Thermal Relaxation of Residual Stresses in Shot Peened Surface Layer on TiB$_2$/Al Composite at Elevated Temperatures

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The residual stresses and work hardening relaxations of the shot peened layer on the TiB$_2$/6351Al composite during thermal exposure were investigated. The results showed that the residual stresses were relaxed in the whole deformation layers especially under higher temperatures. The relaxation processes during isothermal annealing can be described using a Zener-Wert-Avrami function. The thermal stability for the fatigue properties improvement.

Keywords: thermal relaxation, residual stresses, work hardening, shot peening, TiB$_2$/Al composite

1. Introduction

Metal matrix composites, MMCs, have been widely concerned because of their excellent physical and mechanical properties such as specific high modulus, and strength etc.$^1$ But the tensile stresses in the matrix always generated during manufacturing and subsequent heat treatments, and they may deteriorate the fatigue properties of MMCs.$^2$ It is therefore of interest to apply a mechanical surface treatment to enhance their fatigue properties.

Shot peening (SP) is an effective method employed by numerous industries to impart compressive residual stresses and work hardening states into metallic components to suppress crack initiation and crack growth, and then improve their fatigue strength and fatigue life.$^3$ Unfortunately, these residual stresses and work hardening states could relax significantly under thermo-mechanical loadings.$^5$ The relaxations in traditional alloys and metals have been extensively investigated.$^5$ However, there is little information on the relaxation behaviors in shot peened MMCs at elevated temperatures. The understanding of the residual stresses and work hardening states relaxations of the composite is crucial for the fatigue properties improvement.

It was found that the thermomechanical residual stresses relaxation can be separated into mechanical and thermal relaxation control mechanisms.$^6$ The mechanical residual stresses relaxation of the shot peened composite used in the present study had been investigated.$^9$ Then the short report deals with the relaxation behaviors of the residual stresses and work hardening states, in the shot peened surface layer on an in-situ TiB$_2$/6351Al, under high temperatures. The results are also discussed.

2. Experimental

The TiB$_2$/6351Al composite (10 vol% TiB$_2$) used in this study was synthesized in-situ according to Ref. 10) with a nominal chemical composition of 1.0 Si, 0.6 Mg, 0.6 Mn, 6.7 B, 3.0 Ti, and balance Al (in mass%). The size of the reinforcements is between 50 nm and 500 nm. Their shapes and dispersions are as shown in Ref. 9). The synthesized composites were hot extruded to a rod with a diameter of 35 mm at a temperature of 450°C using extrusion ratio of 10 : 1. Before SP, heat treatments were conducted, that is, solution treatment at 530°C for 110 min, then quenching into the water, and finally aging at 170°C for 6 h. The Young’s modulus $E$ and proof stress $\sigma_{0.2}$ of the composite are 80 GPa and 300 MPa, respectively. The formed sphere precipitates with about 150 nm distributed homogeneously in the matrix. This was regarded as the initial state of the composite. Samples were cut from the center of the rod along the extrusion direction (longitudinal direction) with the dimensions of $15 \times 15 \times 2$ mm$^3$.

The SP treatments were carried out according to the conditions: 0.3 MPa jet pressure, 1 min time, 0.25 mm average diameter of Al$_2$O$_3$ ceramic beads, 100 mm distance between nozzle and specimen, and 0.24 mm A Almen peening intensity. After SP, isothermal annealing treatments were carried out at 150°C, 200°C, 250°C and 300°C, respectively. The measurements of the depth distribution of the residual stresses were performed by iterative electrolytical removal thin surface layers and subsequent X-ray measurements. For the measured values were nearly identical, then the average values of the residual stresses of three peened samples at the same depth were used for describing their depth distributions. Besides, in order to obtain the relaxation behavior of the residual stresses during isothermal annealing, another set of peened samples were electro-polished to the subsurface layers with higher compressive residual stresses, and then annealed under the same four temperatures mentioned above. In all experiments, the residual stresses in the longitudinal direction were determined by the X-ray stress analyzer according to the sin$^2 \psi$ method after the samples cooling from high temperatures to the room temperature. Cr-K$_\alpha$ radiation was used, and the shifts of Al(311) diffraction profiles were detected.
3. Results and Discussion

After annealing, the residual stresses were relaxed in the whole deformation layers. Figure 1 shows the depth distributions of the residual stresses of the peened TiB$_2$/6351Al composites after annealing 1 h at the temperature 150°C, 200°C, 250°C, 300°C, respectively. The results showed that the higher the temperature, the more obvious the stresses relaxation is. At the annealing temperature 300°C, the recrystallization has been completed which results in almost completely stresses relaxation.

During isothermal annealing, thermal residual stresses relaxations of the peened samples were observed, as shown in Fig. 2. It can be seen that the relaxations depend on the time and temperature. With the temperature increased and the annealing time prolonged, the residual stresses relaxed importantly. After annealing, the residual stresses of the sample annealed at 300°C were relaxed almost completely, which was identical to the result showed in the Fig. 1.

Thermal relaxations of residual stresses are controlled by thermally activated mechanism that can be described by a Zener-Wert-Avrami function

$$\frac{\sigma_{R,S}^g}{\sigma_o^g} = \exp[-(A)^{mRS}]$$  (1)

where $\sigma_o^{RS}$ is the initial residual stress, $\sigma_{R,S}^g$ is the residual stress under temperature $T$ and time $t$. $m_{RS}$ is a numerical parameter dependent on the dominant relaxation mechanism. For non ferrous alloys, the value of $m_{RS}$ should be between 0.1 and 0.3. $A$ is a function dependent on the material and temperature according to

$$A = B_{RS} \exp(-\Delta H_{RS}/kT)$$  (2)

where $B_{RS}$ is the material constant, $k$ is the Boltzmann constant, $\Delta H_{RS}$ is the activation enthalpy for the relaxation process. Using eq. (1)–(2) and the datum in Fig. 2, the activation enthalpy of the relaxation process $\Delta H_{RS} = 1.64$ eV, the coefficients $B_{RS} = 6.5 \times 10^{11} / s^{-1}$ and $m_{RS} = 0.2363$ had been obtained through regression analysis.

