STUDIES ON MICROYIELD BEHAVIOR OF A SiC_p/2024Al COMPOSITE①

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ABSTRACT Microyield behavior of a silicon carbide particles reinforced 2024 aluminum alloy (SiC_p/2024Al composite) was investigated. The results showed that the composites exhibited some types of notable strain relaxation before microyielding when subjected to an applied stress far lower than conventional yield stress. The microyield mechanism was not conformed to the classical linear relation between the applied stress (σ) and square root of plastic strain($\varepsilon_p^{1/2}$), proposed by Brown N and Lukens K F. Microyield strength could be strongly affected by heat treatment routes. An appropriate aging treatment would significantly increase microyield strength of the SiC_p/2024Al composite, whereas thermal cycling with large upper-lower cyclic temperature interval would lead to deterioration of microyield strength. Finally the effects of microstructures on microyield behavior of the composite were discussed.

Key words microyield behavior strain relaxation SiC_p/2024Al composite

1 INTRODUCTION

Due to the excellent comprehensive properties such as high specific strength and Young's modulus, lower thermal conductivity and thermal expansion coefficients, the silicon carbide particles reinforced aluminum alloy composite (SiC_p/Al) has been gradually employed in some optical precision instruments and systems[1]. As used for precision devices, dimensional stability of the material is very important. Most common causes of dimensional instability in materials are phase transformation, relief of residual stresses, and microplastic deformation induced from an applied stress. The effects related to phase transformation and residual stresses can generally be controlled through properly selecting component materials and appropriate dimensional stabilizing heat treatment procedures. However, the dimensional instability led by microplastic deformation is more difficult to control because the internal stresses, which may come from assembly operation, shocking or vibrating in service, are unavoidable. So it is desirable to improve the resistance to microplastic deformation (i. e. microyielding) of materials, and the microyield strength (MYS, the applied stress at plastic strain $\varepsilon_p = 10^{-6}$) is recommended as one important measuring of dimensional stability.

Microplasticity of metallic materials had been paid attention long time ago. The early achievements have been gathered into some collected works and treatises[2-4]. But all these studies were emphasized on single crystals, polycrystalline metals and common metallic materials. Since SiC_p/Al composite is a kind of newly developing material, in addition, the testing on microplasticity is quite difficult, only a few literatures concerning microyield behavior of the composites have been reported[5-7], resulting in a lack of understanding about microyield behavior of the composite. By selecting a most promising system, SiC_p/2024Al, as our objective of investigations, this paper dealt with the microyield behavior and the effects of different heat treatments in order to get basic knowledge about the rule, mechanism and influential factors of microyielding of the composite material.

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2 EXPERIMENTAL PROCEDURES

A commercial 2024 aluminum alloy (Al-4.00% Cu-1.31% Mg-0.58% Mn) was selected as the matrix of experimental composites, and the silicon carbide particles with 7 μm of mean size were used as the reinforcement. By vacuum pressure infiltration method[8], the 35% SiC_p/2024Al composite was fabricated.

To check the effects of different type heat treatments on microyield behavior, several treating routes listed in Table 1 were employed to the composite.

After thermal treatments the dog-bone-shaped coupons with 3 mm thickness and 8 mm gage length were made and tested on a MTS New 810 testing machine by means of continuous loading method[9]. In contrast to step load-unload method, the former method could diminish the side effect of micro-mechanical cyclic strengthening and temperature change induced error of strain measurements during load-unload process, but the errors in strain measurements were slightly higher than those in load-unload method because the Young's modulus, to evaluate plastic strain, must be rigorously determined in the continuous loading method, which was proved quite difficult. The load train design of the MTS New 810 machine permitted an acceptable level of alignment. The continuous tension was performed with load control mode at a rate of 3kN/min. The strain was measured using a MTS special extensometer which had a sensitivity of 6×10^{-7} and 0.006 maximum range. The acquisition of applied stress (σ) and strain (ε) data, as well as determination of Young's modulus (E) were carried out using a MTS system computer and the special testing software. The plastic strain (ε_p) was calculated according to the following equation:

$$\varepsilon_p = \varepsilon - \sigma/E$$

Finally, the σ-ε_p, σ-$\varepsilon_p^{1/2}$ relationships and microyield strength could be obtained. Each MYS value was the average from three specimens.

