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Surface microstructure and mechanical property of WC-6% Co hard alloy irradiated by high current pulsed electron beam

Y. Xu[a,b], Y. Zhang[a,d], S.Z. Hao[a,*], O. Perroud[c], M.C. Li[a], H.H. Wang[a], T. Grosdidier[c,d], C. Dong[a,d]

[a] Key Laboratory of Materials Modification & School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, China
[b] College of Materials Science and Engineering, Liaoning Technical University, Fuxin 123000, China
[c] Université de Lorraine, Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux (LEM3), CNRS UMR 7239, Ile du Saulcy, 57045 Metz, France
[d] Université de Lorraine, Laboratoire d'Excellence on Design of Alloy Metals for Low-Mass Structure (DAMAS), Ile du Saulcy, 57045 Metz, France

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ABSTRACT

The surface microstructure of WC-6% Co hard alloy irradiated by high current pulsed electron beam (HCPEB) at a moderate energy density of 3 J/cm^2 and pulse number of 1–35 was investigated by using scanning electron microscopy, X-ray diffractometry and transmission electron microscopy. It is found that the WC particles got remelted with the increasing number of HCPEB pulses, and a flat and compact surface with micro-crack network of cell size ∼several decades of μm was generated. At the same time, the rapid thermo cycles during HCPEB irradiations led to the formation of surface nano-grained microstructure on WC-6% Co hard alloy with a thickness of 0.8–1 μm. When using 20 HCPEB pulses, an optimum surface microstructure composed of a mixture of nano-grained (20–100 nm) WC_{1-x} and $Co_3W_9C_4$ phases was obtained which gave rise to a significant improvement in surface microhardness of 21.8 GPa and wear resistance by 4 times. The performance of irradiated surface would be deteriorated by overused HCPEB irradiations due to the excessive dissolution of WC hard particles and the large amplitude of residual tensile stress accompanied by severe surface cracking and local cavity defects.

1. Introduction

Cobalt cemented tungsten carbide (WC-Co) alloys, due to their excellent mechanical properties and wear resistance, are widely used for the fabrication of cutting tools. To further improve their performance in severe abrasive and corrosive working conditions, much effort has been paid to modify their surface microstructure with surface treatment techniques [1–5].

High current pulsed electron beam (HCPEB) has been proved to be a powerful tool for surface modification of materials in recent years [5–15]. Especially for the WC-Co system materials, Proskurovsky et al. [5] conducted the HCPEB irradiation of BK8 (WC-8% Co), T15K6 (WC-15% TiC-6% Co) and T5K10 (WC-5% TiC-10% Co) hard alloys and achieved the increased surface hardness. In the experiments of Ivanov et al. [6], the energy density of 3 J/cm^2 and 5 HCPEB pulses was demonstrated to be the better treating conditions for T15K6 hard alloy. Gnyusov et al. [7] found the excessive high energy density of ∼40 J/cm^2 would cause severe crack on the irradiated surface. Uglov et al. [8] gave the results of surface modification of T15K6 with long pulse duration of 200 μs and high energy density of 40 J/cm^2, where the good surface performance was attributed to the formation of W_2C carbide phase and (Ti, W)C solid solution.

In this paper, the energy density of HCPEB irradiation was limited at a moderate level to avoid the severe surface crack phenomenon and the pulse duration fixed at 2.5 μs, while the effect of increasing number of HCPEB irradiation would be investigated thoroughly to understand the HCPEB modification mechanism on a cemented carbide alloy and also its influence on surface mechanical properties.

2. Experimental procedures

The samples of size Φ15 mm × 5 mm were directly bought from a hard alloy factory with product name YG6. The chemical composition (wt.%) is 6% of Co and WC in balance. The WC particles

* Corresponding author. Tel.: +86 411 84707240; fax: +86 411 84707240.
E-mail addresses: ebeam@dlut.edu.cn, hao_shengzhi@yahoo.com.cn (S.Z. Hao).

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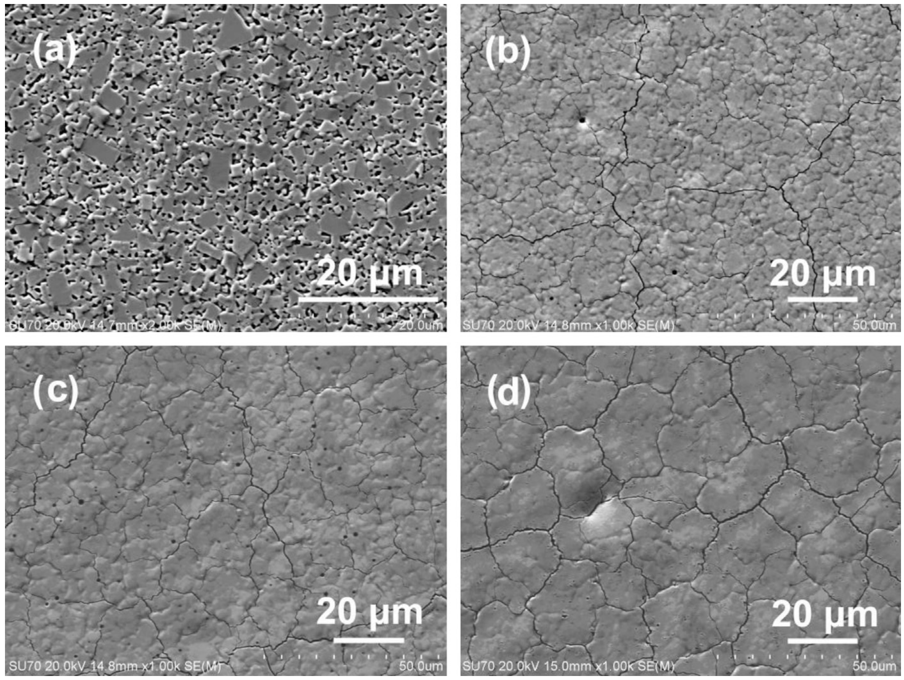

