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Original Article

Microstructure, mechanical and tribological properties of WC-WCoB coating

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ABSTRACT

A new kind of WC-based coating with superhard WCoB compound as the binder was fabricated by the high velocity oxy-fuel spraying of WC-WB-Co powder. The microstructure, mechanical and tribological properties of the WC-WCoB coating were investigated, together with those of the conventional WC-Co coating for comparison. The results demonstrated that the WC-WCoB coating has simultaneously improved hardness and fracture toughness, and thus remarkably decreased wear rate as compared to the conventional coating. The enhanced tribological properties of the WC-WCoB coating are attributed to the low plastic deformation and the resultant inhibition of the micro-ploughing wear and the increased fracture toughness and interfacial bonding, which can reduce the amount of large cracks. Moreover, the high intrinsic hardness of WC and WCoB, as well as their good interfacial bonding, are more effective in resisting against wear as compared with the conventional coating.

1. Introduction

Thermal-sprayed WC-Co based coatings are important wear resistant materials used in many fields such as aircraft industry [1], steel manufacturing [2], hydro turbines [3] and petrochemical engineering [4], etc. Great efforts have been made to improve the wear resistance of WC-Co coatings in order to satisfy the growing demands for high-performance surface protection materials. The methods that are used to enhance the properties of WC-Co coatings can be summarized as (i) introduction of metals or ceramics to the starting powder [5–10], (ii) decreasing the WC grain size [11–13] or optimizing the combination of WC grains with different sizes [14–16], (iii) structural modification and improvement of the physical properties of the spray feedstock [17–20], (iv) innovation of thermal spraying technologies and optimization of spray parameters [21–25], and (v) post-treatments for coatings [26–28]. In most cases, these methods were used in combination.

Regarding the relationships between composition and properties of WC-Co based coatings, some interesting results have been obtained. Myalska et al. found that the addition of nano-sized TiC to WC-Co coating could increase its microstructure stability during the deposition process, i.e. lower degree of WC decomposition, inhibition of W formation and its diffusion into cobalt; hence, the mechanical properties of the prepared coating are enhanced [6]. The study of Luyckx et al. indicated that addition of VC led to finer WC grain size and formation of (W, V)C with fine grain size and high hardness in the WC-VC-Co coating [7]. The (W, V)C grains were not only resistant to abrasion but also fracture. As a result, higher dry abrasion resistance was obtained for the WC-VC-Co coating as compared to the WC-Co coating. Basak et al. demonstrated that the wear resistance of the nanostructured WC-Co coating with 1 wt.% Al was more than twice as high as that without Al, and three times higher than that of the micron-sized WC-Co coating [8]. The presence of Al mainly increases the cohesion within the coating, forms Al_2O_3 as well as reduces the porosity of the nanostructured coating.

According to the above literatures, the wear resistance enhancement of WC-Co coatings is always associated with the improvement in mechanical properties of the hard particles and the metallic binder phase, and the bonding strength of their interfaces. To achieve this goal, a partial substitution of W-B compounds (e.g. WB, W_2B, and W_2B_5) for WC in the WC-Co coating may be an optional choice. Firstly, the W-B compounds have ultrahigh hardness of about 20–50 GPa (even harder than WC with a hardness of 16–22 GPa) and high chemical inertness [29–31]. Moreover, the element B easily reacts with WC-Co and forms WCoB with a hardness of 45 GPa [32], which is much harder than the Co binder phase (the hardness of which was reported as 6–11 GPa) [10,33]. Though there exists uncertainty concerning the interfacial bonding, higher properties are expected for the new WC-WB-Co coating.

In this work, commercially available WC, WB and Co powders were used as raw materials to fabricate WC-based cermet coatings. In order to investigate the effects of WB addition on the properties of conventional WC-Co coating, a comparison between the microstructure, mechanical and tribological properties of the WC-Co coatings with and without WB addition was performed.

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Table 1
HVOF spraying parameters for both coatings.

Parameter	Value
Nozzle length (mm)	102
Kerosene flow rate (l/min)	0.38
Oxygen flow rate (l/min)	944
Carrier gas N_2 (l/min)	11.8
Spraying distance (mm)	380
Powder feed rate (g/min)	90

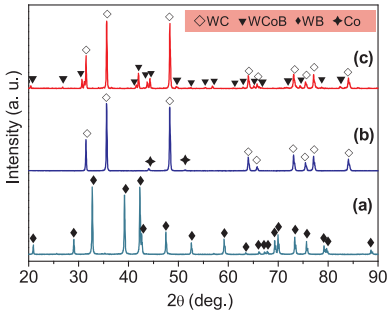

Fig. 1. XRD patterns of the initial WB powder (a) and the prepared WC-Co (b) and WC-WCoB (c) thermal spraying feedstock powders.

