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Contact damage and residual strength in hardmetals

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ABSTRACT

In most of the applications where hardmetals are implemented, mechanical contact plays an important role from a design viewpoint, either as direct key parameter (e.g. wear resistance) or as indirect relevant factor (e.g. residual strength associated with contact-induced damage). In this work, the contact response of three cemented carbides WC–Co with different microstructural features is evaluated. The study is performed using spherical indenters (Hertzian contact) and it is focused on: 1) determining the critical loading parameters affiliated to the emergence and evolution of damage; and 2) investigating the relevance of microstructure on the levels of residual strength attained. It is found that strength retention is improved as contact damage mode goes from brittle to quasi-plastic, a transition directly dependent on microstructure. Hence, microstructural design searching for higher damage tolerance (i.e. deformation prevailing over fracture as damage mode) is concluded to be an optimal approach for the development of hardmetals with improved reliability. In practical terms, this is achieved by enhancing toughness through either higher binder content and/or microstructural coarsening, as far as the field application requirements are satisfied.

1. Introduction

The evaluation and understanding of strength properties of cemented carbides in relation to processing inherent flaws is a common practice since more than thirty years ago (e.g. Refs. [1,2]). This is generally implemented on the basis of linear-elastic fracture mechanics (LEFM) under the consideration that mechanical failure is given by the ensuing propagation of the pre-existing defects. However, if damage is induced during service (e.g. by occasional hard body impacts or continuous contact-related degradation), similar information on structural integrity protocols is quite limited. Hence, it is relevant to find out how the limit state (defining failure) or the boundary between acceptable or unacceptable performance is affected by such extrinsic damage.

Regarding controlled damage, Lawn and coworkers have proven, systematically and extensively since the early 1990s, that Hertzian testing using spherical indenters is a very effective tool for inducing it (e.g. Ref. [3]). Within this context, it is known that above some critical load, depending on the radius of curvature of the contacting surfaces, ceramic-based structures sustain irreversible damage that compromise their useful lifetime. However, consequent structural integrity effects (e.g. strength lessening) are found to depend on the nature of the induced contact damage. Ideally brittle homogeneous materials experience abrupt strength losses once the critical load for cone crack initiation is reached. Meanwhile, for tough heterogeneous ceramics strength decrease is rather gradual and continuous as microdamage cracking associated with a quasi-plastic response develops.

There are only a few works involving spherical indentation on cemented carbides [4–9]. Common to all these studies is their focus on investigating mechanical characteristics directly related to the contact response of the studied grades, namely: indentation stress–strain curves [4,6–9], deformation and fracture mechanisms [6–9], and brittleness index [5,7]. On the other hand, exception of the prospective study conducted by Tarrés et al. [6], none of them considered Hertzian tests as a means for: 1) inducing controlled extrinsic damage; and 2) subsequently evaluating strength retention associated with it. Following these ideas, it is the purpose of the present work to assess the effective strength of cemented carbides after sustaining contact damage. Of particular interest is: 1) to determine the critical loading parameters affiliated to the emergence and evolution of damage; and 2) to investigate the relevance of microstructure, through its influence on nature of the induced damage, for developing strength retention capability in hardmetals.

2. Experimental aspects

The study was conducted on three microstructurally different WC–Co cemented carbides (often simply termed as hardmetals): binder

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content ranging from 6% (low) to 25% (high) in weight, and carbide size running from 0.2 μm (ultrafine) to 1.6 μm (medium) length scales. They correspond to experimental grades provided by Sandvik Hard Materials (Coventry, UK). Designation, chemical composition and mean carbide grain size of the studied materials are listed in Table 1. Mean carbide grain size was determined by image analysis of micrographs taken from polished surfaces, using atomic force (Model Dimension 3100 Nanoman, Veeco) and scanning electron (Model JMS 6400, JEOL) microscopy (SEM). Fig. 1 shows typical microstructural aspects of the studied materials. Hardness, fracture toughness and flexural strength for the three hardmetal grades are also included in Table 1. Hardness was measured using a 30 kgf (294 N) Vickers diamond pyramidal indentation. Ten indentations were made per grade. Fracture toughness was evaluated following the single edge notched bend (SENB) method. The sample geometry employed was a rectangular bar of 45 × 10 × 5 mm dimensions. The effective evaluation of fracture toughness using LEFM requires the suitability of a procedure for introducing a sharp pre-crack into the sample. In this study it was achieved through application of cyclic compressive loads by reverse bending to a SENB specimen, followed by stable crack growth under far-field tensile stresses. The latter step was conducted to relieve residual stresses induced during the previous cyclic compression. A detailed description of the pre-cracking procedure used has been reported elsewhere [10,11]. Fracture toughness values were determined by testing the pre-cracked SENB samples to failure. At least three specimens were evaluated for each material. Finally, fracture resistance was assessed under four-point bending, on rectangular bars of 45 × 4 × 3 mm dimensions, with inner and outer spans of 20 and 40 mm respectively. Before testing, the longitudinal section later subjected to the maximum stress in bending was ground in two steps, through 200 grit (68 μm) and 600 grit (30 μm) diamond-containing disks, and finally polished, ultimately with 3 μm diamond paste, up to optical finish (Ra ~ 0.01 μm). Additionally, longitudinal edges of all the samples were beveled. All the mechanical tests (fatigue pre-cracking, fracture toughness and flexural strength) were conducted using a servohydraulic testing machine (Model 8511, Instron Ltd.) in a room air environment. As expected, an increase of binder content and carbide size yields lower hardness and higher fracture toughness values. On the other hand, flexural strength exhibits a maximum for the intermediate hard/tough M12 grade. A SEM fractographic analysis of broken samples pointed out critical flaws of similar nature and shape geometry for the three hardmetal grades, i.e. microstructural heterogeneities such as pores or binderless carbide agglomerates. In general, there was a trend for mean value of critical flaw size to scale with the mean carbide grain size, although experimentally measured dispersion bands for this parameter (in the range of 10 to 40 μm) were found to overlap for the materials studied. Hence, observed strength–microstructure correlation may be rationalized on the basis of LEFM, being fracture toughness the effective controlling parameter for describing fracture behavior of cemented carbides [1,2,10].

