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Thermal Relaxation of Residual Stresses in Shot Peened Surface Layer of SiCw/Al Composite

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The residual stress relaxation of the shot peened layer on the SiCw/Al composite during isothermal annealing was investigated. The results showed that the residual stresses relaxed in the whole deformation layer especially when the annealing temperature was higher than 200 °C. The relaxation process during isothermal annealing could be described precisely using Zener-Wert-Avrami function. Because of high intensity dislocation around reinforcements producing a large amount of stored energy, the residual stress relaxation activation enthalpy of shot peened SiCw/Al was smaller than self-diffusion activation enthalpy of pure aluminum. According to the analysis of full-width at half-maximum (FWHM) of the shot peened composite in different annealing temperatures, it can be concluded the recovery and recrystallization behavior became intensely when anneal temperature was larger than 200 °C. The small relaxation of residual stress in low annealing temperature was mainly due to partly recovery and recrystallization in a very low level.

Keywords residual stress, shot peening, SiCw/Al composite, thermal relaxation

1. Introduction

Shot peening (SP) is an effective method to improve metallic components' fatigue strength and fatigue life by means of introducing compressive residual stresses and work hardening states into those components, which can suppress crack initiation and crack growth. However, these compressive residual stresses could relax significantly due to subsequent under thermo-mechanical loadings during service. Therefore, the stability of residual stress field induced by shot peening is a very important factor for component' fatigue strength and fatigue life (Ref 1-3). The residual stress field stability is related to the elastic deformation energy inside material and the value of residual stress can be consider as a deviation from material equilibrium state. In thermodynamics, the high energy state always transforms to low energy state, which is the internal dynamic force for residual stress relaxation. Besides internal factor, there are two main categories of external factors, which can promote residual stress relaxation, temperature (Ref 4), and loading (Ref 5). The relaxations in traditional alloys and metals have been extensively investigated (Ref 6-9). However, the residual stress relaxation behaviors of metal matrix composites (MMCs) after SP treatment, especially in temperature annealing have been carried out only by few works (Ref 4, 10). As a lot of MMCs components are always served at elevated temperature condition, the understanding of the residual stress and work hardening relaxation of MMCs components at different temperatures is crucial for the fatigue properties improvement of this kind material component (Ref 7). Therefore, a study on residual stress and work hardening relaxation of MMCs components after SP was carried out on SiCw/Al composite in this study. By accurately documenting the changes of residual stresses and FWHM in different annealing temperatures, the influence of temperature and time on residual stresses and microstructure were evaluated and discussed.

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2. Experiment

The SiCw/Al composite (in situ, 10 vol.% SiCw) used in this article was synthesized according to Ref 11. During the synthesis, SiC whisker reinforcement was formed in certain shape and then was placed inside a mold. Al liquid was injected into mold with pressure to make Al into SiC and then cooling with pressure. The synthesized composites were hot extruded to a rod with a diameter of 50 mm at a temperature of 450 °C using extrusion ratio of 10:1. After that, heat treatments were conducted: solution treatment at 530 °C for 2 h, then quenched into water and finally aging at 170 °C 6 h. Table 1 shows the chemical composition of 6061 Al alloy. Table 2 shows the mechanical properties of matrix Al (6061 Al alloy) and SiCw/Al composite. Specifically, the mechanical properties of matrix Al (6061 Al alloy) and SiCw/Al composite were isotropic. Figure 1 shows the microstructure image of the SiCw/Al composite. The diameter of whisker was about 1 μm and the length of whisker was about 10-20 μm. All the specimens were cut with the dimensions of $15 \times 10 \times 4$ mm for shot peening next step.

