Rare Metal Materials and Engineering
Volume 45, Issue 12, December 2016
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2016, 45(12): 3085-3088.

ARTICLE

Effects of Heat Treatment on Microstructure and Corrosion Behavior of SiC$_p$/Al-6wt%Mg Composites

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Abstract: The present work investigated the influence of heat treatment (T1, T4, T6 and annealing) on the microstructure related to the interfacial reaction and corrosion behavior of SiC$_p$/Al-6wt%Mg composites prepared by a pressureless infiltration technique. The results show the occurrence of the precipitates of Si, $MgA1_2O_4$ and Mg_2Si as a result of the interfacial reaction between the SiC particle and the matrix of the composites during heat treatment. The precipitates contents (f) of the composites correlate with T1, T4, T6 and annealing heat treatment, following the order of $f_{T1} < f_{T4} < f_{T6} < f_{annealing}$. The precipitates near SiC particles are responsible to pitting corrosion as a degradation mechanism of the composites. The heat treatments carried out on the composites present a significant influence on the corrosion rate (j_{corr}). The correlation between j_{corr} and heat treatment shows the characteristic of $j_{corr\text{-}ann} > j_{corr\text{-}T6} > j_{corr\text{-}T4} > j_{corr\text{-}T1}$, which may be attributed to the interfacial reaction precipitates of the composites during heat treatment.

Key words: heat treatment; SiC$_p$/Al-6wt%Mg composite; precipitates; corrosion

Due to their unique properties such as outstanding specific strength and modulus, improved wear-resistance, and tailorable thermo-physical properties, SiC$_p$/Al metal matrix composites (MMCs) represent attractive materials for advanced electronic packaging and thermal management application[1,2]. It is well accepted that the service life of the composites is significantly determined by their corrosion resistance, especially used in moving engine components and airframes that are expected to be exposed to the marine environment. Because of corrosion, the composites will lose their mechanical properties and fail during the service. Some works reported in literatures[3-6] have been devoted to the corrosion resistance of SiC$_p$/Al MMCs and the relation to processing and microstructure. The effect of SiC particles on the corrosion behavior of SiC$_p$/Al MMCs was discussed in previous studies[3,5,6]. The SiC particles in the metal matrix serve as active cathodes and tend to reduce corrosion resistance of the metal matrix. An improvement in corrosion resistance has been declared with decreasing the volume fraction of SiC particles or increasing the SiC particle size in SiC$_p$/Al MMCs. Some researchers [7,8] suggested possible interfacial reactions between the matrix components and the SiC particles during the fabrication process and the heat treatment has an important influence on the corrosion behavior of SiC$_p$/Al MMCs. Candan and Bilgic[7] studied the corrosion behavior of Al-4wt%Mg alloy matrix composites with 60 vol% SiC particles. They reported that the precipitated Mg_2Si as a result of the reaction between Al-Mg alloy and SiC particle has a beneficial effect on corrosion resistance of Al-4wt% Mg alloy matrix composites. To improve the mechanical properties of SiC$_p$/Al MMCs, the heat treatment is an efficient method[9,10], but possible interfacial reactions will arise between the matrix components and SiC particles during the heat treatment and corrosion resistance of SiC$_p$/Al MMCs changes[11].

The present work aims at understanding the effect of heat treatment on microstructure and corrosion behavior of SiC$_p$/Al-6wt%Mg composites produced by a pressureless infiltration technique. The precipitates as a result of the interfacial

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Received date: December 25, 2015
Foundation item: National Natural Science Foundation of China (51262023); the Key Laboratory Open Foundation of Micro Structure of Metal Materials in Jiangxi Province of China (JW201323001); the Priority Academic Program Development of Jiangsu Higher Education Institutions

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reaction between the matrix and SiC particles were investigated. Efforts were also made to explain the relationship of precipitation and corrosion resistance of the composites.

1 Experiment

The SiC particles with an average particle size of 106 μm as reinforcements and Al-6wt%Mg alloy as a matrix material were chosen in order to produce 16 vol% SiC particulates reinforce SiC_p/Al-6wt%Mg composites by a pressureless infiltration process. The SiC particles were pre-oxidized at 1000 °C for 6 h to remove the impurities and to introduce a SiO_2 layer on the particle surfaces. To examine the influence of heat treatment on the microstructure related to the interfacial reaction and corrosion behavior of the SiC_p/Al-6wt%Mg composites, heat treatments of the composites were conducted as follows: T1(natural aging for 165 h), T4 (solution treatment at 500 °C for 2 h and natural aging for 165 h), T6 (solution treatment at 500 °C for 2 h and artificial aging at 190 °C for 8 h) and annealing (500 °C) for 2 h, which was usually adopted to improve mechanical properties of Al-alloys.