Contact damage on the hardmetals was introduced by means of spherical indentation techniques on longitudinal sections of previously ground and polished specimens. Monotonic loading was used as model of incidental impacts. Hertzian tests were conducted in the same servohydraulic equipment described above, by using hardmetals pins with spherical tips of 2 mm in radius and applying loads ranging from 300 to 5000 N. The main goal of these tests was to attain irreversible damage, particularly circular surface cracks. Surface damage produced by the Hertzian contacts was observed through optical and confocal laser scanning (Model LEXT OLS3100, Olympus) microscopy (CLSM) by means of Nomarski interference contrast. It allowed to define the range of applied indentation loads to be used for the subsequent strength retention study.

Table 1
Mean and standard deviation values for basic microstructural and mechanical parameters for the cemented carbides (WC–Co) studied.

Hardmetal grade	Metallic binder content (% wt Co)	Mean WC grain size (μm)	Hardness HV30 (GPa)	Fracture toughness (MPa√m)	Flexural strength (MPa)
L21	6.0 ± 0.2	0.2 ± 0.1	20.5 ± 0.6	6.8 ± 0.3	1847 ± 425
M12	10.0 ± 0.4	0.4 ± 0.2	15.7 ± 0.6	10.4 ± 0.5	3422 ± 514
H14	25.0 ± 1.2	1.6 ± 0.8	7.7 ± 0.1	19.7 ± 1.4	2431 ± 124

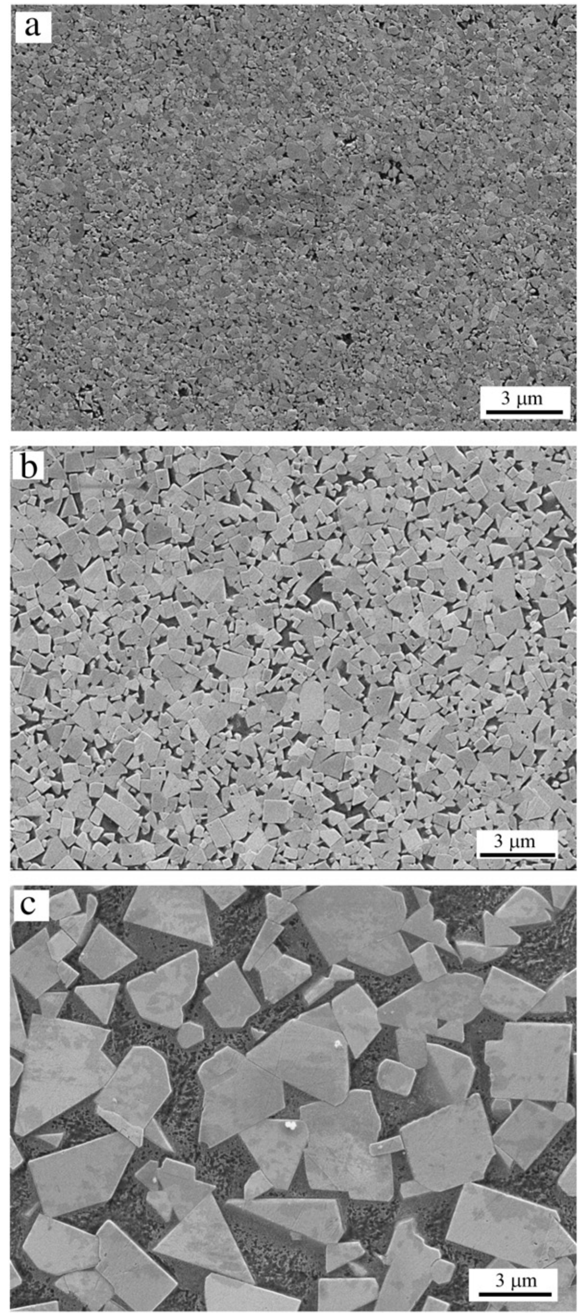

Fig. 1. Microstructures of the three hardmetal grades studied: a) L21, b) M12, and c) H14.

From the contact damage behavior observed, four indentation loads (1500, 2000, 2500 and 3000 N) were chosen to evaluate residual strength of the materials considered. Due to the particular strength retention behavior exhibited by the H14 grade (to be shown later), in this material the study was extended to include three additional indentation load levels (300, 500 and 1000 N). Fracture resistance tests were conducted, as before, under four-point bending on indented polished bars. At least three samples were evaluated for each grade and