Influence of Isothermal Annealing on Stress Relaxation of Shot Peened SiCw/Al Composite

Junjie Huang[1], Chuanhai Jiang[1], Qi Wang[2]

1School of Material science and engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, P.R. China
2Dafeng Daqi Metal Grinding Material CO., LTD, Dafeng 224100, P.R. China

Abstract: 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 using Zener-Wert-Avrami function when the annealing temperature was larger than 200°C. Because of high intensity dislocation around reinforcements producing a large amount of stored energy, activation enthalpy of shot peened SiCw/Al was smaller than self diffusion activation enthalpy of pure aluminum. According to the full width at half maximum (FWHM) of the shot peened composite vs time in different temperatures annealing, 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: thermal relaxation, residual stress, shot peening, SiCw/Al composite

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. Therefore, the stability of residual stress field induced by shot peening is a very important factor of component' fatigue strength and fatigue life [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. Beside internal factor, there are two main categories of external factors, which can promote residual stress relaxation, temperature [4] and loading [5]. The relaxations in traditional alloys and metals have been extensively investigated [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 [4, 10]. As a lot of MMCs components are served at relative high temperature condition, the understanding of the residual stress and work hardening relaxation of MMCs components in high temperature (higher than room temperature) is crucial for the fatigue properties improvement of this kind material component [7]. Therefore, a parametric study on residual stress and work hardening relaxation of MMCs components after SP was carried out on SiCw/Al composite in this work. By accurately documenting the changes of residual stresses and FWHM in different temperature annealing, the influence of temperature on residual stresses and microstructure were evaluated and discussed.

2. Experiment

The SiCw/Al composite (in situ, 15 vol.% SiCw) used in this paper was synthesized according to Refs [11]. The reinforcement in composite was SiCw whisker. The diameter of whisker was about 1μm and the length of whisker was about 15μm. Tab.1 shows the chemical composition of 6061 Al alloy. The mechanical properties of matrix Al (6061 Al alloy) and SiCw/Al composite are listed in Tab. 2 respectively. Before SP, heat treatments were conducted: solution treatment at 530°C for 120min, then quenched in water, and finally aging at 170°C for 6h. All the specimens were cut with the dimensions of 15mm×10mm×4mm. The SP intensity was 0.3mmA for all specimens in order to make sure the initial microstructure and residual stresses were uniform before different temperatures isothermal annealing treatments. Isothermal annealing treatments were carried out at 150°C, 200°C, 250°C and 300°C with 1h, 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. Residual stress tests were determined by the X-ray stress analyzer according to the $\sin^2\psi$ method via Cr-Kα radiation. 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.

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 and SiCw/6061Al composite

Material	v	σ0.2 / MPa	σb / MPa	E / GPa
6061Al alloy	0.33	290	290	70-80
SiCw/6061Al	0.31	451	584	102

3. Results and Discussion

During shot peening process, a great amount of balls with high velocity impact on the surface of specimen which causes elastic and plastic deformation. As a result, a compressive residual stress field is introduced at and beneath the exposed surface layer. However, these residual stresses could relax significantly in thermal loading due to recrystallization. Fig. 1a shows the depth profiles of the residual stresses of the peened SiCw/6061Al composites after annealed 1h at the temperature 150°C, 200°C, 250°C, 300°C, respectively. The results showed that the higher the temperature, the more obvious the stress relaxation was. The stress relaxation was relatively small when the annealing temperature was 150°C. At the annealing temperature 300°C, the recrystallization had been completed which results in almost completely stress relaxation.

In order to investigate the stress relaxation development in different annealing temperatures, stress measurements were carried out on annealing specimens in different time points. For the purpose of getting larger initial residual stress value, the residual stress values in 25μm depth were measured by X-ray measurement after electrolytic removal 25μm depth surface layers in all specimens. The surface residual stress relaxation time history analysis in different annealing temperatures is shown in Fig. 1b. It could be seen that with the annealing time increasing, the residual stresses relaxed rapidly in the early period and than 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, the residual stresses of the specimen annealed at 150°C decreased 24% (from -225MPa to -170MPa) but the residual stresses of the specimen annealed at 300°C relaxed almost completely, which was identical to the result showed in Fig.1a.

