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Hardness of WC-Co hard metals: Preparation, quantitative microstructure analysis, structure-property relationship and modelling

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ABSTRACT

Different commercial WC-Co hard metals with carbide grain sizes ranging from ultrafine to coarse and Co contents between 4.2 and 25 wt.% have been investigated with regard to their microstructural and mechanical properties. Therefore, novel preparation strategies – including specific etching reactions – and microscopic methods for the microstructural characterization were developed. Two sets of microscopic images were generated suitable for further semi-automatic determination of either the Co volume fraction φ_{Co} or the mean maximum Feret diameter d_{Fer} of the WC grains considering the irregular shape of the grains. Subsequently, the determined microstructural parameters and measured Vickers hardness values were used to develop a novel model calculating the hardness of WC-Co hard metals. The total hardness is mainly determined by the hard carbide whereby its influence is reduced by the soft Co binder phase. The current model is in good agreement with the measured values within almost the whole relevant hardness range of WC-Co hard metals (700 - 2300 HV 10) and do not require any statement of the existence of a carbide skeleton within the material and thus the Co binder mean free path which is essential for hardness models established so far but also hard to determined experimentally. So the current model is a significant simplification and improvement of the prediction of the hardness of WC-Co hard metals by means of microstructural parameters.

1. Introduction

Hard metals (also called cemented carbides) are composite materials containing a hard material phase (mostly carbide) embedded in a tough metallic binder matrix which leads to excellent mechanical properties. The most important system is WC-Co because of the combination of excellent toughness and wear resistance which makes it applicable for a broad range of industrial applications depending on its microstructure (see Fig. 1) [1]. Coarse-grained WC-Co hard metals with a high Co content are usually applied as material for mining tools because of their excellent toughness and impact resistance. WC-Co systems with finer microstructures and lower Co contents exhibit high hardness and wear resistances and are therefore, used for machining tools cutting various materials like steel, nickel-base alloys or carbon fiber reinforced plastics (CFRP) [2,3]. However, there is little current systematic research work on modern hard metal based cutting materials. Therefore, it is difficult for the applicants to identify the best material to specific machining task combination and therefore, the usage of a not optimally chosen cutting material leads to increased tool wear as well as machining induced damage in the work piece, like delamination and therefore, a decreased quality and finally benefit-cost ratio.

Hard metals used for cutting tools are classified by an international standard regarding their mechanical properties like hardness and toughness as well as the particular machined materials described by one non-quantitative figure [4]. However, the hardness and the toughness, which influence relevant process parameters like the cutting speed and the feed rate, respectively, are opposed, i.e. one property can only be improved by impairing the other one [5,6]. In the actual release of the standard, nowadays interesting machined materials like CFRP are not mentioned and therefore, selection recommendations are mainly provided by the hard metal manufacturers based on empirical findings. For a solid recommendation the mechanical behavior has to be measured or calculated from a model based on the microstructural features of the particular material, like e.g. the size d of the embedded particles and the mean free path λ of the binding matrix as well as the volume fraction φ_{Co} of the Co binder phase. In case of the hardness, first studies about the influence of microstructural parameters were established since the 1950s [7,8] and lead to various models calculating the hardness by means of these parameters with different assumptions [9–11].

The aims of this study were:

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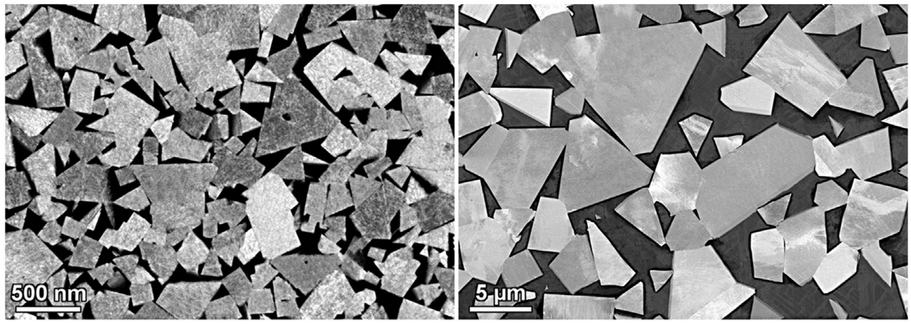

Fig. 1. SEM micrographs of an ultrafine-grained WC-9Co (left, 30,000 × magnification) and a coarse-grained WC-25Co hard metal (right, 3000 × magnification). The images were captured by means of a ZEISS Sigma 300 VP using backscattered electron contrast, WD 4.5 mm and EHT 5 kV.

