Thermal relaxation of residual stress in a carbon nanotube reinforced aluminium matrix composite

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Introduction

Shot peening (SP) is an important method to enhance metallic superficial properties [1-4]. After SP, the introduced compressive residual field (CRS) and change of microstructure could improve the surface properties significantly [5-7], such as surface microhardness, stress corrosion property, fatigue life, ect [8,9]. Stress peening is a special and important shot peening method. It is mainly used in stress peening forming to fabricate thin parts with complicated shapes, such as sheet with double curvatures, aerofoils. In the process of stress peening, specimens were elastically prebended in certain directions for peening forming. And a CRS field, a critical parameter for the component, were induced by high energy “shots”. After stress peening, the prestresses were released and the CRS field was changed by elastic recovery. This change could be considered as a superposition of two stress fields: one is a CRS field introduced by SP, another one is a stress field generated by release of the prestress. Specially, for different materials, the CRS field was different with same peening parameter and prestress [10-15].

Recently, the CNTs reinforced aluminium matrix composites have attracted wide and growing attentions to develop a new generation of high-stiffness metallic, high-strength, lightweight materials [16-22]. Due to it would be used for the fields of the electronic and military devices, high speed transportation. In these fields, the new material might be formed by stress peening to fabricate some complicated shapes. After stress peening, the CRS field induced by stress peening should be retained or released by annealing treatment due to specific requirements. In addition, few investigations have been made on thermal relaxation of an anisotropic CRS field.

Objectives

A carbon nanotube (CNT) reinforced Al matrix composite was fabricated and treated by stress peening. After stress peening, anisotropic compressive residual stress (CRS) fields were induced in peened layers. The change law of CRS in two directions (parallel and perpendicular to the length direction of the specimens) in different annealing time and temperatures was investigated. The variance of microstructure and microhardness were also measured.

Methodology

The microstructure of the CNT/Al-Mg-Si composite before stress peening was characterized by transmission electron microscopy (Fig. 1). As observed in Fig. 1(a), CNTs (~1–2 μm in length, ~20 nm in diameter) are homogeneously distributed in the equiaxed crystal matrix. The crystal size of Al matrix was about 300 nm, a few Al4C3 rods existed. As shown in Fig. 1(b), the CNTs have graphitic layers with a spacing between two neighboring lattice fringes of ~0.34 nm, which is consistent with the (002) plane of graphite.

Fig. 2 shows a sketch diagram of the stress peening. As shown in Fig. 1, the specimens were preloaded by three-point bending method during shot peening. The value of stress induced by the preloading in the length direction was 100MPa. An air blast machine (Carthing Machinery Company, Shanghai) were used for SP treatment. After stress peening, the preloaded were relieved and bending elastic resilience was generated. Isothermal annealing treatment was performed at 150 °C, 200 °C, 250 °C.

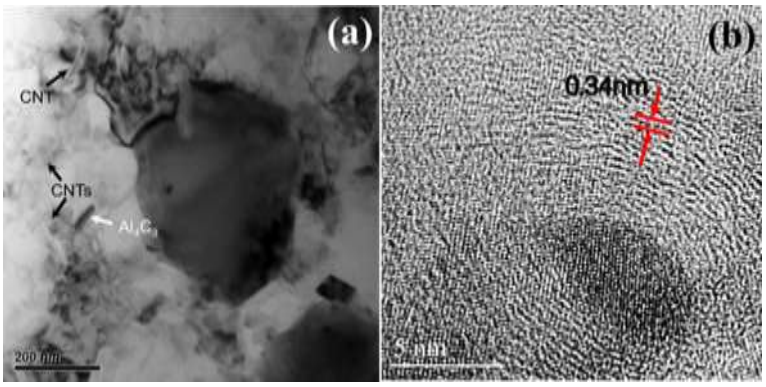

Fig. 1. The microstructure of CNTs/ Al-Mg-Si composite before SP observed by TEM, (a)TEM micrograph, (b) HRTEM