The shot peening treatments were carried out according to the following conditions: 3 bar peening pressure, 1 min

Table 1 The chemical composition of 6061Al alloy

	Mg	Si	Fe	Cu	Mn	Zn	Ti	Cr	Al
Element composition (wt.%)	0.8-1.2	0.4-0.8	≤0.7	0.15-0.4	≤0.15	≤0.25	≤0.15	0.04-0.35	Balance

Table 2 Mechanical properties of 6061Al alloy with T6 heat treatment and SiCw/6061Al

Material	ν	$\sigma_{0.2}$, MPa	σ_b, MPa	*E*, GPa
6061Al alloy	0.33	290	290	70-80
SiCw/6061Al	0.31	451	584	102

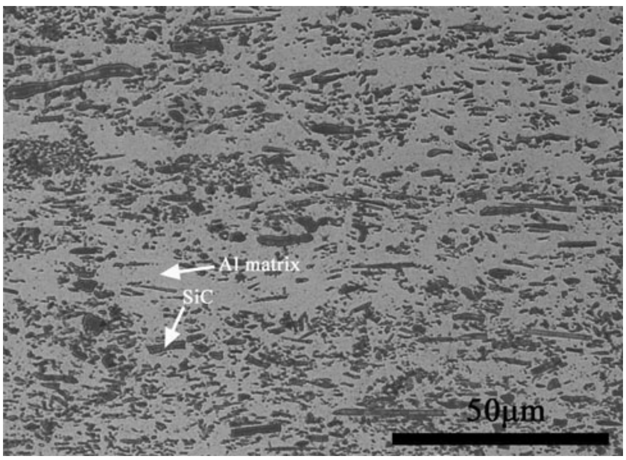

Fig. 1 Microstructure image of the reinforcements (SiCw/Al) distributed in the matrix

duration time, 0.25 mm average diameter of Al_2O_3 ceramic beads, 100 mm distance between nozzle and specimen and, 0.3 mm A peening intensity. These peening parameters were carried out on all specimens to make sure the initial microstructure and residual stress were uniform before annealing treatment. It is well known that the surface residual stresses (σ_s), the maximum compressive residual stresses (σ_{max}), the depth of maximum compressive residual stresses (δ_{max}), and the depth of compressive residual stress zone (δ_0) are the four most important outcomes for shot peening process and the effect of shot peening on residual stress distribution is usually evaluated by these four characteristic parameters (Ref 6). The residual compressive stress relaxation of shot peening produces under temperature. In Al alloy, when the working temperature was higher than 300 °C, the residual stresses of annealed sample were relaxed intensively (Ref 10). Therefore, in this experiment, the maximum annealing temperature of SiCw/6061Al was 300 °C. Isothermal annealing treatments were carried out at 150, 200, 250, and 300 °C with 1 h. In order to investigate the stress relaxation development in different annealing temperatures, residual stress measurements were carried out on annealing specimens in different times. Figure 2 shows the microphotograph of the peened surface of SiCw/Al. As some micro-defect existed on the surface after shot peening, the residual stress relaxation kinetics were measured on specimen after removal of 25 μm from the shot peened surface to avoid the micro-defect effect. The measured point was on the

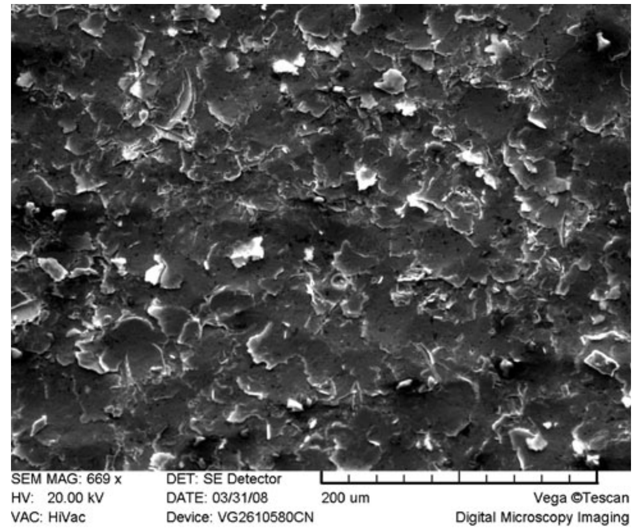

Fig. 2 Microphotograph of the peened surface of SiCw/Al, peening intensity 0.3 mm A

