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Thermal stability of residual stresses and work hardening of shot peened tungsten cemented carbide

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ABSTRACT

Tungsten cemented carbide of WC-10 wt.% Co with shot peening treatment was isothermal annealed at the temperatures ranging from 550 to 850 °C for different time. The relaxation behavior of residual stresses and full width at half maximum (FWHM)[1] of the X-ray diffraction profiles was investigated using the X-ray stress analyzer. The variations of structure in the top surface layer were also determined via the X-ray diffractometer. The results showed that both the residual stresses and the FWHM reduced sharply in the initial stage, and then they gradually declined to the stable state. The thermal activation enthalpy of WC and Co phases calculated by Zener-Wert-Avrami function indicated that the predominant relaxation mechanism was thermally activated gliding of dislocations. The work hardening effect presented better resistance to thermal relaxation in comparison with the residual stresses. The microhardness also declined with the heating temperature and the annealing time, which was analogous to the changes of residual stresses and FWHM. The residual stresses in WC and Co phases remained at compressive state suggesting that the shot peened WC-Co composite has good thermal stability under the working temperature of up to 850 °C.

1. Introduction

As one of the most flexible mechanical surface treatments, shot peening (SP)[2] has been widely used to improve the fatigue life of engineering components made of metals and alloys by refining the microstructure (Hassnani-Gangaraj et al., 2015) and inducing the compressive residual stress (Taro et al., 2015) in the near-surface regions where fatigue failure usually initiates. At the same time, SP can harden the treated surface where the localized plastic deformation occurs as the shot balls impact on it (Child et al., 2011).

Ceramic and cemented carbide are favored in manufacturing cutting or drilling tools (Shi et al., 2008) due to their excellent properties such as high wear resistance (Xiao et al., 2011). Many methods, such as heating and forced air cooling (Thakur et al., 2008), have been developed to further improve their mechanical properties and extend their service life to meet the mounting demand, especially as they working at elevated temperatures (Tsai et al., 2010). However, the SP treatment at room temperature was once considered not available upon ceramic or cemented carbide components because of the micro-cracks are more likely generated on the surface layer prior to the formation of plastic strain. Several researchers claimed recently that they had successfully strengthened the ceramics and cemented carbides with tailored SP parameters. For example, Pfeiffer and Wenzel (2010) introduced the compressive residual stress of up to 2500 MPa into the cemented carbide BC 20 via conventional mechanical SP method. Shukla and Lawrence (2015) improved the fracture toughness of the zirconia-advanced ceramics using micro-shot peening treatment. Our previous work (Wang et al., 2016) also demonstrated that the near-surface region of tungsten cemented carbide YG 10 can be efficiently enhanced by SP under specific condition. Given the temperature at the interface of these shot peened components, such as cutting tools, will rise sharply during the practical applications, the helpful effects introduced by SP may be diminished in part or even completely. Although a thin layer of intergranular glassy film which is likely formed at high temperature seems helpful to the fracture toughness because it can promote "brittle to ductile" transition and lubricate the grain boundary sliding (Mari et al., 2006), it is usually at the cost of the beneficial compressive residual stress and work hardening effects. Therefore, how to keep these advantageous effects in the near-surface regions of components being stable and durable, especially in the harsh conditions,

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[1] Full width at half maximum (FWHM).

[2] Shot peening (SP).

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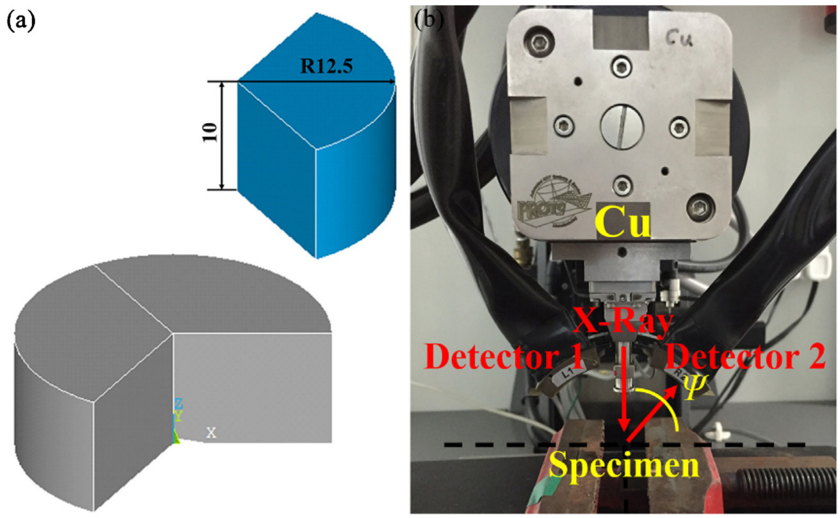