The disc-shaped specimens with the diameter of 14 mm and the thickness of 3 mm were machined from the prepared composites, and then polished up to 1200 grit surface finish and then cleaned with distilled water followed by acetone. All corrosion tests of the composites were carried out in a still solution of 3.5 wt% NaCl in deionized water exposed to atmospheric air. A platinum rod and a saturated calomel electrode (SCE) were used as counter electrode and reference electrode, respectively. The tested area of the films was a circle of 1 cm in diameter. Potentiodynamic polarization curves were generated by sweeping the potential from cathodic to anodic direction at a scan rate of 0.1 mV/s. Microstructural evaluations were conducted on optical microscopy, scanning electron microscopy and energy dispersive spectroscopy (SEM/EDS) and X-ray diffraction (XRD).

2 Results and Discussion

2.1 Microstructural evolution

The micrographs in Fig.1 show microstructure evolution related to the interfacial reaction precipitates of the SiC_p/Al-6wt%Mg composites during different heat treatment processes. Significantly different precipitates contents (f) from the composites after heat treatments are observed. In the case of the composite with T1 heat treatment (Fig.1a), the edges of the SiC particulate are clean and sharp, indicating that no or insignificant amounts of interfacial reactions occur. With T4 heat treatment, the interfacial reaction precipitates of the composite can be seen (denoted by the arrows in Fig.1b). It is also evident that the concentration of the precipitates is more pronounced near the interface between SiC particle and matrix of the composite. After T6 heat treatment, more precipitates occur and the regions near the SiC particle surfaces are decorated with the precipitates (Fig.1c). When the annealing treatment is carried out, it is clear that evidence supporting more remar-kable precipitates of the composites is abundant (Fig.1d).

2.2 Interfacial reaction precipitates

Fig.2 displays the XRD results obtained from the composites, showing how the extent of the interfacial reaction varies with different heat treatments. As seen in the graphs, the interfacial reaction precipitates are identified as Si, $MgA1_2O_4$ and Mg_2Si, as a result of direct reactions as follows[8,12]:

$$2SiO_2+Mg+2Al \rightarrow MgA1_2O_4+2Si \tag{1}$$

$$2Mg+Si \rightarrow Mg_2Si \tag{2}$$

The intensities of diffraction peaks reflect the extent of the reaction products qualitatively. Insignificant amounts of interfacial reactions could be seen for the composite with T1 heat treatment, because the aging temperature is not high enough for the interfacial reaction of the composite. However, for T4, T6 and annealing heat treatments the mass formations of Si, $MgA1_2O_4$, including some Mg_2Si, within the composites are confirmed from the X-ray diffraction (XRD) patterns of this specimen (Fig.2). Supplementary analysis obtained from scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) provides an evidence for the existence of Si phase, as shown in Fig.3. Also an evidence is provided for the existence of $MgA1_2O_4$ phase, as shown in Fig.4, in which the content ratio of Mg, Al and O reaches an approximation of 1:2:4. The interfacial reaction related to the matrix containing Mg was reported by several researchers[13,14]. When the matrix contains more than 2% Mg, however, the interfacial reaction according to the reaction (1) to form $MgA1_2O_4$ will occur[12]. In this experiment, the formation of $MgA1_2O_4$ by interfacial

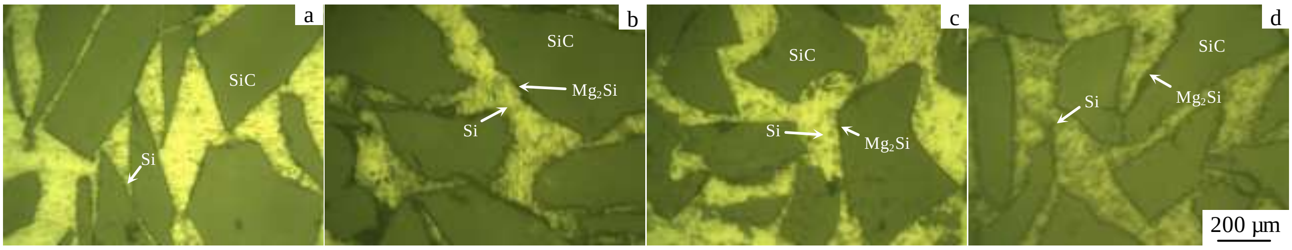


Fig.1 OM images of SiC_p/Al-6wt%Mg composites with different heat treatment: (a) T1, (b) T4, (c) T6, and (d) annealing