top surface after electrolytic polishing for 25 μm depth layer. The residual stresses were measured in the direction parallel to shot peened surface. The depth profiles of residual stress were determined by iterative electrolytic removal of thin surface layer and subsequent x-ray measurement. The measured interference peaks were evaluated according to the $\sin^2\psi$ method via Cr-Kα radiation and angle of ψ was varied every 10° in the range from −70° to +70°. No stress correction was carried out after electrolytical material removal of surface layer. In order to avoid the influence of electrolytic etching on original residual stress distribution, small electrolytic etching circle area with diameter of 1 mm was carried out in iterative electrolytic removal process. FWHM were determined by x-ray diffraction profiles via Cu-Kα radiation. The detected peaks in both residual stress and FWHM measurements were Al (311) diffraction profiles. Residual stress and FWHM of all tested area were measured three times and averaged.

3. Results and Discussion

During shot peening process, a great amount of balls with high velocity impact on the surface of specimen which leads to repetitive plastic deformation at the local surface of component. Due to the unequal plastic deformation between the surface and the internal layer of material, a compressive residual stress field is introduced at and beneath the exposed surface layer. These compressive residual stress field relax in thermal condition, which can be attributed to plastic misfit by diffusive or dislocational movement of atoms driven by the reduction of stored energy (Ref 6). Figure 3 shows the depth profiles of the residual stresses of the peened SiCw/6061Al composites after annealed 1 h at the temperatures 150, 200, 250, 300 °C. The

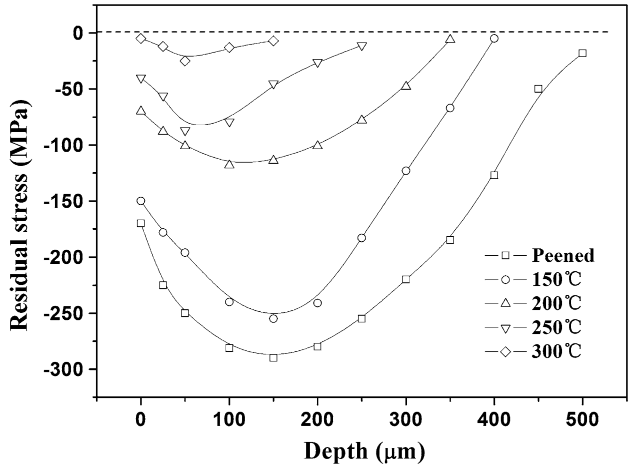

Fig. 3 Depth distribution of residual stresses of shot peened SiCw/6061 Al composites after annealing with temperature 150, 200, 250, and 300 °C, annealing time 1 h, Peened represents the initial residual stresses after shot peening

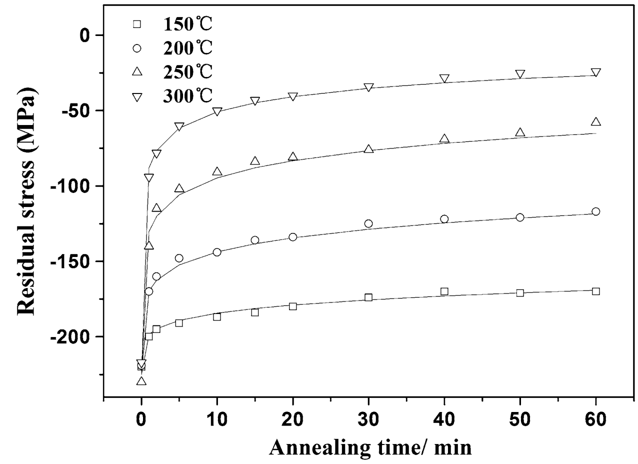

Fig. 4 Residual stress relaxation behaviors of the peened SiCw/6061Al composites during isothermal annealing, temperature 150, 200, 250, and 300 °C, depth 25 μm from surface

Table 3 The characteristic parameters of residual stress field after annealed 1 h at the temperatures 150, 200, 250, and 300 °C