To check the relationship between microyield behavior and microstructure, a JEOL 200CX electron microscope was used for performing TEM analyses, and X-ray diffraction analyses were performed with a D/Max-II A diffractometer. In X-ray test, the (222) diffraction peak of 2024Al matrix was selected for qualitatively analyzing microscope residual stresses in matrix of the composites.

3 RESULTS AND DISCUSSIONS

3.1 Microyield behavior

The experimental σ-ε_p curves for several typical treated specimens are shown in Fig. 1. It is noted that there exists quite apparently small permanent strain at very low applied stress. The observed strain in our works has a variety of different types and no clearly corresponding relation to heat treatment routes. But they can be generally divided into positive, negative and combined strain respectively as shown in Fig. 2. Because it occurs at near zero stress, and even conceals linear elastic stage that should exhibit as a straight-line perpendicular to ε_p coordinate axis at $\varepsilon_p\approx0$,

Table 1 Different heat treatment routes

Regime	Parameters
Annealing	400 ℃, 3 h, F. C.
Quenching	500 ℃, 1 h, W. Q.
Aging	(1) 500 ℃, 1 h, W. Q. + 190 ℃, 4, 8, 12, 16, 20 h, A. C.
	(2) 500 ℃, 1 h, W. Q. + 110 ℃, 150 ℃, 190 ℃, 230 ℃, 270 ℃, 8 h, A. C.
Cycling	(1) 500 ℃, 1 h, W. Q. + 190 ℃, 2.5 h ⇔ - 196 ℃, 1 h, 1, 3, 5 times respectively
	(2) 500 ℃, 1 h, W. Q. + 110 ℃, 150 ℃, 190 ℃, 230 ℃, 270 ℃, 2.5 h ⇔ - 196 ℃, 1 h, 3 times
T6+ Cycling	500 ℃, 1 h, W. Q. + 190 ℃, 8 h, A. C. + 190 ℃, 2.5 h ⇔ - 196 ℃, 1 h, 3 times

this kind of permanent strain prior to microyielding is defined as "strain relaxation" in this paper.

