Materials and Design 97 (2016) 492–501

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Microstructural effects on the R-curve behavior of WC-Co cemented carbides

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ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form 24 February 2016
Accepted 26 February 2016
Available online 27 February 2016

Keywords:
Cemented carbides
Fracture
Strength
R-curve
Reliability

ABSTRACT

The influence of microstructure on the R-curve behavior of hardmetals and its implication on their strength and reliability are studied. In doing so, an already validated model for R-curve description is implemented for rationalizing the fracture behavior of five microstructurally different WC-Co cemented carbides. Results indicate that hardmetals with R-curves developing smoothly over relatively long multiligament zones (i.e. lower slopes) exhibit reduced strength variability than those with steeper and shorter (i.e. higher slopes) ones. The reduced strength scatter associated with a low-slope R-curve behavior is discussed on the basis of the effectively developed toughness and the subcritical crack extension reached before unstable growth is triggered, both being dependent on microstructural length scale and initial flaw size. The results of this investigation highlight the relevance of an in-depth knowledge of R-curve characteristics of hardmetals in order to optimize the performance of engineering parts by means of microstructural design.

1. Introduction

Technical success of tools, wear parts and structural components made of WC-Co cemented carbides (also referred to as hardmetals) is intrinsic to the chemical nature and composite character of these materials. On the one hand, they are composites constituted by two completely different phases (hard, brittle carbides and a soft, ductile metallic binder) with optimal interface properties [1–3]. On the other hand, they are assembled as two interpenetrating-phase networks where toughening is enhanced by plastic stretching of crack-bridging ductile enclaves located at the crack wake (e.g. Refs. [4,5]). Therefore, mechanical and tribological performance of cemented carbides is closely related to their particular microstructure, being the content and physical dimensions of each constituent phase the most common features for defining them [1–3]. Within this context, the principal parameters used to characterize the microstructure of hardmetals are the average grain size of WC particles (d_{WC}) and the binder volume content. However, both parameters are frequently varied simultaneously, and correlation between property and microstructure requires of additional two-phase normalizing parameters. Among them, the binder mean free path (λ_{Co}) is the most used one as it refers to the mean size of the metallic phase. In general, an increase of the binder mean free path implies a rise of the fracture toughness of the material at the expense of a decrease in hardness [2]. Main reason behind it is the fact that thicker and less constrained (i.e. effectively more ductile) ligaments exist for hardmetal grades with higher binder contents and coarser microstructures [2,4–6].

As it is the case for other brittle solids reinforced with a ductile phase (e.g. Refs. [7–9]), development of an effective multiligament zone implies an increase of fracture toughness with crack extension; and thus, the existence of a rising crack growth resistance (R-curve) behavior in hardmetals [10–13]. Within the above framework, the contribution of the constrained ductile reinforcements to fracture toughness of a medium grain sized WC-11 wt% Co hardmetal has been recently investigated by the authors of this study [13]. It was done on the basis of experimental information attained through serial Focused Ion Beam (FIB) sectioning and Field Emission Scanning Electron Microscopy (FESEM) imaging. This investigation provided unequivocal proof of the development of a multiligament zone consisting of ductile metallic enclaves at the crack wake as the main foundation for understanding toughness and R-curve behavior of cemented carbides. This is illustrated in Fig. 1, where it is clearly discerned that crack-bridging ligaments fail by the nucleation, growth and coalescence of microcavities [4,5,7,13]. Tarrago et al.'s work [13] also included an analytical assessment of

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http://dx.doi.org/10.1016/j.matdes.2016.02.115
0264-1275/

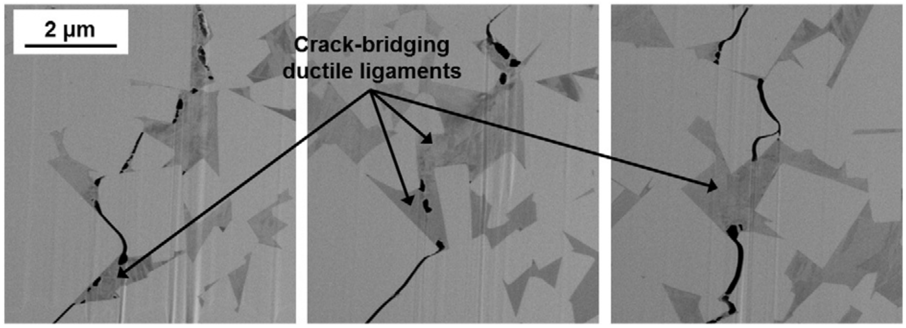

Fig. 1. FESEM micrographs illustrating crack-microstructure interactions at the crack wake of a stably propagated crack under monotonic loads in a WC-11wt% Co hardmetal. Failure mechanisms within the ductile metallic ligaments are clearly discerned.

gathered data and the proposal of a model for the description of R-curve behavior of WC-Co cemented carbides. It was found that these materials exhibit a steep but short R-curve behavior, due to the large stresses supported by the highly constrained and strongly bonded ligaments. Moreover, R-curve description proposed and validated by the authors is expected to capture microstructural effects on the crack-growth resistance of these materials throughout the dependence of the multiligament zone size (and fracture toughness measured in long cracks) upon the width and strength of the metallic bridges. The former is intimately related to the microstructural length scale of hardmetals (i.e. added value of carbide grain size and binder mean free path $[d_{WC} + \lambda_{Co}]$), whereas the latter is given by the effective ductility of the constrained binder.