Fig. 1. Surface SEM morphology of WC-6% Co hard alloy after the HCPEB irradiation with 1 (a), 5 (b), 20 (c), and 35 (d) pulses, respectively.

are of size in middle grade ranging from 1.25 to 5 μm. Before the HCPEB irradiation, all the samples were grounded, polished and ultrasonically cleaned in acetone.

The HCPEB irradiation was carried out in a HOPE-I type HCPEB apparatus, which is an upgraded version of the type Nadezhda-2 [5] by optimizing the production of anode plasma and the design of high voltage switch. The typical parameters of HOPE-I are accelerating voltage 20–30 kV, peak current ~10 kA, pulse duration 0.5–5 μs, beam diameter Φ40 mm, and energy density 1–30 J/cm^2 [16,17]. In the present experiment, the parameters were chosen as follows: working vacuum 8×10^{-3} Pa, accelerating voltage 27 kV, sample-anode distance 6 cm, pulse duration 2.5 μs, energy density 3 J/cm^2, pulse interval 10 s, and the number of pulse 1, 5, 10, 20, and 35.

The surface microstructure was observed using a HITACHI SU-70 scanning electron microscope (SEM) and an FEI Tecnai G2 high resolution transmission electron microscope (TEM). The foils for TEM tests were prepared by one-sided milling and subsequent ion thinning. The phase structure of modified surface was examined using a Shimadzu XRD-6000 X-ray diffractometer (XRD) with Cu and Cr Kα radiation. The Knoop microhardness (HK) was measured using a DMH-2LS microhardness tester at a load of 10 g. The wear resistance was tested using a UMT-2 type system with the testing conditions as following: SiN counterpart of diameter 4.4 mm, working load 30 N, dry sliding distance 7 mm and velocity of 2 mm/s for 30 min.

3. Results and discussion

3.1. Surface and cross-sectional morphology

Fig. 1 shows the typical surface morphologies of WC-6% Co hard alloy after the HCPEB irradiation with increasing numbers of pulses. As shown in Fig. 1a, after a single pulse of irradiation, numerous craters were observed around the irregular WC particles. After 5 pulses of irradiation, as shown in Fig. 1b, the modified surface became smooth and compact where the WC particles was remelted drastically and showed a rounder shape and blurred boundaries. The surface craters were sealed mostly and several micro-cracks were observed extending on the surface to form a micro-crack network with cell size ranging in 50–60 μm. As the number of pulse increased up to 20, as shown in Fig. 1c, a flat and compact surface was generated with the WC particles fully remelted, the big surface craters could not be found and the formation of micro-crack network became more severe with an average cell size decreasing to ~30 μm. After 35 pulses of irradiation, as shown in Fig. 1d, the general aspect of the surface was rather similar but no obvious craters were detected. The surface cracks developed in a much broader way and some local cavity defects were observed.

Fig. 2 gives the cross-sectional morphologies of WC-6% Co hard alloy after the HCPEB irradiation, where the samples were rotated by 5–10° to contain the surface aspect information simultaneously. As shown in Fig. 2a, the modified surface was rather coarse with lots of discrete pits corresponding to the local eruptions. The WC particles were only melted slightly at the tips and edges. When the number of pulses increased to 5, as shown in Fig. 2b, a smoother surface was achieved. In Fig. 2c, a surface layer composed of a very fine microstructure was observed with a thickness of 0.8–1 μm. After 35 pulses of irradiation, as shown in Fig. 2d, the thickness of surface layer increased a little, but the microstructure was not as compact as that shown in Fig. 2c. In Fig. 2e, the microstructure difference between the surface modified layer and the initial state of WC-6% Co hard alloy could be seen more clearly. Another important aspect is about the small holes and cavities shown as dark sites in Fig. 2b–e beneath the surface at a depth of 1–2 μm. These structural defects emerged always at the locations where the initial Co phase existed, and denoted the preferred positions of crater eruptions.

To understand the evolutions of surface morphology on WC-6% Co hard alloy, the rapid thermo-dynamic cycle during HCPEB irradiations must be considered comprehensively. As for the surface craters, the formation mechanism have been broadly investigated and attributed totally to the four necessary factors: the penetrating energy deposition mode featured by electron beam treatment, the existence of microstructure irregularities in the beam energy deposition zone and the thermal stress induced by non-equilibrium heating, as well as the rapid solidification of surface melting materials by self-cooling effect [16–18]. In the case of WC-6% Co hard alloy,