti_2$ and α-Al.

4 Conclusion

Diffusion couple methods, optical microscope, scanning electron microscope, energy dispersive spectrometry and x-ray diffractometry were used to investigate the evolution of Ti-containing intermetallic compounds in alloy 2618-Ti. The conclusions are as follows:

1. Al_3Ti particles introduced by means of solid-liquid mixing and near-liquidus casting exist mainly in the matrix of as-cast alloy 2618-Ti with size about 2–15 μm in length and 2–5 μm in width. After homogenization, the size of Al_3Ti particles decreases gradually and a new ternary phase-$Al_{18}Mg_3Ti_2$ is identified to form around these particles combining means of Al-Mg-Ti diffusion pairs and a series of typical characterization methods.
2. The formation of $Al_{18}Mg_3Ti_2$ in the alloy could be explained by the theory of "peritectic reaction". This reaction is sensitive to homogenization temperature and time within 24 h, but not so sensitive to homogenization time after 24 h because of its special growth pattern.
3. Although much Al_3Ti particles coexist with $Al_{18}Mg_3Ti_2$ in homogenized alloy 2618-Ti depending on the composition of Al-Mg-Ti system after homogenization, there is only a few single $Al_{18}Mg_3Ti_2$, which can be attributed to the local composition fluctuation of the alloy.

Funding: This work was supported by a grant from National Natural Science Foundation of China (no. 51074030) and Qinglan Project.

References

[1] Z.W. Du, G.J. Wang, X.L. Han, et al., *J. Mater. Sci.,* 47 (2011) 2541–2547.
[2] J.H. Wang, D.Q. Yi, B. Wang, *Trans. Nonferrous Met. Soc. China,* 13 (2003) 590–594.
[3] F. Nový, M. Janeček, R. Král, *J. Alloys Compd.,* 487 (2009) 146–151.
[4] K. Yu, S.R. Li, W.X. Li, *J. Mater. Sci. Technol.,* 16 (2000) 416–420.
[5] K.T. Kashyap, *Bull. Mater. Sci.,* 24 (2001) 643–648.
[6] B.Y. Zong, Derby, *Acta. Mater.,* 45 (1997) 41–49.
[7] F. Ji, M.Z. Ma, A.J. Song, et al., *Mater. Sci. Eng. A,* 506 (2009) 58–62.
[8] P. Cavaliere, *Compos. A,* 36 (2005) 1657–1665.
[9] J.M. Wu, S.L. Zheng, Z.Z. Li, *Mater. Sci. Eng. A,* 289 (2000) 246–254.
[10] S.H. Wang, P.W. Kao, *Acta Mater.,* 46 (1998) 2675–2682.
[11] J. Li, Y.F. Song, J.H. Wang, et al., *Trans. Mater. Heat. Treat.,* 34 (2013) 64–69.
[12] T.T. Liu, X.P. Su, Y. Liu, et al., *High Temp. Mater. Proc.,* 33 (2014) 85–94.
[13] K.M. Kerimov, S.F. Dunaev, E.M. Sljusarenko, *J. Less-common Met.,* 133 (1987) 297–302.
[14] K.M. Kerimov, S.F. Dunaev, *J. Less-common Met.,* 153 (1989) 267–273.
[15] M. Gao, S.W. Mei, X.Y. Li, et al., *Scripta Mater.,* 67 (2012) 193–196.