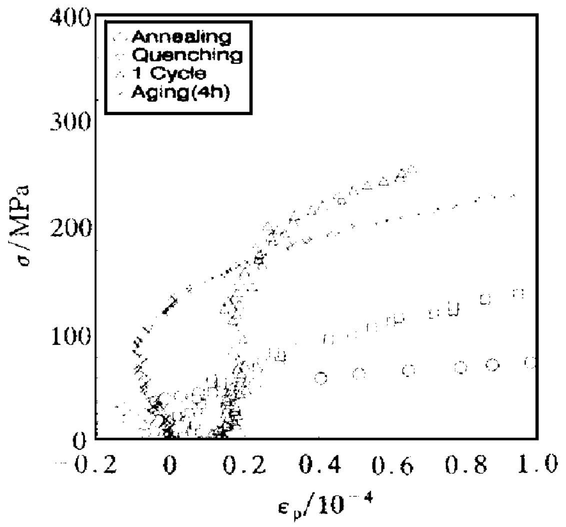


Fig. 1 Experimental σ-ε_p curves under several typical treatments

It is believed that the plastic strain relaxation is also the outcome of dislocation movement and probably related to the special microstructure features in the SiC_p/2024Al composite material. Because of the large difference of thermal expansion coefficients (ΔCTE) between SiC_p and 2024Al matrix($\alpha_{SiC}/\alpha_{2024Al} \approx 1/10$), the residual thermal mismatch stress (ΔCTS stress) imparted by various thermal processing operations could reach to a high level and even exceed the yield strength of aluminum matrix alloy[10], leading to the microplastic deformation and stress relaxation in the matrix. Concomitantly, the rapid multiplication of dislocations in the matrix occurs. It has been reported[11] that when SiC_p/Al composites cooled from fabricating temperature to room temperature, the density of dislocations in matrix would increase by 1~ 2 order of magnitude. These dislocations are ring shaped and easy to move when subjected a small stress. On the other hand, the irregularly shaped SiC_p could bring high local stress concentration in the matrix. Thus, even subjected to a very low applied stress, the local stress at some microzone in the matrix could exceed the conventional yield stress. Owing to the complexity of stress concentration and ΔCTE stress distribution, the direction of local stress may not be along that of the applied stress and the strain relaxation can take place in all possible orientations. Only when the applied stress reaches a higher amplitude level, the strain led by dislocation motion will proceed in the expected direction and exhibit a "whole" microyielding characteristic. The microyield behaviors discussed below in this paper are those in which the strain relaxation before microyielding has been removed.

Fig. 3 demonstrated a group of experimental σ-$\varepsilon_p^{1/2}$ curves under some aging treatment conditions. In this figure the data of elastic stage and the data of $\varepsilon_p > 10^{-4}$ (the range of $\varepsilon_p > 10^{-4}$ belongs to macroyield stage) have been removed in order to focus on the "whole" microyield behavior. It can be seen that the relationship between applied stress(σ) and square root of plastic strain ($\varepsilon_p^{1/2}$) presents a curved line form and does not obey Brown-Lukens equation[12]:

$$\sigma = \sigma_0 + K\varepsilon_p^{1/2}$$

where σ_0 is initial resistance to dislocation gliding, K is a coefficient associated with shear modulus, mean grain size, dislocation density as well as σ_0 of the matrix.

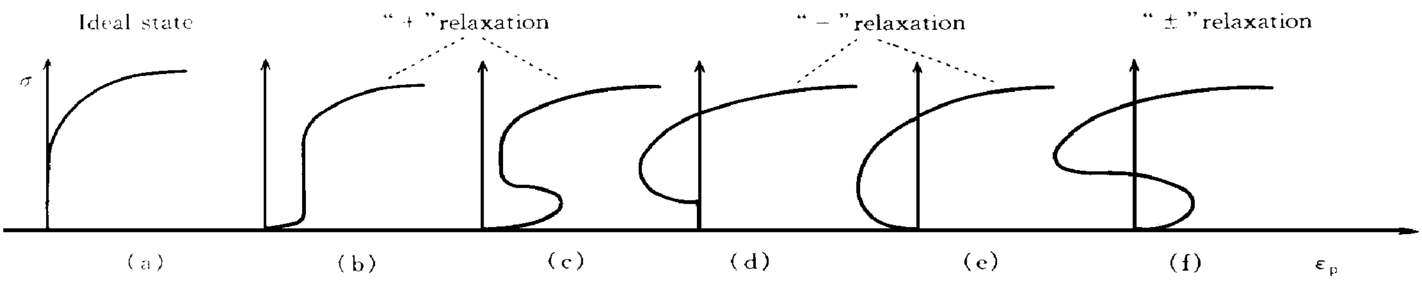


Fig. 2 Schematic illustration of several kinds of permanent strain at near zero applied stress