2. Experimental

2.1. Materials preparation

The WC-WCoB coating was prepared using commercially available WC (1.0 μm, > 99.9%), 30 wt.% WB (0.8 μm, > 99.9%) and 12 wt.% Co (1.2 μm, > 99.9%) powders as the starting materials, which were provided by the Luoyang Golden Egret Geotools Co., Ltd. The raw powders were wet ball-milled for 10 h. The ball-to-powder weight ratio was 3:1 and the rotation speed was 180 rpm. In order to avoid contaminations, both the grinding balls with a diameter of 8 mm and the inner wall of the milling vial were made of WC-Co cemented carbide. Then the powder mixture was agglomerated into spherical particles by spray drying and a subsequent heat-treatment process. Prior to spray drying, the powders were mixed with 4% polyethylene glycol and 75% distilled water by mechanical stirring to prepare the slurry. The spray-dried particles were heat-treated at 1180 °C for 3 h. After sieving, the thermal spraying powder with particle size distribution of 15–45 μm was obtained. A JP-5000 HVOF spraying system was used to deposit the coating on carbon steel substrate. The spraying parameters are listed in Table 1. For comparison, the WC-Co coating with 12 wt.% Co was prepared by the same procedures.

2.2. Characterization

The thermal stability analysis of the mixed WC-WB-Co powder was performed with differential scanning calorimetry (DSC) method, using NETZSCH STA 449 F3 instrument and a platinum crucible in argon atmosphere. Approximately 20 mg of the powder was used for DSC measurement from 25 °C to 1200 °C with a heating rate of 10 °C/min. The phases in the thermal spray powders and the coatings were examined by X-ray diffraction (XRD) using Cu Kα radiation in a Rigaku Ultima IV diffractometer.

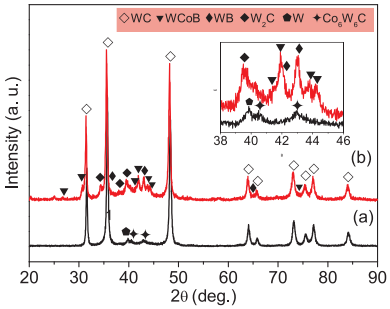

Fig. 3. XRD patterns of the HVOF sprayed WC-Co (a) and WC-WB-Co (b) coatings. The inset shows an enlargement of the diffraction peaks at 2θ = 38–46°.

The microstructures of the coatings were examined by scanning electron microscopy (SEM, Nova NanoSEM 200). The microhardness of the coatings was tested with a 300 g load and a dwell time of 15 s using a Vickers indenter (FM-700, Future Tech, Japan) on the polished cross-sections of the coatings. Fifteen indentations were made for each sample. The fracture toughness of the coatings was determined by the indentation method using the following equation [34], with a 10 kg load and a dwell time of 15 s:

$$K_c = 0.079\ (P/a^{3/2})\log\ (4.5a/c) \quad (1)$$

where P (N) refers to the load applied to the indenter, a (μm) and c (μm) correspond to the half-diagonal and crack length of the indentation, respectively. The equation is applicable when the c/a ratio in the range of 0.6–4.5.

Nano-scratching test was carried out on the coating surface by Agilent Nano Indenter G200 with a Berkovich diamond indenter using 5 mN load. The Berkovich indenter is a three-sided pyramid with a face angle of 65.3°. The scratch length was set as 30 μm and the wear velocity was 20 μm/s. 10 cycles of scratch were performed for both coatings. In each scratch test, the displacement into the coating surface as a function of the scratch distance was automatically recorded. After the scratching tests, the 3-dimensional topography of the wear track was reconstructed by the interactive scan method using the same nanoindenter. The scratch track deformation (S) is defined as the area of the section of the groove along the scratch direction, i.e. $S = L \times d$, where L is the scratch distance and d is the average residual depth of the groove. This value is calculated automatically during the scratch test and given in the output file by the nanoindentation system. The elastic recovery rate (W_e) is described as $W_e = (d_{max} - d_{res}) / d_{max}$, where d_{max}

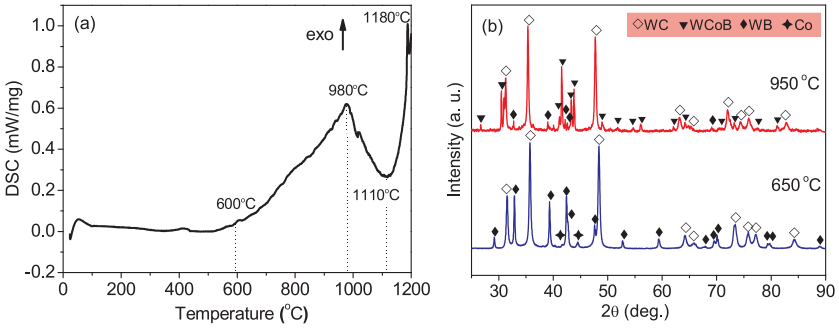

Fig. 2. DSC curve of the mixed WC-WB-Co powder (a) and corresponding phase analysis of the powders heat-treated at different temperatures (b).