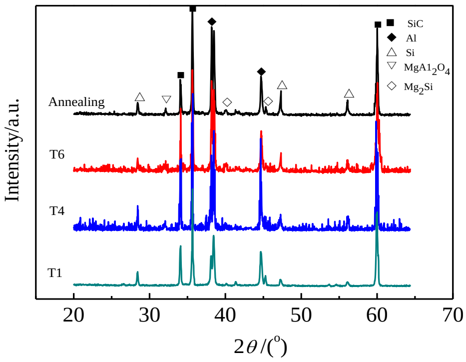
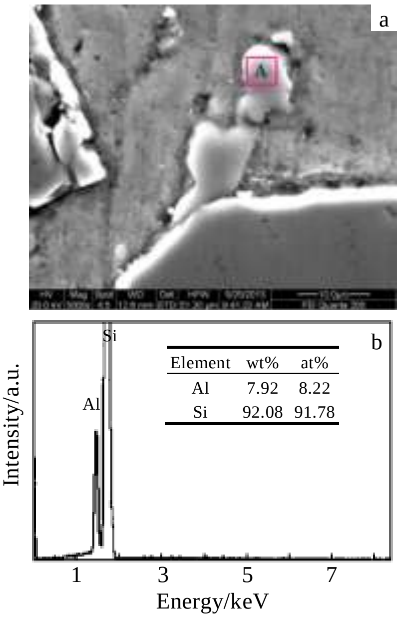


Fig.2 XRD patterns of the composites after heat treatments

reaction of the composites during heat treatment may benefit from the Mg content of 6 wt%, in which the Mg reacts with the SiO_2 layer of SiC particles and Al matrix to form $MgA1_2O_4$.

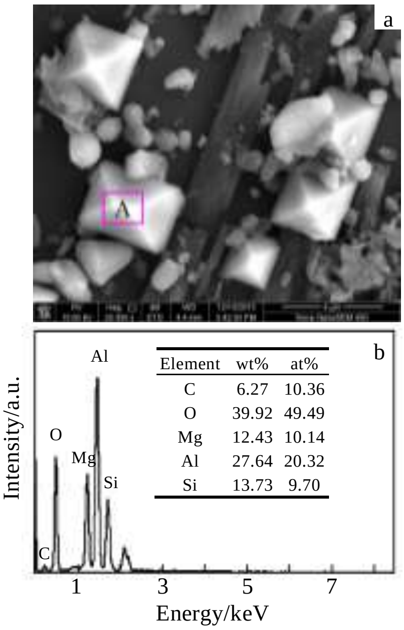
2.3 Corrosion behavior

The potentiodynamic polarization behaviours in 3.5% NaCl solution for the composites with different heat treatments are shown in Fig.5. The corrosion potential (E_{corr}) and corrosion current density (j_{corr}) calculated from polarization curves are summarized in Table 1. As can be seen, the corrosion potential varies significantly from -0.692 to -0.846 mV, which might be related to an obvious difference of the precipitate content for the composites with different heat treatments. It indicates that the precipitates may polarize the composites in the negative direction. In other words, the corrosion potential of the composites is affected by the presence of precipitates, although the poor electrical conductivity of Si, $MgA1_2O_4$ and Mg_2Si is provided[8].



Element	wt%	at%
Al	7.92	8.22
Si	92.08	91.78

Fig.3 SEM image (a) and EDS analysis (b) of the interfacial reaction products of Si phase in Al-6wt%Mg alloy matrix composite



Element	wt%	at%
C	6.27	10.36
O	39.92	49.49
Mg	12.43	10.14
Al	27.64	20.32
Si	13.73	9.70

Fig.4 SEM image (a) and EDS analysis (b) of the interfacial reaction products of $MgA1_2O_4$ phase in Al-6wt%Mg alloy matrix composite

