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Nanoindentation of WC–Co hardmetals

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Abstract

WC–Co cemented carbide has been investigated using instrumented indentation with maximum applied loads from 0.1 to 10 mN. The hardness and indentation modulus of individual phases and the influence of crystallographic orientation of WC on the hardness and indentation modulus have been studied. The hardness of the Co binder was approximately 10 GPa and that of WC grains up to 50 GPa with relatively large scatter under the indentation load of 1 mN. Investigation of the role of crystallographic orientation of WC grains on hardness at 10 mN load revealed average values of $H_{\mathrm{ITbasal}} = 40.4$ GPa ($E_{\mathrm{ITbasal}} = 674$ GPa) and $H_{\mathrm{ITprismatic}} = 32.8$ GPa ($E_{\mathrm{Itprismatic}} = 542$ GPa), respectively. The scatter in the measured values at low indentation loads is caused by the effects of surface and sub-surface characteristics (residual stress, damaged region) and at higher loads by "mix-phase" volume below the indenter.

Keywords: WC crystals; Nanoindentation; Hardness; Load-size effect; Orientation effect

1. Introduction

Cemented carbides are widely used as cutting, forming and machining tools in different areas of industry because of their high hardness and strength, good fracture toughness and excellent wear resistance.[1] This is due to their complex composite structure of interpenetrating networks of a hard, brittle carbide phase, usually WC, and a tough metallic binder, usually Co, with dissolved tungsten and carbon. Structurally, dilute Co alloys including Co–W–C can exist in either of two allotropic forms, hcp or fcc. The ratio of these two forms is determined by processing treatment and composition. Both tungsten and carbon stabilize the fcc phase and in most hardmetals, the binder is present largely in fcc form.[2]

The physical properties of tungsten carbide are generally known very well; WC is a non-oxide ceramic where hexagonal closely packed layers of W atoms are separated by closely packed layers of C filling one-half of the interstices, giving rise to a six-fold trigonal prismatic coordination for the atomic structures.

The lattice shape is hexagonal, with lattice parameters $a = 0.2906$ nm and $c = 0.2837$ nm.[2] The WC grains generate three types of facets: two types of prismatic facets and the basal (0 0 0 1) facet which delimit the flat triangular prism (Fig. 1).[3]

The individual grains of WC within the WC–Co are essentially single crystals, each with orientation-dependent mechanical properties. Understanding this orientation dependence is important in optimizing microstructures for enhanced combinations of hardness, toughness and wear resistance, e.g., in the case of composites with the preferred orientated grains.

A number of studies have been devoted to characterization of the effect of the microstructure of WC–Co system on its hardness and the effect of the crystallographic orientation of WC single crystals on their hardness.[4–8] French and Thomas[5] used Knoop indentations to indent single crystals at basal and prismatic planes and found that the Knoop hardness could vary by a factor of 2 for indentations of the prismatic planes. Knoop hardness values were higher in the basal plane with values from 2300 to 2500. On the prismatic planes $(1\,0\,\bar{1}\,0)$ the hardness varied from 1000 to 2400 as the direction of the indent

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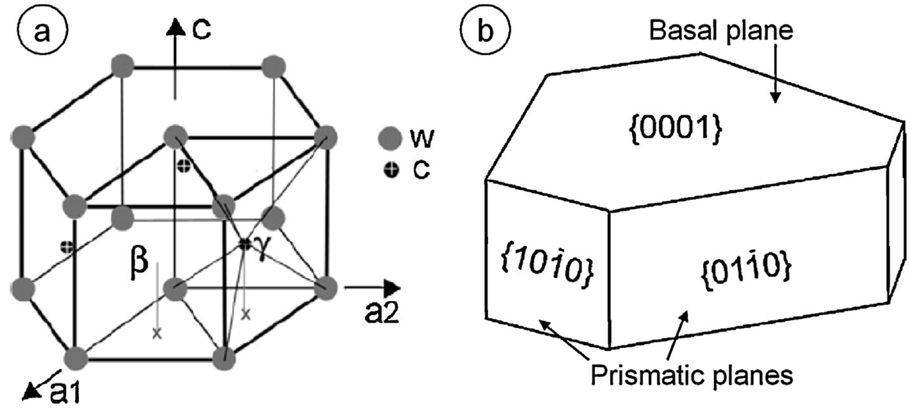

Fig. 1. Crystal lattice of WC with C atoms at (1/3, 2/3, 1/2) sites, while the (2/3, 1/3, 1/2) sites are empty (a), shape of WC grains in the WC–Co system (b).[3]

declined from the [0 0 0 1] direction. Takahashi and Freise[6] used Vickers microhardness measurements at an applied load of 1 kgf and reported values of 2100 for the basal plane and 1080 for the (1 0 $\bar{1}$ 0) prismatic plane. Pons[7] used Vickers microhardness at a load of 0.1 kgf and reported hardness of 1950 and 1360 for the basal and prismatic planes, respectively.