Knowledge of microstructural effects on R-curve description of hardmetals is of great relevance for optimizing their fracture resistance on the basis of microstructural design [14–17]. Similar to other brittle materials, strength of cemented carbides is limited by the presence of processing, shaping- or service- induced defects (e.g. Refs. [1,2, 18–23]). Accordingly, Linear Elastic Fracture Mechanics (LEFM) theory has been extensively invoked for rationalizing the fracture behavior of cemented carbides within this research field (e.g. Refs. [24–26]). However, as failure in these materials is intimately related to relatively short cracks, total development of their R-curve may not take place before rupture. In these cases, the crack-tip resistance steady-state level, i.e. that corresponding to plane-strain fracture toughness measured in long cracks (K_{Ic}), would not be reached [17]. Hardmetals would thus be expected to fracture at different crack-tip stress intensity factor values (K_R), always lower than K_{Ic}. Under these conditions, unstable crack growth occurs at a critical K_R value which depends on the initial crack size and on the R-curve characteristics, i.e. effective slope and length of K_R as a function of stable crack extension, both directly related to the microstructure of the material. It is the main purpose of this study to assess the influence of the microstructure on the effective action derived from the crack-bridging toughening mechanism of hardmetals. In doing so, the model proposed and validated in Ref. [13] was implemented for describing the R-curve behavior of five cemented carbides grades with different microstructures. Furthermore, R-curve behavior translates into subcritical crack growth of the preexisting flaws, i.e. critical crack size is larger than the initial flaw size. As a consequence, higher reliability should be expected in hardmetals, as compared with that of materials exhibiting a flat R-curve with the same crack-tip toughness [14,27,28]. Hence, R-curve effects on strength and reliability (on the basis of Weibull statistics) are finally evaluated and discussed, taking into account the effectively developed toughness and the subcritical crack growth experienced before fracture by each cemented carbide studied.

2. Materials and experimental aspects

Five experimental WC-Co grades, corresponding to different combinations of binder content and carbide mean grain size, were selected for the study. Such grades were selected in order to cover a wide range of fracture toughness levels. All investigated materials were supplied by Sandvik Hyperion. Nomenclature and key microstructural parameters: binder weight content (wt% binder), mean grain size, carbide contiguity (C_{WC}) and binder mean free path are listed in Table 1. Note that the nomenclature is composed by two terms, the former referring to the binder weight content and the latter associated with the mean grain size of the carbide phase, being UF for ultrafine and M for medium. Binder content values are given as supplied by the manufacturer, whereas the mean grain size of the carbide phase was measured following the linear intercept method in micrographs acquired using a FESEM [29]. Two-phase microstructural parameters, C_{WC} and λ_{Co}, were estimated from best-fit empirical equations given in literature [2,30]. FESEM micrographs corresponding to the microstructure of the hardmetals here studied are shown in Fig. 2.

Mechanical testing was conducted using a four-point bending fully articulated test jig with inner and outer spans of 20 and 40 mm, respectively. Flexural strength (σ_r) tests were performed on an Instron 8511 servohydraulic machine at load rates of 100 N/s [31]. Between 10 and 15 prismatic bars of 45 mm × 4 mm × 3 mm dimensions were tested per grade. On the other hand, crack growth resistance was determined using 45 mm × 10 mm × 5 mm single edge pre-cracked beam (SEPB) specimens with a notch length-to-specimen width ratio of 0.3.

Table 1
Microstructural parameters of the investigated cemented carbides. The term SD refers to standard deviation values.

Hardmetal grade	V_{Co} (wt%)	d_{WC} (μm)	C_{WC}	λ_{Co} (μm)
6UF	6	0.40 ± 0.21 (SD)	0.61 ± 0.12 (SD)	0.12 ± 0.06 (SD)
10UF	10	0.39 ± 0.19 (SD)	0.46 ± 0.06 (SD)	0.16 ± 0.06 (SD)
11M	11	1.12 ± 0.71 (SD)	0.38 ± 0.07 (SD)	0.42 ± 0.28 (SD)
15M	15	1.15 ± 0.92 (SD)	0.30 ± 0.07 (SD)	0.55 ± 0.46 (SD)
22M	22	1.64 ± 0.75 (SD)	0.19 ± 0.04 (SD)	1.13 ± 0.56 (SD)