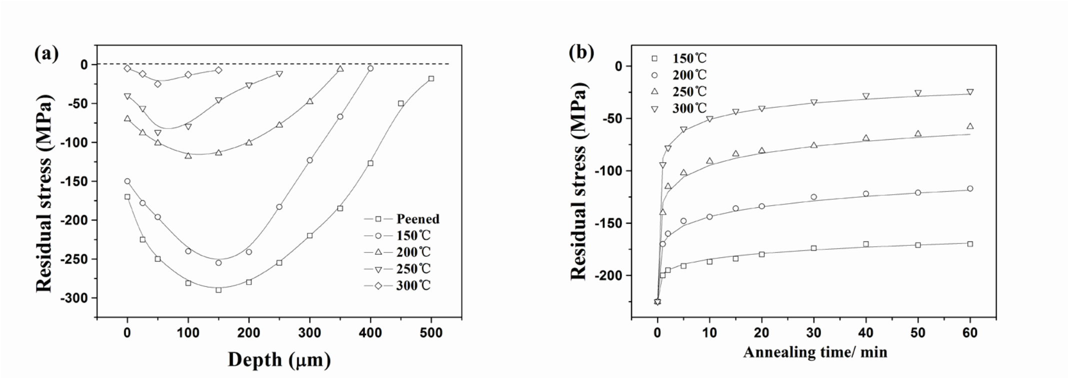

Fig. 1. (a) Depth distribution of residual stresses of shot peened SiCw/6061 Al composites after annealing with temperature 150°C, 200°C, 250°C and 300°C, annealing time 1h, Peened represents the initial residual stresses after shot peening, (b) Residual stress relaxation behaviors of the peened SiCw/6061Al composites during isothermal annealing, temperature 150°C, 200°C, 250°C and 300°C, depth 25μm from surface.

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 [8,9,12]:

$$\sigma_{T,t}^{RS} / \sigma_0^{RS} = \exp\left[-(Ct)^m\right] \tag{1}$$

where σ_0^{RS} is the initial residual stresses, $\sigma_{T,t}^{RS}$ is the residual stresses under temperature T and time t, m is a numerical parameter dependent on relaxation mechanism. For non ferrous alloys, the value of m should be between 0.1 and 0.3[13]. C is a temperature function depending on the material property according to:

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

Where D is the material constant, k is the Boltzmann constant with value of 8.617343×10^{-5}eV/K. ΔH is the activation enthalpy for stress relaxation process. According to eq. (1), (2) and the datum in Fig. 1b, the specific values of the residual stress relaxation process can be calculated. The following equation is described the stress relaxation through regression analysis:

$$\sigma_{T,t}^{RS} / \sigma_0^{RS} = \exp\left\{-\left[2.5\times10^8 \exp\left(-\frac{1.40eV}{kT}\right)t\right]^{0.2}\right\} \tag{3}$$

The results showed that the activation enthalpy for stress relaxation of SiCw/Al composite was 1.40eV. Comparing this value with previous result [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 (1.64ev), but also even smaller than the self diffusion activation enthalpy of aluminum (1.45eV). As the reinforcements always acted as sink sources of dislocations during repeated deformation [14], the dislocation density around reinforcement increased significantly [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 [16, 17]. At high temperature annealing, 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 [18]. These two controversial factors determined the value of activation enthalpy for stress relaxation. As we known that 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, the sizes of TiB_2 reinforcement particles were very small (the average dimension was from 50-500nm) but in SiCw/Al composite the sizes of SiCw reinforcement whiskers were relative larger (the diameter of whisker was about 1μm and the length of whisker was about 15μm). Therefore, the activation enthalpy for stress relaxation of SiCw/Al composite was smaller than that of TiB2/Al composite. Furthermore, in SiCw/Al composite, the increment of stored energy induced by high dislocation density around reinforcement particle was dominating factor so that the activation enthalpy for stress relaxation of TiB2/Al composite was even less than that of pure aluminum.