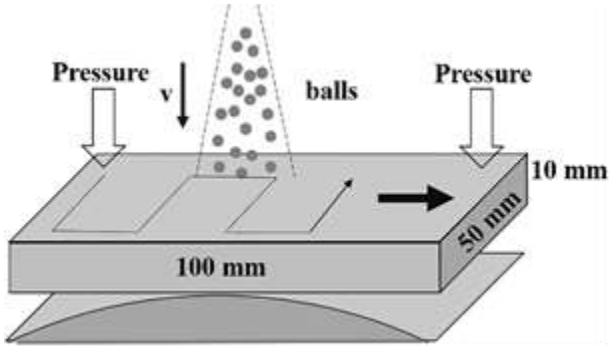

Fig. 2. Schematic diagram of the stress peening process

Residual stress fields at different annealing time (0, 20, 60, 120 min) were measured in two directions (parallel and perpendicular to the length direction). Thin surface layers of three other specimens were prior removed one by one via the method of chemical etch until the surface stress increased to maximum. Then the three specimens were annealed at 150, 200, and 250 °C, respectively. The surface stresses of the three specimens were measured at specific time intervals (1, 2, 4, 8,15, 30, 60, and 120 min).

The CRS of specimens were measured by an X-ray Stress Analyser (μ-X360n, PULSTEC, Japan, Cr-K, radiation, Ni filter current of 25 mA, voltage of 30 kV) based on the full width at half maximum (FWHM). The XRD patterns of specimens were acquired by Smart Lab X-ray diffractometer (Cu target). The scan step and scan rate were 0.02° and 2°·min^{-1}. The layers of the specimens were stripped by electrochemical corrosion. The solutions were distilled water.

Results and analysis

Fig. 3 illustrates the residual stress–depth relationship after annealing treatment for 120 min. It was observed that the residual stress reached their peak and then decreased rapidly with the increase in depth. The rising annealing temperature could have decreased the residual stress and depth. Furthermore, through the comparison between WD and LD, the descending rate of residual stress in the length direction was higher than that in the width direction.

As shown in Fig. 4, the generation of CRS field might be described as Al-Hassani [16]: a superposition of an isotropic CRS field induced by tradition SP and external load after SP [18-20]. Especially as the applied load was different in directions (Fig. 6), the CRS, in the direction ψ = 0° decreased further due to the external load. Thus, the CRS stabilities in the two directions were possibly different during annealing treatment.

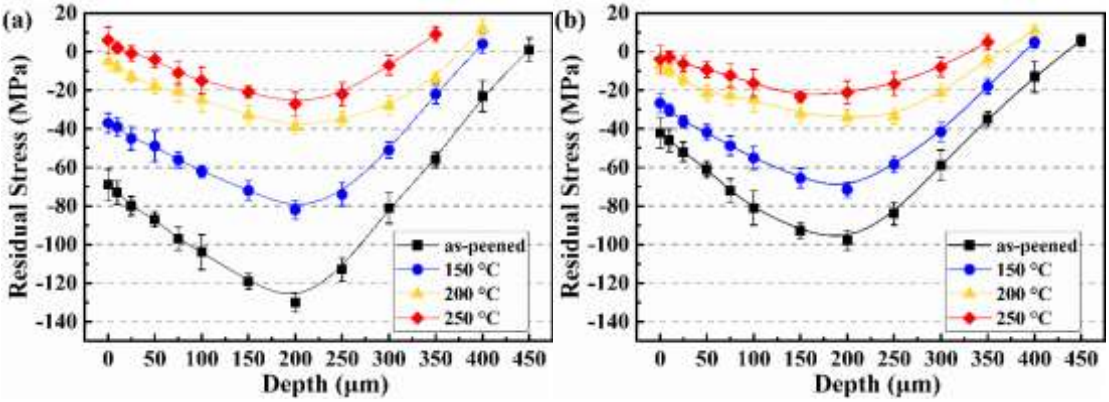

Fig. 3. Residual stress–depth relationship in two directions. (a) Length direction, (b) width direction.

