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Mechanics and mechanisms of fatigue in a WC–Ni hardmetal and a comparative study with respect to WC–Co hardmetals

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ABSTRACT

There is a major interest in replacing cobalt binder in hardmetals (cemented carbides) aiming for materials with similar or even improved properties at a lower price. Nickel is one of the materials most commonly used as a binder alternative to cobalt in these metal-ceramic composites. However, knowledge on mechanical properties and particularly on fatigue behavior of Ni-base cemented carbides is relatively scarce. In this study, the fatigue mechanics and mechanisms of a fine grained WC–Ni grade is assessed. In doing so, fatigue crack growth (FCG) behavior and fatigue limit are determined, and the attained results are compared to corresponding fracture toughness and flexural strength. An analysis of the results within a fatigue mechanics framework permits to validate FCG threshold as the effective fracture toughness under cyclic loading. Experimentally determined data are then used to analyze the fatigue susceptibility of the studied material. It is found that the fatigue sensitivity of the WC–Ni hardmetal investigated is close to that previously reported for Co-base cemented carbides with alike binder mean free path. Additionally, fracture modes under stable and unstable crack growth conditions are inspected. It is evidenced that stable crack growth under cyclic loading within the nickel binder exhibit faceted, crystallographic features. This microscopic failure mode is rationalized on the basis of the comparable sizes of the cyclic plastic zone ahead of the crack tip and the characteristic microstructure length scale where fatigue degradation phenomena take place in hardmetals, i.e. the binder mean free path.

1. Introduction

Since the emergence of the first WC–Co cemented carbides in 1923, cobalt has been the dominating metal used as binder in these metal-ceramic composite materials, also referred to as hardmetals [1]. This is due to the especially favorable chemical bonding between tungsten carbide and cobalt that results in a very low interfacial energy, nearly perfect wetting and a very good adhesion in the solid state [2]. However, the toxicity and high price of cobalt metal together with the need for improving the performance of cemented carbides under severe working conditions, such as corrosion and high temperature, have promoted the search and usage of grades with alternative binders [3–5]. Among them, nickel has received the most attention as an alternative binder to cobalt because of its similarity in structure and properties, besides its good corrosion resistance. Proof of that is the increasing number of research papers focussed on Ni-base cemented carbides published in recent years (e.g. Refs. [6–12]). Both cobalt and nickel exhibit good wettability with WC, and fully dense hardmetals without anomalous porosity can be produced [3]. The principal difference between them is the higher stacking fault energy of Ni that results in lower hardening rates [5]. Thus, hardness and strength of WC–Co grades tend to be superior to those exhibited by WC–Ni ones. However, an increase of the work hardening rates of the Ni binder may be achieved by means of minor and moderate additions of other elements such as chromium [3] or silicon [7], yielding as a result similar or even superior hardness and fracture strength levels for Ni-base cemented carbides, as compared to those exhibited by plain WC–Co grades. Furthermore, Cr additions result in a large increase of the corrosion resistance of WC–Ni hardmetals [12].

On the other hand, a better understanding of service degradation phenomena in hardmetals is required for industrial manufacturers,

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if material performance and lifetime of tools and components are to be improved. Among them, premature fatigue failure is an important one since cemented carbides are commonly used in applications involving high cyclic stresses (e.g. Ref. [13]). Fracture and fatigue behavior of hardmetals has been extensively rationalized within the Linear Elastic Fracture Mechanics (LEFM) framework, since failure of these brittle materials is governed by unstable propagation of preexisting flaws (e.g. Refs. [14–17]). Following these ideas, and taking into account that subcritical crack growth is the controlling stage for fatigue failure in cemented carbides [18], Torres and co-workers proposed the fatigue crack growth threshold as the effective toughness under cyclic loading [19]. Experimental validation for such approach was then presented for a series of WC–Co hardmetal grades [20]. Moreover, such results pointed out a strong microstructural influence on the fatigue sensitivity of hardmetals, depending on the compromising role played by the metallic binder as both toughening and fatigue susceptible agent [21]. Schleinkofer et al. [18] reported that as a result of the accumulation of plastic deformation and/or due to high stresses during cyclic loading, cobalt binder martensitically transforms from the FCC structure to the HCP one. This deformation micromechanism restricts significantly the ductility of the metallic binder, recognized as the main toughening phase in cemented carbides [17,22–24]. On the other hand, nickel binder accumulates deformation in the form of slip plus twinning damage mechanisms [25–27], but without evidence of such transformation. Thus, it is not clear whether above relationships, regarding either fatigue mechanics perspective or microstructural influence on the basis of binder mean free path, may be directly extrapolated to hardmetals other than the Co-base previously studied. To the best knowledge of the authors, there is not any information about fatigue strength and fatigue crack growth behavior of WC–Ni cemented carbides in the open literature. It is then the aim of this investigation to study the fatigue mechanics and mechanisms of a Ni-base hardmetal grade.

