STUDY ON DIMENSIONAL STABILITY OF SiC_p/Al COMPOSITE

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Keywords: SiC_p/Al composite; dimensional stability; heat treatment; microstructure

Abstract

The influence of alloying element Mg and heat treatment on the dimensional stability of SiCp/Al composite was studied through testing the micro-deformation resistance and the dimensional change rate under thermal cycling condition. The mechanism of dimensional stabilization was discussed and the optimal heat treatment process was determined.

1. Introduction

The dimensional stability of the material is very important for precision instruments. With the development of modern science and technology, the requirement for dimensional stability of materials is raised. After nearly a century of development and perfection, aluminum alloys have become one of the important structural materials in the manufacturing industry of precision instruments [1]. However, aluminum alloys with the larger coefficient of thermal expansion and lower stiffness can't meet growing high precision and high reliability requirements of precision instruments. It is very necessary to develop new materials for precision instruments. Particles reinforced aluminum matrix composites have many other outstanding features, such as the high specific stiffness and strength, the good thermal conductivity and the low thermal expansion coefficient, and therefore it shows a broad application prospects in the field of aviation, aerospace, automotive, electronics and so on [2~5]. The application of this material in the optical precision components and inertial instruments has also caused more and more attention [6~7].

In this paper, a non-heat treatment hardening Al-Mg alloy was selected as the matrix alloy and SiC particles reinforced aluminum composite was manufactured. The influence of alloying elements and heat treatment process on the dimensional stability of composite was studied by testing the micro-plastic deformation resistance and the dimensional change rate under thermal cycling condition. The mechanism of dimensional stabilization was discussed and the optimal heat treatment process was

determined by analyzing the microstructure.

2. Experimental

The average nominal particle size of reinforcement SiCp particles is 4.5 μm, industrial pure aluminum 1060 and Al-Mg alloys 5A06 and 5A12 were selected as matrix. The chemical compositions of the matrix alloys are shown in Table 1. The 42% volume fraction of SiC particles reinforced Al composites were prepared by squeeze-exhaust casting method.

	Elements									
	Mg	**Mn**	**Sb**	**Be**	**Ti**	**Fe**	**Si**	**Cu**	**Zn**	**Al**
1060Al	—	—	—	—	—	0.25	0.2	0.01	—	Bal.
5A06Al	5.8~6.8	0.5~0.8	—	0.0001~0.005	0.02~0.1	0.4	0.4	0.1	0.2	Bal.
5A12Al	8.3~9.6	0.4~0.8	≧0.004	—	0.05~0.15	0.3	0.3	0.05	0.2	Bal.

Table 1 Chemical compositions of Al matrix alloy (wt.%)

$\sigma_{0.01}$ is the stress values causing the material to produce a 10^{-4} residual deformation correspondingly. $\sigma_{0.01}$ of the SiCp / Al composite materials was tested by the continuous loading method. Tensile test is carried out on Instron5569 electronic tensile testing machine under room temperature, the displacement rate of the crosshead beams is 0.1mm/min, the extensometer is used to record the stress (σ) – the strain (ε) curve, the gauge of the extensometer is 10mm, the accuracy of sensor is 10^{-6}.

The dimensional stability of the composite specimens was measured by the real-time detection method under thermal-cooling cycle. The cylindrical specimens with dimensions of Φ6×25mm were used. The real-time change of the axial dimension of cylindrical specimens was tested in the process of thermal-cooling cycles.

Under the thermal-cooling cycling condition, the specimens' magnitude of accumulative residual relative length change (ARRLC) for i times can be showed as the following equation:

$$\frac{\Delta L_i}{L_o} = \frac{L_i - L_o}{L_o} \tag{1}$$

Where L_0— the specimen's original length at 20℃;

L_i— specimen's axial length after cycling for i times.

A curve was then built up, of which y-axis stands for $\frac{\Delta L_i}{L_0}$ and x-axis stands for n, the cycling times. The materials dimensional stability can be evaluated according to

the curve of $\frac{\Delta L_i}{L_0}$ and thermal-cooling cycling number. After experiencing thermal cycling for *i* times, the MRRLC of specimens can be assessed by the following equation:

$$\bar{\Delta} = \frac{\sum \left| \frac{L_i - L_{i-1}}{L_o} \right|}{N} \qquad i = 1, 2, 3 \ldots N \tag{2}$$

Where $\bar{\Delta}$—the mean residual relative length change;
L_i— specimen's axial length after cycling for i times;
N—the total cycling times.