In annealing process, temperature not only influenced the residual stress filed of MMCs specimen but also influenced the microstructure of MMCs specimen. In order to investigate the recrystallization behavior of SiCw/Al composite during isothermal annealing process, different annealing temperatures were carried out on SiCw/Al composite and structurally breadth FWHM development in different annealing temperatures were calculated by Gaussian method shown in Fig. 2. The FWHM values in 25μm depth were measured as standard width for comparison by X-ray measurement. It could be seen that the FWHM values decreased with increasing time in all temperature annealing processes, which meant the peening microstructures recovered and recrystallized during annealing. According to Scherrer equation, the decrement of FWHM means grain size became larger. In 150°C annealing condition, the FWHM decreased slowly, which meant recovery and recrystallization behavior took place in only one part of SiCw/Al composite specimen. However, when the annealing temperature became higher, FWHM decreased rapidly in the initial period of annealing, which meant the internal energy of SiCw/Al composite specimen was larger than recrystallization activation energy of SiCw/Al composite at this temperature. Grains grew up very quickly and the store energy induced by high dislocation density promoted this process, which led to residual stress fully relaxation.

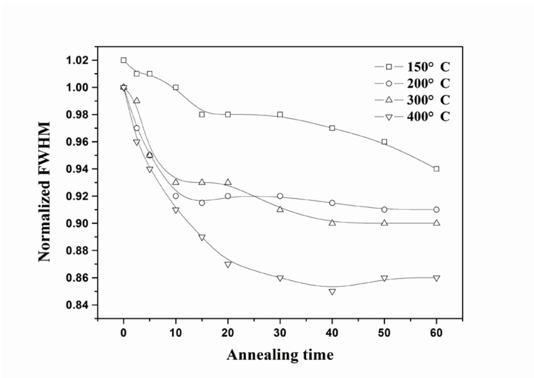

Fig. 2. FWHM of peened SiCw/Al composites *vs* annealing time t with different temperatues, Al (311) reflection.

4. Conclusion

The thermal relaxation of residual stresses in shot peening layer of SiCw/Al composite were investigated. The results showed that the residual stresses were relaxed in the whole deformation layer especially in the initial period of annealing. The residual stress relaxation behavior was in accordance with Zener-Wert-Avrami function when the annealing temperature was higher than 200°C. The regression equation was $\sigma_{T,t}^{RS} / \sigma_0^{RS} = \exp\left\{-\left[2.5\times10^8 \exp\left(-\frac{1.40eV}{kT}\right)t\right]^{0.2}\right\}$, which meant the residual stress relaxation of SiCw/Al composite during annealing was a creep process. As the size of SiCw/Al reinforcement particle was relative larger, the hindrance effect of reinforcement particles on dislocation movement was relative smaller and the high stored energy induced by high dislocation density around reinforcement particle was dominating factor during annealing process. Furthermore, according to FWHM analysis during annealing process, it could be seen 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.

Acknowledgements

The authors are grateful to Shanghai Carthing Machinery Co. Ltd for supporting this work.

Reference

[1] N. Sidhom, A. Laaouri, R. Fathallah, C. Braham, H.P. Lieurade, *Fatigue strength improvement of 5083 H11 Al-alloy T-welded joints by shot peening: experimental characterization and predictive approach*, Int. J. Fatigue, Vol. 27 (2005), pp 729-745.

[2] Y.F. Al-Obaid, *The effect of shot peening on stress corrosion cracking behaviour of 2205-duplex stainless steel*, Eng. Fract. Mech. Vol. 51 (1995), pp 19-25.