Quantitative indications as to the behavior of near-surface work hardening states can be obtained from the measurements of the full width at half maximum values of the X-ray diffraction profiles (FWHM). In X-ray diffraction, the measured line profile $h$ is always a convolution of the structurally broadened profile $f$ and the instrumental profile $g$. And the structurally breadth of $f$ is in fact mainly determined by the sample’s microstructures such as domain size, microstrain/dislocation density etc., and related to the work hardening states of the peened samples.

In the present study, a FWHM of 1.48° (20) of an unpeened and fully annealed sample was selected as the initial breadth of $g$. Further investigation showed that the main components of the measured $h$ and $g$ are Gaussian. Using the Gaussian method, the structurally breadth FWHM$_f$ of the samples had been calculated as shown in Fig. 3. It seems likely that the temperature and time dependence of the FWHM$_f$ decrease is related to the residual stresses relaxation. As the reduction of the FWHM$_f$ is similar to the relaxation of the residual stresses, then the Zener-Wert-Avrami function is used once more to describe the FWHM$_f$ values decreases. The difference between the FWHM$_f$ values during annealing and the initial FWHM$_f$ value substitute the ratio $\sigma_{R,S}^{g/\sigma_o^{g}}$ in eq. (1). Using regression analysis, the coefficients of the Zener-Wert-Avrami function were obtained, which are
\[ \Delta H_{\text{FWHM}} = 2.16 \text{ eV}, \quad B_{\text{FWHM}} = 5.5 \times 10^{13} \text{ s}^{-1} \quad \text{and} \quad m_{\text{RS}} = 0.1317. \]

The results showed that the activation enthalpy of residual stresses relaxation is smaller than the one of FWHM/ decrease. It means that the relaxation of residual stresses is faster than the relaxation of work hardening states since dislocation movement is adequate for relaxation of residual stresses while for the decrease of FWHM/ dislocation annihilation or rearrangement is necessary. The results also showed that the activation enthalpies of both the residual stresses relaxation and the FWHM/ decrease are larger than the self diffusion activation enthalpy of aluminium (1.45 eV). The higher activation enthalpy of the shot peened condition for residual stress relaxation and also of FWHM/ decrease indicates that the relaxation mechanism may be controlled by thermally activated gliding of dislocations.\(^7\) At the temperature 300°C, recrystallization and grain growth was more rapidly. Therefore, residual stresses and dislocation density in the deformation layer are reduced significantly. The dislocation density rapidly obtains small values as a result of the growth of the new grains. This led to small FWHM/ and almost complete removal of macroscopic compressive residual stresses.\(^11\)

The reinforcements in the matrix play important roles in the residual stresses and work hardening relaxation. Since they always act as sink sources of dislocations during repeated deformation,\(^4\) then a large amount of dislocations are generated during SP. It has been reported that high density dislocations around the reinforcement particles promote Recrystallization.\(^15,16\) The growth of recrystallization nucleus largely depends on the stored energy.\(^17\) High dislocation density means high store energy. During annealing, the stored energy was released for recrystallization and the dislocation density decreased. As the reinforcements providing more nucleation sites, there were more new grains with smaller size in the composite after annealing. Then the relaxation of the residual stresses was fast, but the declining of FWHM/ values was not.

In the solution treatment of 6351Al alloy, the precipitation sequence is \(\beta' \rightarrow \beta \rightarrow \beta (\text{Mg}_2\text{Si})\), of which only \(\beta\) phase is stable. It was reported that the precipitation sequence in unreinforced alloy and composite material are similar.\(^18\) Comparing with the reinforcements, the precipitates \(\beta\) are smaller and their distributions are more homogeneous because they are formed through diffusion. Dislocations can transmit across small particles. However, they are almost impossible to transmit across large particles.\(^19\) Therefore, large particles always act as dislocation sink sources while the small ones do not. Upon annealing, the hindrance on dislocation motion represented by the precipitates decreased drastically, but the hindrance effects of the reinforcements remained.\(^20\) It means that the precipitates had little effects on promoting recrystallization. However, they still played important pinning roles in grain and subgrain boundaries movements. Comparing to the self diffusion activation enthalpy of aluminium, the main reason of the activation enthalpies increment of the residual stresses relaxation is the hindrance effects of the reinforcements during annealing. While the combination hindrance effects of the reinforcements and the precipitates increased the activation enthalpies of the work hardening relaxation.

4. Conclusions

The thermal relaxations of the residual stresses and work hardening in the shot peened layer on the TiB\(_2/\)Al composite were investigated. The results showed that the residual stresses were relaxed in the whole deformation layers especially under high temperatures. Besides, the residual stresses and the work hardening states represented by the FWHM/ were relaxed constantly during annealing, and were analyzed by applying a Zener-Wert-Avrami function. The activation enthalpy of work hardening declining is higher than the one of residual stresses relaxation, and both are higher than the enthalpy of self diffusion of aluminium. The most likely relaxation mechanism is controlled by thermally activated gliding of dislocations. The enthalpies of the residual stresses and work hardening relaxations were increased by the hindrance effects of the reinforcements on the dislocations movements. While the pinning effects of the precipitates on the grain (and subgrain) boundaries movements was another reason for the further increment of the enthalpy of the work hardening relaxation.

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