$\bar{\Delta}$ can be used to evaluate dimensional stability under non-load conditions.

The thermal-cooling cycling temperature range is 20～150℃, heating and cooling rates are 8℃/min, the maximum number of thermal cycles is 14 times, the specimen is insulated at 20℃ for 25min before each heat cycle, data processing error is at the range of 10^{-7} to 10^{-6} in the temperature. The testing process is carried out in the helium atmosphere.

The microstructure of the composite was observed by S-570 scanning electron microscope (SEM), and the distribution of the alloying elements in the composite was analyzed by EDS is.

Microstructure analysis was carried on Philips CM-12 and Hitachi H-800 transmission electron microscope (TEM), the accelerating voltage was 120kV and 200kV respectively. The thin film sample for TEM was cut into 1mm thick slices using an electric spark, then it was thinned to 40μm mechanically, finally it was thinned on the ion thinning machine. The accelerating voltage of ion thinning machine is 4kV, the current is 1mA, grazing angle of the ion beam is in the range of 7 angle to15 angle.

3. Results and analysis

3.1 Dimensional stability and micro-plastic deformation resistance of composites

SiCp/Al composites with matrix of pure aluminum and Al-Mg alloys were annealed in different process. The micro-yield resistance and dimensional stability of composites were tested and the results are shown in Table 2.

The SiCp/Al composites prepared by squeeze-exhaust casting have to be treated by homogenization annealing in order to release the residual stress. SiCp/5A06Al composite was annealed using conventional process, i.e. annealed at 475℃ for 4 hours and then cooled in a furnace or in the air to room temperature. The micro-yield resistance and MRRLC $\bar{\Delta}$ of the samples are basically the same for specimens under the two kinds of cooling rates, and they are shown in Table 2 process 5 and 6.

Cooling rate has little effect on the dimensional stability of the materials, therefore the furnace cooling way was used after soaking.

Materials	Process number	Parameters	$\sigma_{0.01}$/MPa	$\overline{\Delta}$ ($\times 10^{-6}$)
SiCp/1060Al	1	330℃/0.5h+ FC	104.9	1.79
SiCp/5A06Al	3	330℃/0.5h+ FC	167.8	1.75
	4	330℃/4h+ FC	190.0	3.25
	5	475℃/24h+ FC	140.6	2.88
	6	475℃/24h+ AC	140.5	2.51
SiCp/5A12Al	7	330℃/0.5h+ FC	190.0	1.92

FC: furnace cooling
AC: air cooling

Table 2. Heat treatment process, micro-deformation resistance and MRRLC of composites

The micro-plastic deformation resistance and MMRLC of SiCp/5A06Al composite can be improved by lowing the annealing temperature to 330℃ soaking the same time (4 hours). Table 1 shows that compared with that of sample 5 the micro-plastic deformation resistance of sample 4 is improved greatly (from 140.6MPa to 190.0MPa) and the mean residual relative length change (MRRLC) is increased slightly (from 2.88×10^{-6} to 3.25×10^{-6}).

Figure 1 shows the influence of the annealing time on the length change rate of specimen of SiCp/5A06Al composite under thermal cycling conditions of 20℃ to 150℃. Seen from Table 2, When the annealing time is extended from 0.5 hours to 4 hours at 330℃, the micro-plastic deformation resistance of materials increases from 167.8MPa to 190.0MPa, and the mean residual relative length change increases slightly from 1.75×10^{-6} increased to 3.25×10^{-6}.

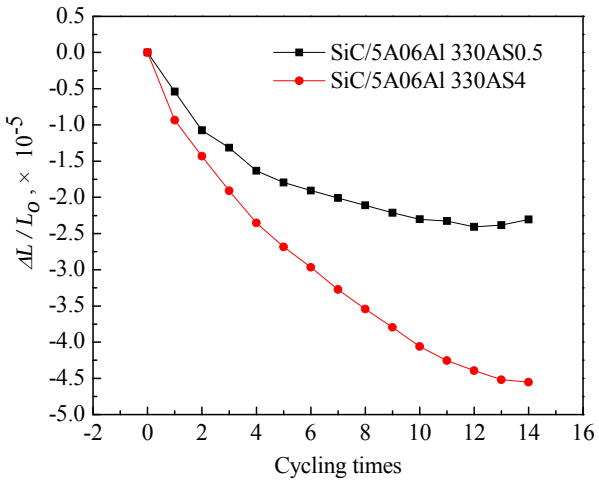

Figure 1. Dimensional change rate of SiCp/5A06Al composite annealed at 330 °C for various time under thermal cycling conditions

Figure 2 shows the dimensional change of the SiCp/Al composites with different Mg content under thermal cycling conditions after 330℃/0.5 hours annealing. It can be seen from Table 1, the micro-plastic deformation resistance of the SiCp/Al composites improves with the increase of Mg content (samples 1,3,7); but the mean residual relative length change increases slightly in composites with higher Mg contents (8.3-9.6wt%). The effect of extending annealing time at 330°C is the same as the effect of increasing Mg content.