2. Experimental aspects

The investigated material is a fine-grained WC–Ni hardmetal with a minor addition of chromium. The key microstructural parameters: binder content ($\%_{\text{wt.}}$), mean grain size (d_{WC}), carbide contiguity (C_{WC}), and binder mean free path (λ_{binder}) of the studied material are listed in Table 1. Mean grain size and carbide contiguity were measured following the linear intercept method using Field Emission Scanning Electron (FE-SEM) micrographs at a magnification of ×4000, whereas binder mean free path was estimated from empirical relationships given in the literature on the basis of empirical relationships given by Roebuck and Almond [28], but extending them to include carbide size influence [29,30].

Mechanical characterization includes hardness (HV30), flexural strength (σ_r), fracture toughness (K_{Ic}), fatigue crack growth (FCG) parameters and fatigue limit (σ_f). Hardness was measured using 294 N Vickers diamond pyramidal indentations. In all the other cases, testing was conducted using a four-point bending fully articulated test jig with inner and outer spans of 20 and 40 mm respectively. For the determination of flexural strength and fatigue limit, $45 \times 4 \times 3$ mm beams were used. The surface which was later subjected to the maximum tensile loads was polished to mirror-like finish and the edges were chamfered to reduce their effect as stress raisers. For both experimental sets, 15 samples were tested. Flexural strength tests were conducted on an Instron 8511 servohydraulic machine at room temperature and the results were analyzed using Weibull statistics. Experimental fatigue limit (“infinite fatigue life” defined at 2×10^6 cycles) was assessed following the stair-case method. Tests were performed using a resonant testing machine, at load frequencies around 150 Hz and under a load ratio (R) of 0.1. After failure, a detailed fractographic inspection was conducted by FE-SEM on tested specimens in order to identify the nature, size and geometry of the critical flaws. Fracture toughness and FCG parameters were determined using $45 \times 10 \times 5$ mm single edge pre-cracked notch beam (SEPNB) specimens with a notch length-to-specimen width ratio of 0.3. Compressive cyclic loads were induced in notched beams to nucleate a sharp crack [31,32] and details may be found elsewhere [33]. The sides of SEPNB specimens were polished to follow stable crack growth by a direct-measurement method using a high-resolution confocal microscope. Fracture toughness was determined by testing SEPNB specimens to failure at stress-intensity factor load rates of about 2 MPa$\sqrt{m}$/s. FCG behavior was assessed for two different R values, 0.1 and 0.5. Fracture surfaces of the SEPNB specimens corresponding to stable and unstable crack growth were also examined by FE-SEM to discern, analyze, and compare damage mechanisms under different load conditions.

Table 1
Microstructural parameters for the WC–Ni cemented carbide studied.

$\%_{\text{wt.}}$ Nickel	d_{wc} (µm)	C_{wc}	λ_{binder} (µm)
11.7 ± 0.4	0.83 ± 0.49	0.39 ± 0.03	0.30 ± 0.18

3. Results and discussion

3.1. Hardness, flexural strength and fracture toughness

Basic mechanical properties for the studied cemented carbide are listed in Table 2. WC–Ni hardmetal exhibits hardness and flexural strength values close to those found in Co-base grades with a similar mean free path [19,34,35]. Such response is different from trends indicated by other authors [36,37], and should be ascribed to the chromium dissolved within the binder. It has been stated that minor and moderate additions of chromium raise the hardness and load–deflection response of WC–Ni up to levels exhibited by WC–Co grades [3] via solid solution in nickel. Moreover, the flexural strength dispersion evidenced is rather small; and accordingly, the corresponding Weibull analysis yields a relatively high value, indicative of similarly high reliability from a structural viewpoint. Fractographic examination reveals critical defects for the studied material (e.g. Fig. 1) with an equivalent diameter ($2a_{cr}$) of about 10–25 µm. It is in agreement with values estimated from a direct implementation of the LEFM equation $K_{Ic} = Y\sigma_r(a_{cr})^{1/2}$ relating strength (σ_r), toughness (K_{Ic}) and critical flaw size (a_{cr}) (see Table 2) by considering defects as either embedded or surface circular cracks. In this equation, Y is a geometry factor that depends on the configuration of the flawed sample and the manner in which loads are applied. This sustains the use of LEFM for rationalizing the fracture behavior of the cemented carbide studied here.

3.2. FCG kinetics

FCG rates are plotted against the range and the maximum applied stress intensity factor, ΔK (Fig. 2a) and K_{max} (Fig. 2b) respectively, for the two load ratios studied. As it has been previously reported for WC–Co hardmetals [15,19,21,38,39], the WC–Ni grade under consideration exhibits: (i) a large-power depen-

Table 2
Hardness, strength and fracture mechanics parameters for the WC–Ni hardmetal investigated.

HV30 (GPa)	σ_r (MPa)	Weibull modulus	K_{Ic} (MPa$\sqrt{m}$)	$2a_{cr}$ (µm)
13.2 ± 0.2	3080 ± 210	17	11.5 ± 0.2	15–30