Annealing condition	σ_s, MPa	σ_{max}, MPa	δ_{max}, MPa	δ_0, MPa
Peened	−170	−290	150	500
150 °C, 1 h	−150	−255	150	400
200 °C, 1 h	−70	−118	100	350
250 °C, 1 h	−40	−87	50	250
300 °C, 1 h	−5	−25	50	150

results showed that the higher the temperature, the more obvious the stress relaxation was. In the condition of 150 °C annealing temperature, the surface residual stress decreased 11.7% (from −170 to −150 MPa) and the maximum residual stress decreased 12.0% (from −290 to −255 MPa). In the condition of 200 °C annealing temperature, the surface residual stress decreased 58.8% (from −170 to −70 MPa) and the maximum compressive residual stress decreased 60.7% (from −290 to −114 MPa). It can be seen that when the annealing temperature was 150 °C, the stresses relaxation was small but when the annealing temperature was larger than 200 °C, the stress relaxation became very large. At the annealing temperature 300 °C, it can be seen that the stress relaxation was almost complete. Table 3 shows four characteristic parameters of residual stress field after annealed 1 h at the temperature 150, 200, 250, and 300 °C specifically.

Figure 4 shows the residual stress relaxation development in different annealing temperatures. The depth of measuring point was 25 μm from the top surface. It could be seen that with the annealing time increasing, the residual stresses relaxed rapidly in the early period and then the relaxation rates became slow in all annealing temperatures. The longer the annealing time and the higher annealing temperature, the more obvious the stress relaxation was. After annealing 1 h at temperature of 150, 200, 250, and 300 °C, the residual stresses value in the depth of 25 μm decreased 20.9% (from −225 to −178 MPa), 60.9% (from −225 to −88 MPa), 75.1% (from −225 to −56 MPa), 94.7% (from −225 to −12 MPa). It can be seen that the residual stresses relaxed almost completely at annealed 300 °C for 1 h, which was identical to the result showed in Fig. 3.

Table. 4 Coefficients of the Zener-Wert-Avrami function of the residual stress relaxation behavior of the shot peened composite during isothermal annealing

ΔH, eV	D, min^{-1}	m
1.40	1.5×10^{12}	0.2

The residual stress relaxation of peened MMCs in high temperature is a thermal activated processing. During annealing process, creep deformation takes place in some regions of peened MMCs specimen in high temperature annealing condition, which results in some residual stress relaxation or even residual stress complete relaxation. Thermal relaxations of residual stresses are controlled by thermally activated mechanism which can be described by a Zener-Wert-Avrami function (Ref 8, 9, 12) (Table 4):

$$\sigma_{T,t}^{RS}/\sigma_0^{RS} = \exp[-(Ct)^m] \quad \text{(Eq 1)}$$

where σ_0^{RS} is the initial residual stress, $\sigma_{T,t}^{RS}$ is the residual stress under temperature T, and time t, m is a numerical parameter dependent on relaxation mechanism. For nonferrous alloys, the value of m should be between 0.1 and 0.3 (Ref 13). C is a temperature function depending on the material property according to (Table 4):

$$C = D\exp(-\Delta H/kT) \quad \text{(Eq 2)}$$

where D is the material constant, k is the Boltzmann constant with value of 8.617343×10^{-5} eV/K, T is the annealing temperature, and ΔH is the activation enthalpy for stress relaxation process.

From Eq 1, a plot of $\log(\ln(\sigma_0^{RS}/\sigma^{RS}))$ as a function of $\log(t)$ for a constant annealing temperature T gave a straight line of slope m. Figure 5 is the relation of $\log(\ln(\sigma_0^{RS}/\sigma^{RS}))$ and $\log(t)$ in according to the residual stress data from Fig. 4. As shown in