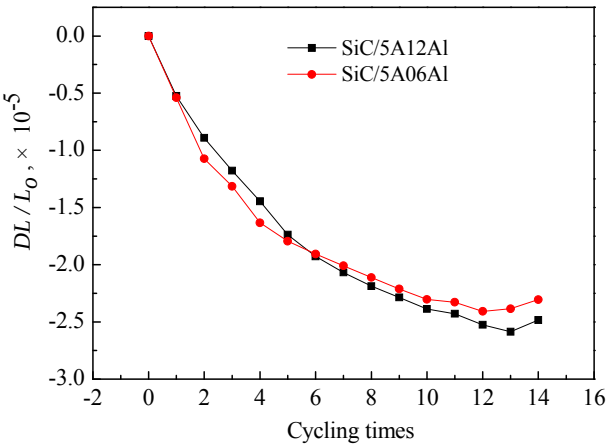

Figure 2. Dimensional changes of different Mg content of SiCp/5A06Al under thermal cycling conditions of 20℃ to 150℃

3.2 Microstructure of composites

Figure 3 shows the dislocation configuration of as-cast and annealed SiCp/5A06Al composite. It can be seen from the figure that the dislocation density of the material inside decreases significantly with the extension of annealing time and the increase of annealing temperature. will produce The intensive thermal mismatch stress exists in as-cast SiCp/Al composites during casting-cooling process due to the larger difference between the thermal expansion coefficients of silicon carbide particles and aluminum alloy; when the thermal mismatch stress is greater than the yield strength of the matrix, the matrix may yield and a large number of dislocation forms; however, the density of dislocation reduces owing to the offset of the positive and negative dislocations moving on the same slip plane during annealing. With extending the annealing time, the positive and negative dislocations offset continuously and the dislocation density drops. With increasing the annealing temperature, the dislocation density in the specimen annealed at the higher temperature than that at the lower temperature within the same holding time.

It is confirmed that the cooling rate after annealing has little effect on microstructure through the observation by transmission electron microscopy because the Al-Mg alloy is non-heat strengthened type alloy; there is no phase changes precipitation during annealing, so the cooling rate has little effect on the dimensional stability.

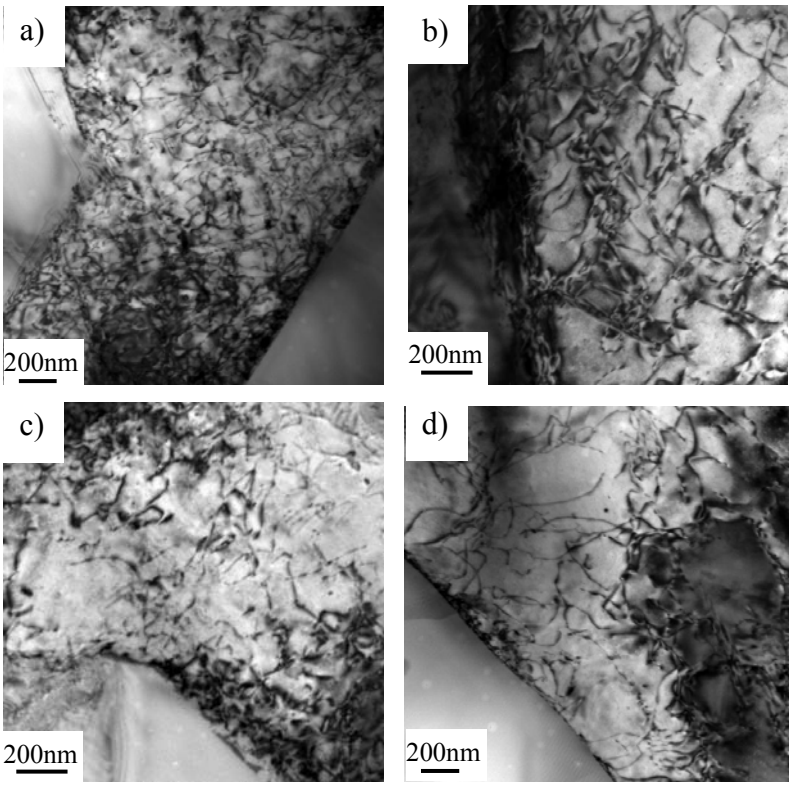

Figure 3. Dislocation configuration of SiCp/5A06Al composite
a) as-cast; b) 330℃/0.5h annealing; c) 330℃/4h annealing; d) 475℃/4h annealing