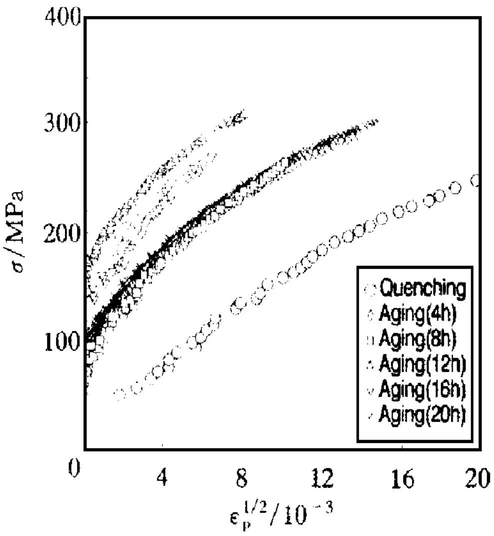


Fig. 3 Experimental σ-$\varepsilon_p^{1/2}$ curves under aging treatments

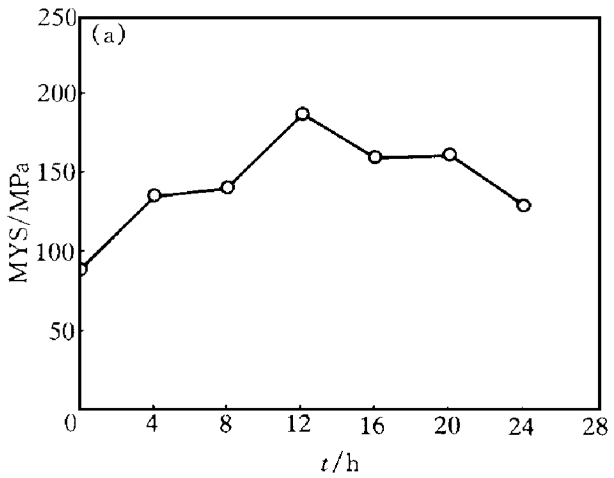
Brown-Lukens relationship was conducted through the hypothesis that the dislocation sources are uniformly distributed in whole volume of materials interior and only grain boundary can hinder dislocation movement. So it is valid only for single crystal or polycrystalline metals in principle. In the case of our experimental materials, there are two microstructure factors deviated from the above basic assumptions: first, in addition to grain boundary there exists another strong barrier to dislocation, that is SiC_p particles; secondly, distribution of dislocations in the matrix is not uniform. Some authors reported that due to relief of ΔCTE stress the dislocation density near the SiC_p-matrix interface is much higher than that in the interior of matrix[11, 13]. Based on the experimental data (see Fig. 3) which revealed the higher working hardening rate at very beginning of microplastic deformation than that at later stage, it is probably deduced that initial microyielding of the composite results from the movement of those dislocations which locate near SiC particles in the matrix.

3.2 Effects of aging and thermal cycling treatments on microyield strength

Fig. 4 and Fig. 5 demonstrate the effects of aging and thermal cycling on the MYS of composite. It can be seen from Fig. 4 that no matter what aging time or aging temperature, MYS presents a peak value. In other word, there exists an optimum time or temperature at which MYS reaches the maximum value. The condition associated with the optimal parameter corresponds to "peak aging". The "under-aging" or "over-aging", that corresponds to shorter or longer time, and lower or higher temperature respectively, would be disadvantageous to MYS of the material. This rule is the same as that in the traditional aluminum alloys for the macroyield strength, implying that MYS of the composite, like macroyield strength, is also controlled by participation behavior of the second strengthening phase. In this work, two strengthening phases, θ and S', would participate in the matrix after aging treatment, in which the S' phase is major one. Fig. 6(a) is a TEM image of 8 h aged specimen (T6 treatment). There exist a lot of fine acicular S' in the matrix, which could remarkably hinder the short range gliding of dislocation and greatly enhance MYS of the composite.

For quenching followed by thermal cycling we can also find the "peak values" phenomenon in MYS versus cycling number or upper cyclic temperature relationships (see Fig. 5). These are comprehensive influence of aging hardening, increasing of both ΔCTE stress and dislocation density. At early stage which means less cycling number or smaller cyclic temperature interval, aging strengthening takes the leading role, while at later stage the effects of aging have been diminished due to "over-aging" and MYS is strongly affected by residual stresses and mobile dislocation density. Fig. 6(b) shows a TEM micrograph of 5 times cycled specimen. A large number of ring-shaped dislocations generated by ΔCTE stress during cycling process, which has high mobility, were observed near the interface.