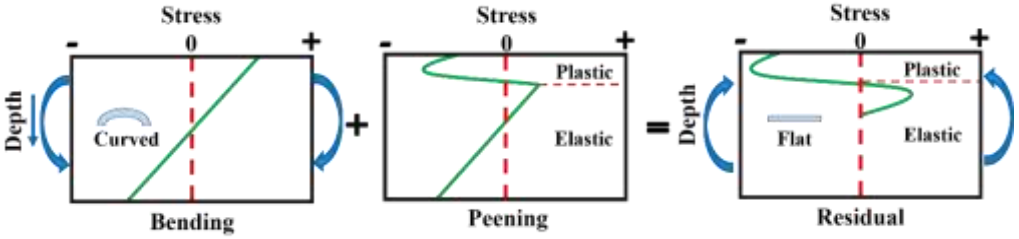

Fig. 4. Schematic diagram of the generation of residual stress fields

To confirm this conclusion, the thermally activated mechanism was investigated using the Zener–Wert–Avrami function, as shown in Eq. (1) [21]:

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

where σ_0^{RS} is the residual stress of the as-peened sample, $\sigma_{T,t}^{RS}$ is the residual stress after exposure to temperature T for time t, and m is a numerical parameter that depends on the corresponding relaxation mechanism. A is a function that depends on the material and the temperature according to Eq. (2) as follows:

$$A = Bexp\left(-\frac{\Delta H}{kT}\right) \quad (2)$$

where B is the material constant, k is the Boltzmann constant, and ΔH is the activation enthalpy for the actual stress relaxation.

The value of the numerical parameter m was calculated based on Eq. (1) and the experimental data through the diagrams of $\lg\left(-ln\sigma_{T,t}^{RS}/\sigma_0^{RS}\right)$ as a function of $\lg(t)$, as shown in Fig. (5). Table 1 presents the values of parameters calculated by the function.

As shown in Table 1, the values of m are similar in different same ψ angle. It illustrated that the CRS relaxation mainly depend on the disappear of dislocation during annealing treatment [22,23]. Moreover, the values CRS relaxation energy in the direction ψ = 0° (168 KJ/mol) were less than that in the direction ψ = 90° (180 KJ/mol). It might illustrate that the residual stress stability in the direction ψ = 90° is better than that in the direction ψ = 0° [22-24].

Conclusions

The residual stress thermal relaxation of stress peened CNT/Al-Mg-Si composite were investigated. The results show that the CRS decreased with the increments in annealing time and temperature. Furthermore, thermal relaxation of CRS perpendicular to prestress direction was more stable than the prestress direction.

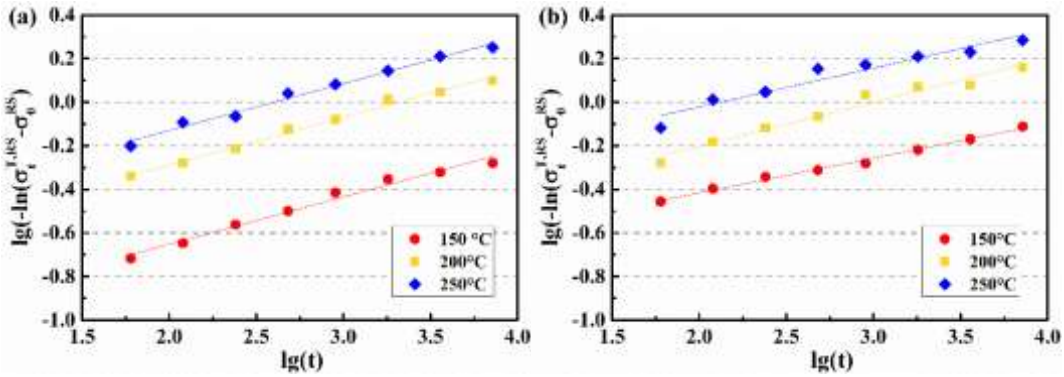

Fig. 5. Influences of annealing temperature and exposure time on residual stresses in the $\lg\left(-ln\sigma_{T,t}^{RS}/\sigma_0^{RS}\right)$ vs. $\lg(t)$ diagram.

Table. 1. Values of *m* after annealing treatment in two directions.

	150 °C	200 °C	250 °C
X Direction	0.26	0.26	0.27
Y Direction	0.3	0.29	0.305

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