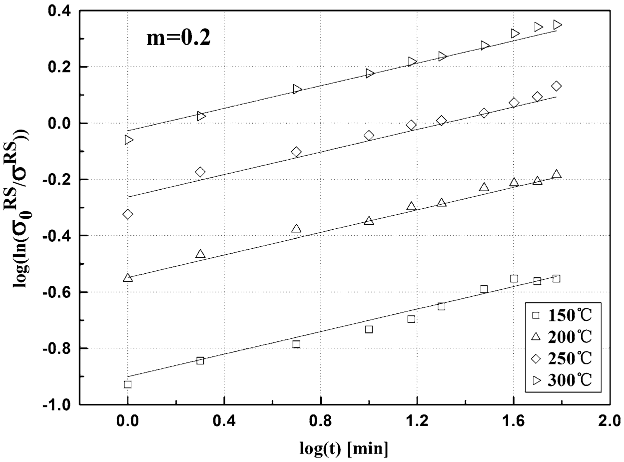

Fig. 5 Influence of annealing time and temperature on residual stresses in $\log(\ln(\sigma_0^{RS}/\sigma^{RS})) - \log(t)$lg diagram

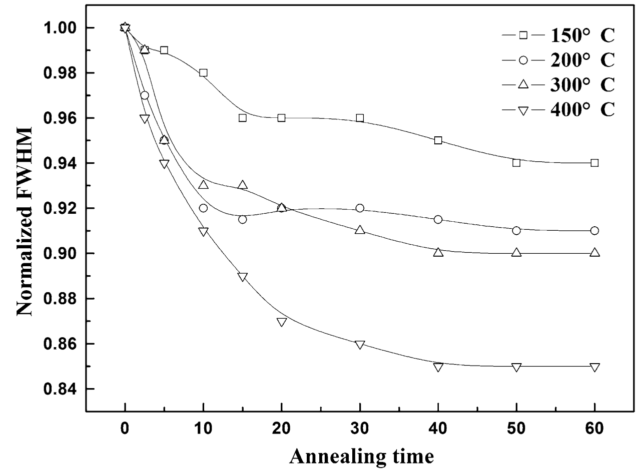

Fig. 6 Normalized FWHM of peened SiCw/Al composites versus annealing temperature T and time t, Al (311) reflection

Fig. 5 the measured residual stress data accords with linear relationship and the slope of straight line is m. During the dynamic process of residual stress thermal relaxation between 150 and 300 °C, it is obvious that thermal relaxation of residual stress is a thermal recovery process. The measured data under different temperatures are fitted by straight lines with an identical slope of $m = 0.2$.

The results showed that the activation enthalpy for stress relaxation of SiCw/Al composite was 1.40 eV. Comparing this value with previous result (Ref 10), it could be seen that the activation enthalpy for stress relaxation of SiCw/Al composite was not only smaller than the activation enthalpy for stress relaxation of TiB_2/Al composite (1.64 eV), but also even smaller than the self-diffusion activation enthalpy of aluminum (1.45 eV). Shot peening could produce plastic deformation in near surface region of SiCw/Al composite specimen. Since the reinforcements always acted as sink sources of dislocations during repeated deformation (Ref 14), the dislocation density around reinforcement increased significantly (Ref 15). On the one hand, the high dislocation density around reinforcement particle could increase the stored energy and make the dislocation in unstable state, which could promote the recrystallization and the growth of recrystallization nucleus (Ref 16, 17). In the annealing condition, the capability of dislocation movement and the rates of dislocation annihilation and rearrangement increased, which led to dislocation density decrease and residual stress relaxation. However, on the other hand, the reinforcement particle strength was still very high in during annealing process, which could hinder the dislocation movement and residual stress relaxation (Ref 18). These two controversial factors determined the value of activation enthalpy for stress relaxation. The movements of dislocation were impeded by the pinning role of the reinforcements, especially the reinforcement sizes were small and the reinforcement distributions were uniform. In TiB_2/Al composite in previous work (Ref 10), the sizes of TiB_2 reinforcement particles were very small (the average dimension was from 50 to 500 nm) but in SiCw/Al composite the sizes of SiCw reinforcement whiskers were relative larger (the diameter of whisker was about 1 μm and the length of whisker was about 10-20 μm). In SiCw/Al composites, the increment of stored energy induced by high dislocation density around reinforcement particle was dominating factor, so the activation enthalpy for stress relaxation of SiCw/Al composite (1.40 eV) was smaller than that of pure aluminum (1.45 eV). However, in TiB_2/Al composites (Ref 10), the reinforcements pinning effect was the dominating factor, so the activation enthalpy for stress relaxation of TiB_2/Al composite (1.64 eV) was larger than that of pure aluminum (1.45 eV).