In addition, the increasing in the width of half $(222)_{Al}$ peak with cycling number indicated the rising of microscope residual stress (see Fig. 7). The two microstructure changes resulted in the decreasing of MYS. So it can be proposed that without age hardening effect the thermal cycling treatment is harmful to MYS of SiC_p/2024Al composite. This deduction had been verified from the experimental data in comparison



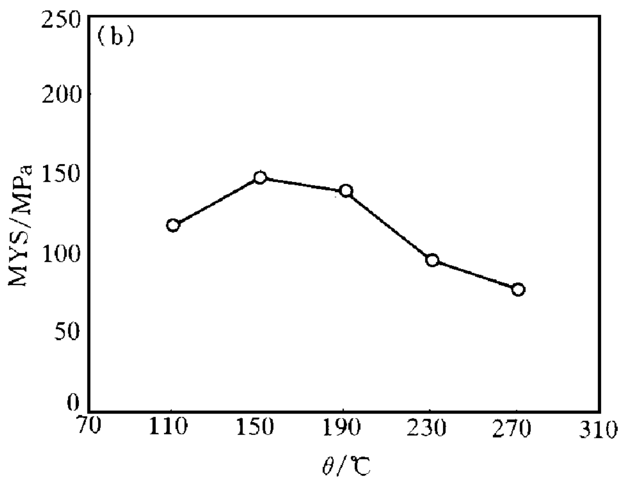
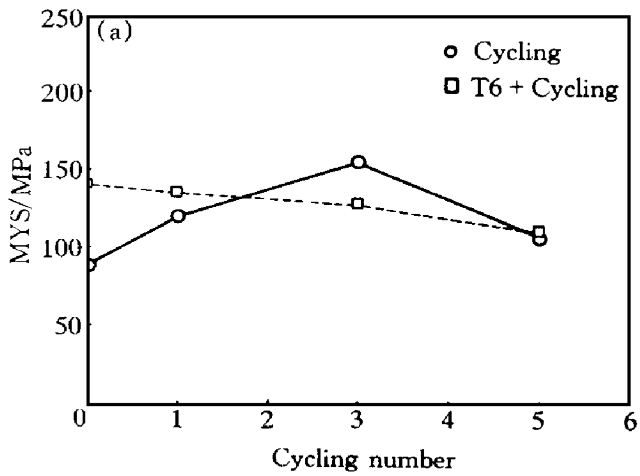


Fig. 4 The effects of aging time (a) and aging temperature (b) on MYS



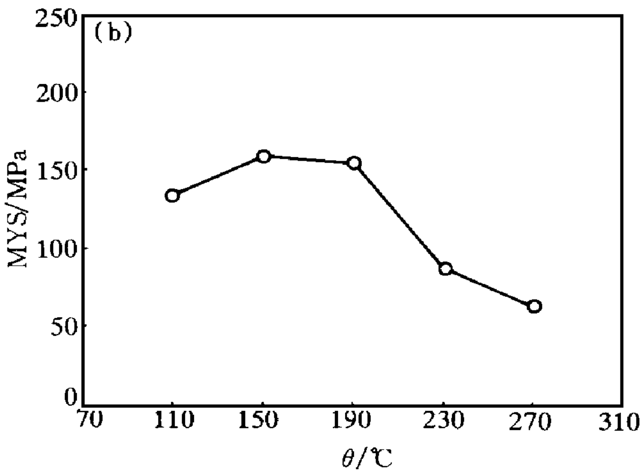


Fig. 5 The effects of thermal cycling number(a) and upper cyclic temperature (b) on MYS