3.3 Discussion

Microstructure is the most important factor that affects materials dimensional stability. Micro-deformation resistance reflects the ability of the material to resist micro-deformation, which is closely related to the critical shear stress for dislocations moving and is affected by the density and the configuration of dislocations. The micro-deformation resistance of composites will be higher if the dislocations are dense and stable. The thermal expansion coefficient and the elastic coefficient of the matrix and the reinforcements in SiCp/5A06Al composite do not match, so that the intensive thermal mismatch stress occurs during the cast cooling. Moreover, if the thermal mismatch stress exceeds the yield limit of matrix, it will lead to the micro plastic deformation and the huge intensity of dislocations in matrix. The thermal mismatch stress is very unstable, and the relaxation of it will lead to tiny change of the material's dimension. In other words, the dimensional stability of as-cast composite is poor, which must be annealed to eliminate the residual stress. Due to the role of thermal activation during annealing, the reverse symbol dislocations moving on the same slip plane interact and vanish each other, so that the dislocation density in the composite reduces greatly. Enhancing the annealing temperature, dislocation mobility increases and the dislocations climb easily, which increases the probability of reverse symbol dislocations cancelling and make dislocation density further decrease, as shown in figures 3c) and d). Therefore, the micro-deformation resistance of composite

is reduced as increasing the annealing temperature. Compared process 4 with 5 in Table 1, the higher micro-deformation resistance of composite is achieved through annealing at lower temperature 330℃.

When SiCp/5A06Al composite is annealed at 330℃ for shorter time, the micro-deformation resistance of it is lower. Mg atoms as solutes exist in the solid solution, matrix of composite. A small quantity of Mg atoms congregates along the dislocations in the composite after annealing short time. Although the dislocation density in the matrix is still high, but the number of dislocations pinned by Mg atoms is small, the dislocations unpinned are easy to slip. This is why the micro-deformation resistance of composite is lower. It is inferred that extending of the annealing time can improve the micro-deformation resistance.

The micro-deformation resistance of samples 1, 3 and 7 (see Table 1) is increased in turn, this phenomenon is related to Mg element. Due to the lack of solute atoms along the movable dislocations pinning and Mg_2Si strengthening effect, The micro-deformation resistance of the pure aluminum matrix SiCp/Al composites is lower than that of the Al-Mg matrix composites because no solute atoms pin the movable dislocations and no strengthening effect from Mg_2Si phase. The more Mg atoms, the more dislocations pinned and Mg_2Si phase. Consequently, the critical shear stress of activate dislocations increases, and the micro-deformation resistance rises.

The ARRLC and MRRLC of sample under thermal cycling conditions reflect the dimensional stability of composite under temperature load. The performance is closely related to the stability of microstructural stress of the composite. Compared three kinds of composite samples treated by different processes in this experiment, it is found that the MRRLC of samples has a little difference in one order of magnitude difference. Pure aluminum and Al-Mg alloy have no phase transformation occurred in the annealing process, in other words, there is no significant change in microstructure. Residual stress changes a little within the range of annealing temperature and time used in this test, so that the MRRLC changes a little, too, that is, the dimensional stability is similar under temperature load.

Considering the micro-deformation resistance and dimensional stability under temperature load, the optimal annealing process is determined, i.e. annealing at 330℃ for 4 hours and then furnace cooling.

4. Conclusions

The micro-plastic deformation resistance of SiCp/Al composites is improved, but the influence on the MRRLC of composites is effected slightly under thermal cycling with the increase of Mg content and the extension of annealing time is conducive to. Increasing the annealing temperature, the micro-plastic deformation resistance of SiCp/5A06Al composite is decreased, and the MRRLC of composite after thermal cycling is increased slightly. The optimal annealing process of SiCp/5A06Al composite is 330℃ for 4 hours and furnace cooling. The micro-plastic deformation resistance of the sample treated by the optimum process reaches 190MPa and the MRRLC of the sample is 2.15×10^{-6}.

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