The effects of shot peening on microstructure include fine domain, high microstrain, and high value of dislocation density. In annealing process, recovered and recrystallized occurred in peened specimen which lead to residual stress relaxation. It is well known that qualitative microstructure change can be obtained from the measurements of the full-width at half-maximum values of the x-ray diffraction profiles (FWHM). Therefore, to investigate the recrystallization behavior of SiCw/Al composite during isothermal annealing process, different annealing temperatures were carried out on SiCw/Al composite and the full-width at half-maximum values were tested by x-ray diffractor. The FWHM data in different annealing temperatures were normalized shown in Fig. 6. The FWHM values of Al (311) plane in 25 μm depth before annealing process were used as standard width for normalizing FWHM. It could be seen that the normalized FWHM values decreased with increasing time in all temperature annealing processes. The normalized FWHM values decreased more rapidly in a higher temperature annealing condition. In 150 °C annealing condition, the FWHM decreased only about 6% after 1 h anneal and the decline rate keep nearly a constant. In 200, 250, and 300 °C annealing condition, the FWHM decreased about 9, 10, and 15%, respectively after 1 h anneal and the FWHMs in these three temperature conditions decreased rapidly in the initial period of annealing. According to Scherrer formula, the FWHM was related to the mean grain size of tested area. The broadening FWHM means small mean grain size. In 150 °C, annealing condition, recrystallization behavior took place in only one part of SiCw/Al composite specimen. However, in 300 °C annealing condition, the activation energy from annealing process was large enough to promote recrystallization of SiCw/Al composite. Grains grew up very quickly and the store energy induced by high dislocation density promoted this process, After 1 h annealing, recrystallization was completed which led to residual stress fully relaxation.

4. Conclusion

The thermal relaxation of residual stresses in shot peened layer of SiCw/Al composite was investigated. The results showed that the residual stresses were relaxed in the whole deformation layer especially in the condition of annealing temperature above 200 °C. During annealing process, the higher the annealing temperature, the more obvious the stress relaxation was. The residual stress relaxation behavior was in accordance with Zener-Wert-Avrami function. The regression equation was $\sigma^{RS}_{T,t}/\sigma^{RS}_0 = \exp\left\{-\left[2.5\times10^8\exp\left(-\frac{1.40\,\text{eV}}{kT}\right)t\right]^{0.2}\right\}$, which meant the residual stress relaxation of SiCw/Al composite during annealing was caused by thermally activated process. From this equation, activation enthalpy for stress relaxation of SiCw/Al composite was obtained with value of 1.40 eV, which was smaller than the activation enthalpy for stress relaxation of TiB_2/Al composite (1.64 eV) and the self-diffusion activation enthalpy of aluminum (1.45 eV) (Ref 10). As the size of SiCw reinforcement particle was larger than the size of TiB_2 reinforcement particle in Al matrix, the hindrance effect of reinforcement particles on dislocation movement in SiCw/Al composite was smaller than that in TiB_2/Al composite. In SiCw/Al, the high stored energy induced by high dislocation density around reinforcement particle was dominating factor during annealing process, which led to the activation enthalpy for stress relaxation of SiCw/Al composite (1.40 eV) was smaller than that of pure aluminum (1.45 eV). Furthermore, according to FWHM analysis during annealing process, it could be concluded that severe recovery and recrystallization behavior took place when the annealing temperature was higher than 200 °C. The small relaxation of residual stress in low annealing temperature was mainly due to partly recovery and recrystallization in a very low level.

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