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Understanding of toughening in cemented carbides by means of small-scale mechanical testing and characterization

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Abstract

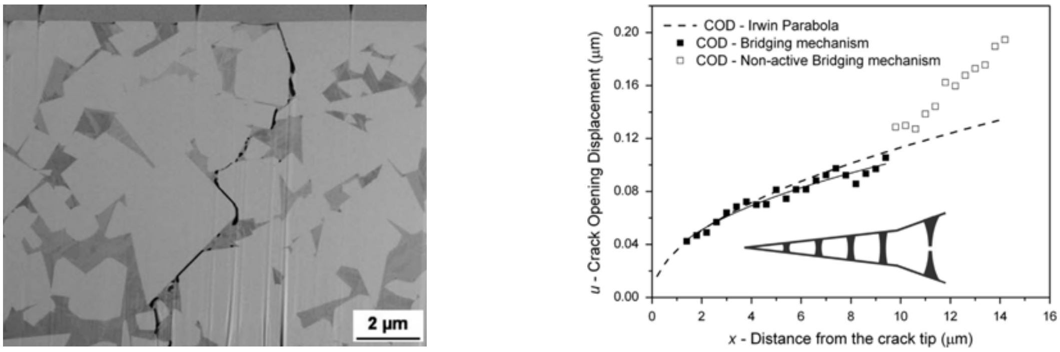
Small-scale mechanical testing (massive nanoindentation, compression of micropillars and fracture of notched microcantilevers) and characterization (cross-section FIB-tomography and FESEM inspection) are proposed and validated as effective tools for studying fracture mechanics and toughening mechanisms governing stable crack growth in cemented carbides. Crack growth resistance behavior of cemented carbides and corresponding microstructural effects are sucessfully described and understood on the basis of ductile ligament reinforcement behind the crack tip as the key toughening mechanism for these materials.

1. Introduction

The unique combination of hardness, toughness and wear resistance exhibited by WC-Co cemented carbides, also referred to as hardmetals, has made them preeminent material choices for extremely demanding applications, such as metal cutting/forming tools or mining bits. The remarkable mechanical properties of these materials results from a two-fold effectiveness associated with their intrinsic composite character. On the one hand in terms of composite nature: combination of completely different phases (hard, brittle and soft, ductile constituents) with optimal interface properties. On the other hand as related to composite assemblage: two interpenetrating-phase networks where toughnening is optimized through different mechanisms. In this regard, it is well-established that the outstanding toughness levels exhibited by these materials are related to the energy required to plastically deform the metallic bridging ligaments that develop behind the tip of preexisting or service-induced cracks. During the last decades, several models have been presented to predict the mechanical response of the constrained ductile bridges and its contribution to the fracture toughness of these composite. However, they are based on the macromechanical response of the materials investigated, and more important, are limited due to the scarce information on the interactive deformation of the constitutive phases at the microstructural length scale. Aiming to fill this knowledge gap, a systematic small-scale study has been conducted using novel micromechanical testing approaches combined with advanced characterization techniques.

2. Results

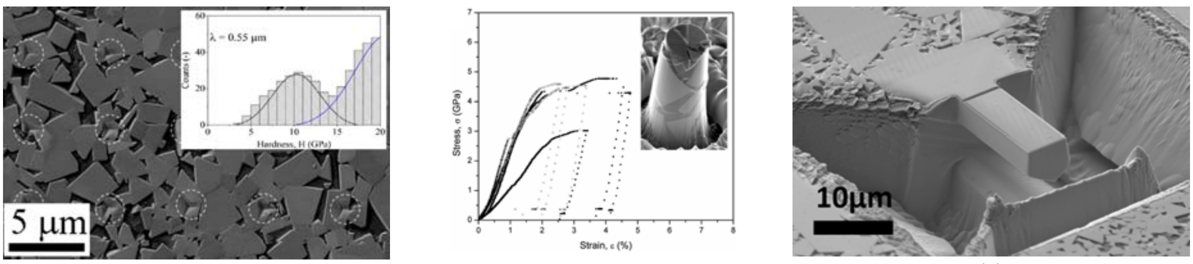
Exceptional fracture toughness levels exhibited by cemented carbides are due mainly to toughening derived from plastic stretching of crack-bridging ductile enclaves. This takes place due to the development of a multiligament zone at the wake of cracks growing in a stable manner, as experimentally validated in serial sectioning and imaging of crack–microstructure interaction in cracks arrested after stable extension under monotonic by means of focused ion beam (FIB) and field-emission scanning electron microscopy (FESEM) inspection (**Figure 1a**). Analytical assessment of the multiligament zone requires experimental information acquired from the referred images, i.e. crack-opening displacement (COD) with respect to distance behind the crack tip (CT) - **Figure 1b**. As a result, the description of the crack growth resistance (R-curve) behavior exhibited by these materials may be successfully done.



(a) (b)

Fig. 1 – Stable crack growth in cemented carbides: **(a)** toughening micromechanisms, and **(b)** COD as a function of distance from the CT.

Moreover, analysis and understanding of toughening needs the assessment of local properties and deformation mechanisms within the individual constitutive phases. This information is gathered through implementation of three different small-scale testing techniques. First, massive nanoindentation and statistical analysis of the collected data for evaluation of microstructural effects on the flow stress of the constrained metallic binder [Hall-Petch like relationship]. Second, experimental validation of the estimated flow stress values by identifying and quantifying yielding phenomena linked to the existence of multiple strain bursts in the stress-strain curves determined during compression of FIB-milled micropillars (**Figure 2b**). Third and finally, determination of reliable values of fracture toughness of single grains of WC, i.e. baseline reference value that could be linked to a "binderless" grade, through fracture testing of FIB-milled microcantilevers (**Figure 2c**).



(a) (b) (c)

Fig. 2 – Assessment of small-scale mechanical properties of the constitutive phases of cemented carbides: effective flow stress of the metallic binder through massive nanoindentation and statistical analysis **(a)** and stress-strain response of compressed micropillars **(b)**; and fracture toughness of single WC grains using **(c)** FIB-milled notched microcantilevers **(c)**.

3. Conclusions

Micromechanical testing and small-scale characterization of cemented carbides allows to provide unequivocal proof of the multiligament zone as the foundation for understanding toughness and R-curve behavior in these materials. Within this context, reiforcement by ductile bridges at the crack wake is validated as the main toughening mechanism in cemented carbides.

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