The j_{corr} of the composites with different heat treatments indicates that treatment conditions has a significant effect on the j_{corr} of the composites, which has the order of $j_{corr\text{-}ann} > j_{corr\text{-}T6} > j_{corr\text{-}T4} > j_{corr\text{-}T1}$. It implies that corrosion rate increases with increasing precipitates of the composites. The contribution of precipitates to increased corrosion rate in aluminum matrix composites has been presented in some literatures[7,8,15]. The potentiodynamic polarization measurements of the composites with different heat treatments (Fig.5) can be correlated with the precipitate content of Si, $MgA1_2O_4$ and Mg_2Si. Since the precipitates, as well as SiC particles, prevent continuity of the matrix leading to preferred sites for passive film breakdown[16], the chloride ions attack makes them become preferential sites for pitting corrosion as a result of the absorption and concentration of chloride ions surrounding the precipitates as evidenced from SEM (Fig.6).

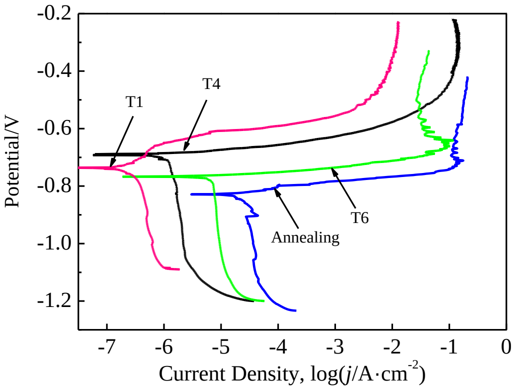


Fig.5 Polarization curves of SiC_p/Al-6wt%Mg composite with different heat treatments

Table 1 Corrosion potential (E_{corr}) and corrosion current density (j_{corr}) of SiC_p/Al-6wt% Mg composites with different treatments

Heat treatment	E_{corr}/V	j_{corr}/μA·cm^{-2}
T1	−0.720	0.25
T4	−0.692	0.82
T6	−0.767	7.91
Annealing	−0.846	15.84

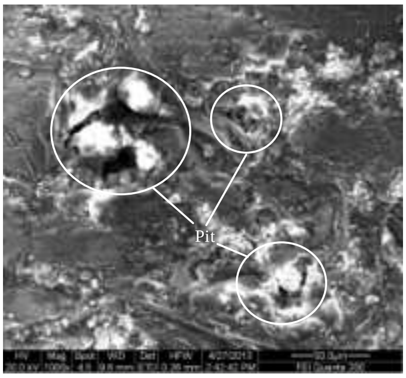


Fig.6 SEM morphology of the localized corrosion pits for SiC_p/Al-6wt%Mg composite with annealing

3 Conclusions

1) The interfacial reactions resulting in the formation of Si, $MgA1_2O_4$ and Mg_2Si precipitates occur between the SiC particles and matrix during the heat treatment.

2) The precipitate contents of the composites after T1, T4, T6 and annealing heat treatment increase.

3) The precipitates located near SiC particles are responsible for pitting corrosion as a degradation mechanism of the composites.

4) The corrosion current density (j_{corr}) is correlated with the precipitate contents or heat treatment of the composites according to the order of $j_{corr\text{-}ann} > j_{corr\text{-}T6} > j_{corr\text{-}T4} > j_{corr\text{-}T1}$.

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热处理对 SiC_p/Al-6%Mg 复合材料显微组织及腐蚀行为影响

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摘 要：采用无压渗透法制备了SiC_p/Al-6%Mg (质量分数)复合材料，并对其进行4种热处理工艺（T1, T4, T6和退火）处理，研究了热处理工艺对SiC_p/Al-6%Mg复合材料显微组织和腐蚀行为的影响。结果表明，复合材料在4种热处理工艺下均出现了界面反应产物Si、$MgA1_2O_4$ 和 Mg_2Si。界面反应产物析出量（f）与热处理工艺密切相关，并呈现出如下规律：$f_{T1} < f_{T4} < f_{T6} < f_{annealing}$。界面反应析出物是导致复合材料发生点蚀的主要原因，从而促进复合材料发生腐蚀。热处理工艺影响界面反应析出量从而影响复合材料的腐蚀速度（j_{corr}）：$j_{corr\text{-}ann} > j_{corr\text{-}T6} > j_{corr\text{-}T4} > j_{corr\text{-}T1}$。

关键词：热处理；SiC_p/Al-6%Mg 复合材料；析出物；腐蚀

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