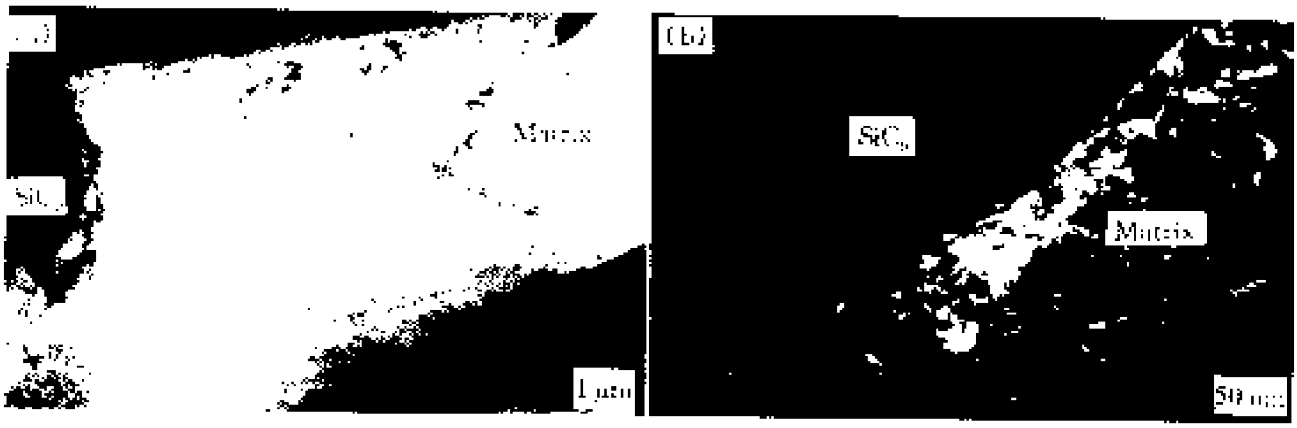


Fig. 6 TEM images of 8h aged specimen
((a), bright field) and 5 times' cycled specimen((b), dark field)

between T6 treatment and T6 followed by cycling treatment (see Fig. 5(a)).

Generally speaking, microyield strength is a kind of mechanical property sensitive to microstructure of a material and its influential factors are quite complicated. The following rules are favorable to obtaining high MYS:

(1) To increase the number of obstacles to

short range gliding of dislocations, such as participated strengthening phase, reinforcing particles, grain boundaries and subgrain boundaries, etc;

(2) To lower the internal residual stresses of a material as possible;

(3) To decrease the density of movable dislocations or get stable dislocation structure such as dislocation network, polygonization of dislocations etc.

The effects of SiC_p on MYS of the composite have two sides. On one hand, SiC_p provides the barriers to dislocation motion and accelerates aging effect, so it is beneficial to MYS; on the other hand , the huge differences of thermal expansion coefficients between SiC_p and 2024Al and the concurrent high residual ΔCTE stress are harmful to MYS of the composite after thermal processing with large temperature chagne such as quenching, high temperature annealing, thermal cycling, etc.

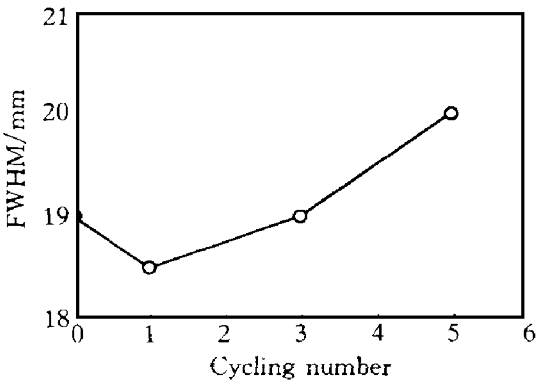


Fig. 7 Relationship between FWHM of $(222)_{Al}$ peak and cyclic numbers

4 CONCLUSIONS

(1) SiC_p/2024Al composite could exhibit varied strain relaxation before microyielding when exposed to a small load. The strain relaxation is associated with the intrinsic ΔCTE stress and high population of mobile dislocations in the matrix.

(2) The relationship between the applied stress (σ) and square root of plastic strain ($\varepsilon_p^{1/2}$) does not obey $\sigma = \sigma_0 + K\varepsilon_p^{1/2}$ equation, indicating that the microyield mechanism of the composites is not the same as that of traditional aluminum alloys because of existence of SiC_p.

(3) The peak-aging, during which dispersed second strengthening phase S' could fully participate, could significantly improve MYS of the composite.

(4) Thermal cycling treatment is not beneficial to MYS because the cyclic treatment would increase residual microscope stress and the density of movable dislocations of the composite.

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