[3] V. Schulze, Proceeding of the Eighth International Conference on Shot Peening ICSP-8 in Garmisch-Partenkirchen DGM, *Characteristics of Surface Layers Produced by Shot Peening*. Wiley-VCH, Weinheim, Germany, (2003), pp 145-160.
[4] G.Bruno, R.Fernandez, G.Gonzalez-Doncel, *Relaxation of the residual stress in 6061Al-15Vol.%SiCw composites by isothermal annealing*, Mater. Sci. Eng. A, Vol. 382 (2004), pp 188-197.
[5] W.Z. Zhuang, G.R. Halford, *Investigation of residual stress relaxation under cyclic load*, Int. J. Fatigue, Vol. 23 (2001), pp 31-37.
[6] A. Evans, S.B. Kim, J. Shackleton, G. Bruno, M. Preuss and P.J. Withers, *Relaxation of residual stress in shot peened udimet 720Li under high temperature isothermal fatigue*, Int. J. Fatigue, Vol. 27 (2005), pp 1530-1534.
[7] P. Juijerm, I. Altenberger, *Residual stress relaxation of deep-rolled Al-Mg-Si-Cu alloy during cyclic loading at elevated temperatures*, Scripta Mater., Vol. 55 (2006), pp 1111-1114.
[8] I. Nikitin, M. Besel, *Residual stress relaxation of deep-rolled austenitic steel*, Scripta Mater., Vol. 58 (2008), pp 239-242.
[9] M.C. Berger and J.K. Gregory, *Residual stress relaxation in shot peened Timetal 21s*, Mater. Sci. Eng. A, Vol. 263 (1999), pp 200-204.
[10] W. Luan, C. Jiang, V. Ji, *Thermal relaxation of residual stresses in shot peened surface layer on TiB2/Al composite at elevated temperatures*, Mater. Trans. Vol. 50(6) (2009), 1499-1501.
[11] Chuan-hai Jiang, Jian-sheng Wu, De-zun Wang, *Shot peening strengthening of the Cast SiCw/Al composite*, Materials for Mechanical Engineering (China), Vol. 26(8) (2002), pp 32-34.
[12] P. Juijerm, I. Altenberger and B. Scholtes, *Influence of ageing on cyclic deformation behavior and residual stress relaxation of deep rolled as-quenched aluminium alloy AA6110*, Int. J. Fatigue, Vol. 29 (2007), 1374-1382.
[13] O. Vohringer, *Relaxation of reisidual stresses by annealing or mechanical treatment* In: A. Niku-Lari (Editor), Advances in surface treatment, Pergamon press, Oxford, (1987), pp 361-396.
[14] F.J. Humphreys, P.N. Kalu, *Dislocation-particle interactions during high temperature deformation of two-phase aluminum alloys*, Acta Metallurgica et Materialia, Vol. 35 (1987), pp 2815-2829.
[15] W.Z. Luan, C.H. Jiang, V. Ji, Y.H. Chen, H.W. Wang, *Investigation for warm peening of TiB_2/Al composite using X-ray diffraction*, Mater. Sci. Eng. A, Vol. 497 (2008), pp 374-377.
[16] M. Ferry, P.R. Munroe, *Recrystallization kinetics and final grain size in a cold rolled particulate reinforced Al-based MMC, Composites Part A*: applied science and manufacturing, Vol. 35 (2004), pp 1017-1025.
[17] P. Cavaliere, E. Evangelista, *Isothermal forging of metal matrix composites: Recrystallization behaviour by means of deformation efficiency*, Compos. Sci. Technol., Vol. 66 (2006), pp 357-362.
[18] P. Fernandez, R. Fernandez, G.G. Doncel, G. Bruno, *Correlation between matrix residual stress and composite yield strength in PM 6061Al-15 vol% SiCw*, Scripta Mater., Vol. 52 (2005), pp793-797.