Gee et al.[8] were possibly the first who used instrumented nanoindentation for determination of the mechanical properties of constituent phases of WC–Co on a local scale. They found difficulty in the mapping of individual phases owing to uncertainties in stage positioning and reliability of software during the measurement, but found the technique promising to yield valuable information about the in situ properties of different phases. Bonache et al.[9] used nanoindentation in a depth-controlled regime with very shallow nanoindentations (30 nm depth) to measure hardness and Young's modulus of the constituents of the WC–Co composite. They reported a hardness and indentation modulus for the WC prismatic planes (1 0 1 0) being within the range of 40–55 GPa and 700–900 GPa respectively. These values decrease to a hardness in the range of 25–30 GPa and a modulus in the range from 450 to 550 GPa for the basal plane (0 0 0 1).

Recently, Cuadrado et al.[10] used a Berkovich diamond indenter with loads up to 0.25 N to measure the hardness of individual crystals of WC in a WC–Co system. Electron backscatter diffraction (EBSD) techniques were used to obtain individual crystal orientations and the hardness values were measured for basal planes (0 0 0 1) and prismatic (1 0 $\bar{1}$ 0) and (1 $\bar{1}$ 2 0) planes of WC crystals. Hardness values for 20 GPa (basal plane) and 17 GPa (prismatic plane) were obtained.

More recently, Roebuck et al.[11] applied depth-sensing microhardness mapping to measure the variation of microhardness with an applied load and orientation of WC crystals of approximately 50 μm in size, embedded in a copper alloy matrix. They found that the most significant effect on microhardness of WC has a deviation angle between the plane of measurement and either the basal or prismatic planes. The grains with a plane close to the basal plane (0 0 0 1) were found to be considerably harder (approx. 55 GPa at 0.4 N load) in comparison to prismatic planes (approx. 25 GPa at 0.4 N). Obviously, these results are contrary to the results of Bonache et al.[9] which can be explained by the differences in the size of the investigated WC grains and/or in applied indentation loads, respectively.

The aim of the present contribution is to evaluate the hardness of individual phases of WC–Co systems and the hardness and indentation modulus of WC crystals as a function of orientation using instrumented nanoindentation in a load range from 0.1 mN to 10 mN.

2. Experimental procedure

The experimental material was supplied by Pramet Sumperk (Czech Republic). The microstructure has been evaluated using standard metallographic procedures (cutting, grinding, polishing, etching) and scanning electron microscopy (SEM) observation (Fig. 2). The microstructure parameters of the investigated WC–Co composite are: volume fraction of binder, $f_{Co} = 10.7$; mean grain size of WC, $D_{WC} = 1.7$ μm, mean free path in binder, $L_{Co} = 0.3$ μm and contiguity, $C_{WC} = 0.37$. Prior to nanoindentation testing, the samples were also ground and polished, with a final step using 0.5 μm diamond paste.

The nanoindentation tests have been performed using Berkovich diamond indenter with a tip radius less than 20 nm

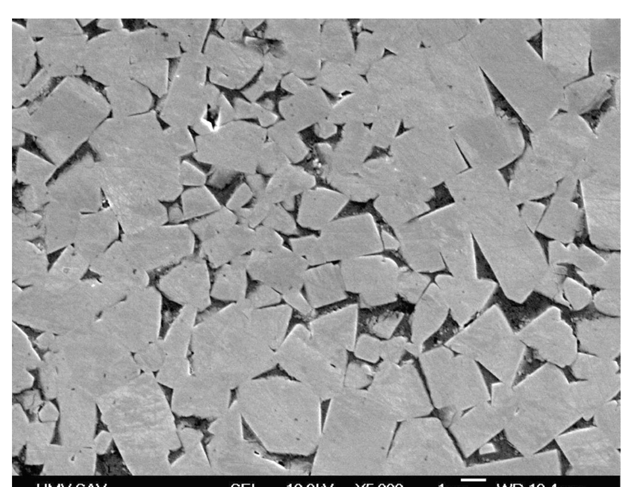

Fig. 2. Microstructure of the WC–Co cemented carbide investigated.