1. Establishing a robust and quick preparation as well as characterization method for hard metals – especially for materials with finer microstructures – to determine the maximum Feret diameter d_{Fer} as a key figure for the WC grain size and its respective area-weighted lognormal distribution as well as the volume fraction φ_{Co} of the Co binder phase.
2. Developing a new model to calculate the composite hardness of WC-Co hard metals which is applicable for the whole range of industrially applied WC-Co materials using their determined microstructural parameters mentioned above.

2. State of the art

2.1. Microstructural analysis

There are different strategies to determine microstructural key figures of WC-Co hard metals. Mathematic models established in several studies allow to calculate the microstructural parameter of the WC-Co hard metals by means of determining the magnetic saturation as well as the coercivity [8,12–24]. Additionally, the quantitative determination of magnetic properties allows proving the existence of additional phases within the material. However, the accuracy of this method is limited due to a number of different factors influencing the magnetic parameters and a complex interaction of the magnetic domains in the Co regions with the non-magnetic carbide grains. As an alternative, metrological methods based on either optical and electron microscopy are aim of recent investigations. These can be roughly divided into two main approaches.

Firstly, the WC grain size d is conventionally measured using linear intercept method on optical or scanning electron microscope (SEM) images. With the importance of this microstructural parameter, a number of studies of the measurement technique itself have been conducted [15–19]. Generally, in an image showing the WC-Co microstructure and containing a sufficient number of WC grains, parallel lines with a constant distance to each other are drawn in in a certain direction. Then the total length of the lines inside the WC phase is measured and divided by the number of times the lines intersect a carbide grain delivering a single average value for the WC grain size [20]. Alternative parameters describing the WC grain size, especially for irregularly shaped particles, are e.g. the equivalent diameter, which is defined as the diameter of a circle with the same area as the particle, or the maximum Feret diameter as the biggest extension of the observed particle. In both cases, the determination of the parameter is carried out for every grain contained completely in the image which leads to a certain frequency distribution so an arithmetic mean value can be determined.

Secondly, SEM equipped with a supporting electron backscatter diffraction (EBSD) detector delivers the crystallographic information of the specimen microstructure and is therefore suitable to determine the grain size d and the mean free path λ by mapping the existing WC/WC and WC/Co grain boundaries [19]. However, in specimens with a low Co content the electrical conductivity is decreased to a critical level leading to an unintended offset in the EBSD patterns. Additionally, energy-dispersive X-ray spectroscopy (EDS) is well established for the determination of the chemical composition and thus the Co volume fraction φ_{Co}. Therefore, microscopic methods combined with automatic image processing were applied in this study to quantitatively describe the microstructure of the investigated hard metal materials.

2.2. Hardness modelling

In previous studies, different models for the prediction of the Vickers hardness of WC-Co hard metals have been presented. In a first study in 1955, Gurland and Bardzil [7] observed an exponential decrease of the Rockwell hardness with increasing mean free path λ. A similar statement regarding the Vickers hardness was made by Fischmeister and Exner in 1966 [8]. They assumed that a certain amount of the WC grains forms a continuous carbide skeleton whereas the amount of the connected WC grains on the total carbide volume can be expressed by the contiguity [21].

$$C = 1 - \frac{d\varphi_{\mathrm{Co}}}{\lambda(1-\varphi_{\mathrm{Co}})} \tag{1}$$

The mean free path thus can be calculated using Eq. (1) and the parameters C and d determined by linear intercept method. Besides the exponential decrease with increasing λ, a linear decrease of the hardness with increasing binder content was also observed. Another improvement of modelling the Vickers hardness by means of microstructural parameters was established in 1978 by Lee and Gurland [9]. They suggested a model whereby both the carbide and the binder phase contribute to the total hardness of the material with their in situ Vickers hardness which were assumed to obey Hall-Petch relationships in dependence on the grain size d and the mean free path λ (both in mm), respectively:

$$H_{\mathrm{WC}}^{\mathrm{LG}} = 1382 + \frac{23.1}{\sqrt{d}} \tag{2}$$

$$H_{\mathrm{Co}}^{\mathrm{LG}} = 304 + \frac{12.7}{\sqrt{\lambda}} \tag{3}$$

However, only the continuous amount of the WC phase is taken into account and the rest of the carbide is regarded as part of the binder volume, so the total hardness can be calculated by

$$H^{\mathrm{LG}} = H_{\mathrm{WC}}^{\mathrm{LG}}\varphi_{\mathrm{WC}}C + H_{\mathrm{Co}}^{\mathrm{LG}}(1-\varphi_{\mathrm{WC}}C) \tag{4}$$

with the volume fraction φ_{WC} of the carbide phase. However, the studies mentioned so far only consider WC-Co hard metals with mean WC grain sizes above 0.9 µm. So these models are not suitable for ultrafine- and submicron-grained hard metals which are the more relevant materials in industry nowadays, especially for machining processes. Eq. (2) indicates that the hardness of the carbide phase goes to