Fig. 1. Schematic of the specimen shape and dimension (a) and the residual stress measurement utilizing the X-ray Stress Analyzer (b).

becomes undoubtedly more significant than just produce them. Residual stresses and work hardening effect introduced by SP relax in many cases such as at high temperature or in cyclic loading environment. The thermal residual stress stability in tungsten carbide has been investigated by several researchers. For instance, D. Mari measured the thermal strains along *a* and *c* axis of the hexagonal WC lattice and then determined the mean hydrostatic stress by neutron diffraction (Mari et al., 2009). D.L. Coats also used the neutron diffraction to reckon the effect of different WC particle sizes on the thermal residual stress in WC-Co (Coats and Krawitz, 2003). And the influence of compositional gradients on the thermal residual stresses in WC-Co was addressed as well (Larsson and Oden, 2004). However, the relaxation behaviors of tungsten cemented carbide, especially with which treated by SP, have not yet been investigated enough. This study is accordingly aim to evaluate the thermal stability of compressive residual stress and work hardening state in the near-surface region of shot peened tungsten cemented carbide at elevated temperatures, and establish the steppingstone on the way to optimizing the SP parameters employed on the surface strengthening of cemented carbides.

2. Experimental methods

The widely used tungsten cemented carbide YG-10 with nominal addition of 10 wt.% Co was adopted for this study. Each specimen with the dimension illustrated in Fig. 1(a) was cut into three small specimens as one batch to implement the isothermal experiment. The average value of their residual stresses, full width at half maximum (FWHM) of the X-ray diffraction profiles and microhardness were recorded in order to ensure the accuracy of experimental results. The SP treatments were performed on an air blasting machine (Carthing Machinery Company, China) with the conditions (see also (Wang et al., 2016)) summarized in Table 1.

The peened samples were put into a muffle furnace to carry out the isothermal annealing at 550, 650, 750 and 850 °C, respectively. After held a period of different time, they were then cooled down slowly to the room temperature preventing the reintroduction of extra thermal stresses. The residual stresses and FWHM in radial direction of all samples were measured by the X-ray Stress Analyzer (LXRD, Proto, Canada, Cu-K_α radiation, 30 kV, 25 mA, Ni filter) using $\sin^2\psi$ method. The crystallographic texture was not likely existed and the shifts of WC (212) and Co (114) were detected, respectively. Since the bulk material presents macroscopically elastically isotropic even though the individual crystallite of WC-Co composite shows elastically anisotropic, the *hkl*-depended X-ray diffraction elastic constants should be adopted here (Welzel et al., 2005). And *S*212 1, 1/2*S*212 2for WC (hcp) were -2.06×10^{-6}, 0.3×10^{-6} Mpa^{-1}, and *S*114 1, 1/2*S*114 2for Co (hcp) were -6.06×10^{-6}, 1.22×10^{-6} Mpa^{-1}, respectively. Fig. 1(b) shows the residual stress measurement utilizing the X-ray Stress Analyzer.

Rigaku Ultima IV X-ray diffractometer (Cu-K_α radiation, 40 kV, 30 mA) was employed to determine the structure changes of the composite with scan speed of 2°/min. The hardness measurement was implemented on DHV-1000 Digital Microhardness Tester with a loading force of 9.8 N and a holding time of 15 s, and the mean of 5 readings was taken for every specimen.

3. Results

3.1. Residual stress relaxation due to annealing

The residual stresses of WC and Co phases in the impacted surface layer after isothermal annealing were obtained and shown in Fig. 2.

Where the annealing time as zero meant the as-peened samples. It was noted that residual stresses in WC and Co phases decreased with both the heating temperature and the annealing time increasing. The thermal relaxation of all samples had the maximum rates in the first few minutes, then they gradually declined to a very small value (in close proximity to zero). The higher the temperature or the longer the exposure time, the greater the relaxation of residual stresses. And the residual stress became to a stable state after annealed at 850 °C for more than 40 min. In comparison to the as-peened state, the residual stresses reduced by 40, 49, 64 and 82% in WC and 48, 63, 77 and 91% in Co phase after annealed for 128 min at 550, 650, 750 and 850 °C, respectively.

Zener-Wert-Avrami relationship (Juijerm and Altenberger, 2006) shown as fellows can well describe the thermal activated mechanism which controls the thermal relaxations of residual stresses.

$$\sigma^{RS}_{T,t}/\sigma^{RS}_{0} = exp\left[-(At)^{m}\right] \tag{1}$$

where σ^{RS}_{0} is the residual stress of the as-peened sample, $\sigma^{RS}_{T,t}$ is the residual stress after exposed under temperature *T* for time *t*, *m* is a numerical parameter depending on the corresponding relax-