# 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.

**Keywords:** WC-Ni hardmetal, fatigue mechanics, fatigue crack growth, fatigue strength, fatigue mechanisms, fatigue sensitivity.

## 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, 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 ($\%_{wt}$), mean grain size ($d_{WC}$), carbide contiguity ($C_{WC}$), and binder mean free path ($\lambda_{binder}$) of the studied material are listed in **Table I**. 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 X4000, 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 ($\sigma_r$), fracture toughness ($K_{Ic}$), fatigue crack growth (FCG) parameters and fatigue limit ($\sigma_f$). Hardness was measured using 294N Vickers diamond pyramidal indentations. In all the others 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, 45x4x3 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 $2 \times 10^6$ 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 45x10x5 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√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.

## 3. Results and discussion

### 3.1. Hardness, flexural strength and fracture toughness

Basic mechanical properties for the studied cemented carbide are listed in **Table II**. 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. **Figure 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 ($\sigma_r$), toughness ($K_{Ic}$) and critical flaw size ($a_{cr}$) (see **Table II**) 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, $\Delta K$ (**Figure 2a**) and $K_{max}$ (**Figure 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 dependence of FCG rates on ΔK, as indicated by the high m values within Paris relationship – equation (1) below – (**Table III**), and (ii) subcritical crack growth at ΔK values much lower than fracture toughness. Also, a very pronounced load ratio effect is observed in the dependence of FCG on ΔK. However, as observed for other brittle-like materials, R effects are largely reduced when plotting FCG against $K_{max}$. This is an indication of predominance of static over cyclic failure modes [21,37].

$$\frac{da}{dN} = C(\Delta K)^{m} \qquad (1)$$

To assess the relative dominance of $K_{max}$ and ΔK as the controlling fatigue mechanics parameters under fatigue, $K_{max}$ was expressed as ΔK/(1-R). It allows plotting a modified Paris relationship with the form given in expression (2), where C', p and q are constants.

$$\frac{da}{dN} = C'(K_{max})^{p}(\Delta K)^{q} \qquad (2)$$

Factoring out $(1\text{-}R)^q$ as a constant, FCG data collapse onto a nearly single curve for an optimal q value (**Figure 3**). Then C' and p parameters can be deduced from the least squares regression knowing that the slope of the curve is the addition of p and q. Values for the FCG threshold (measured for FCG rates of $10^{-9}$ m/cycle), as well as for p and q constants of the modified Paris relationship are listed in **Table III**. The larger value of p in the modified Paris relationship indicates that $K_{max}$ governs fatigue crack growth over ΔK, pointing out once again the above referred predominance of static over cyclic failure modes.

### 3.3. Fatigue mechanics: FCG threshold – fatigue limit correlation

One of the main purposes of this investigation is to extend the FCG – fatigue life relationship proposed and validated by Torres and co-workers for WC-Co cemented carbides [19,20] to Ni based hardmetals to optimize a proper design and material selection in fatigue-limited applications involving hardmetals. Although this might be attempted following a damage tolerance methodology, it does not seem to be an amenable route because the enormous prediction uncertainties associated with marked power-law dependences of FCG rates on $\Delta K$ (or $K_{max}$) as those shown in **Figure 2**. Instead, a classical approach on the basis of fatigue limit, within an infinite life framework, and FCG threshold ($K_{th}$) is implemented by defining the latter as the effective toughness under fatigue for a given critical flaw size. Thus, fatigue limit is deduced from the stress intensity factor threshold of a small non-propagating crack emanating from a defect of critical size, $2a_{cr}$, according to a relationship of type (3):

$$\sigma_f = \frac{1}{Y} * \frac{K_{th}}{\sqrt{a}_{cr}} \qquad (3)$$

Hence, the fundamental LEFM correlation among strength, stress intensity factor and defect size applies also for natural defects too in cemented carbides. This assertion may be done considering that: (i) size of the critical natural flaws are larger than the microstructural unit; (ii) plasticity is confined to process zone ahead the crack tip; and (iii) process zone governing fracture (multiligament zone behind the crack tip) extends over a relatively short distance (about five ligaments) [19,40]. Thus, fatigue limit values can be estimated from the relation given by the expression (4) under the assumption that flaws controlling strength have the same size, geometry and distribution under monotonic and cyclic loading.

$$\sigma_f = \sigma_r * \frac{K_{th}}{K_{Ic}} \qquad (4)$$

Attempting to validate the estimated fatigue limit, an experimental study was conducted using 15 samples and following an up-and-down load (stair-case) fatigue test (**Figure 4**). Predicted and experimentally determined fatigue limits are listed in **Table IV**. FCG threshold – fatigue limit correlation is validated by the excellent agreement attained between them. Furthermore, the fractographic examination conducted on failed specimens reveals that size, geometry and nature of the critical defects are similar under both monotonic and cyclic loading conditions. This supports prediction of fatigue limits from the corresponding fatigue sensitivity, parameter here defined as [1 – ($K_{th}$/$K_{Ic}$)] and ranging thus from 0 to 1. Within this context, fatigue sensitivity represents an index for describing the susceptibility to mechanical degradation of a material when subjected to cyclic loads.

### 3.4. Fatigue sensitivity

Llanes et al. [21] investigated the fatigue sensitivity - [1 – ($K_{th}$/$K_{Ic}$)] - and the modified Paris law exponent ratio (q/p) of a series of WC-Co hardmetals as a function of their binder mean free path and applied load ratio. The corresponding results are plotted in **Figure 5**, together with the fatigue sensitivity and p/q ratio exhibited by the studied WC-Ni cemented carbide. Results show that the fatigue sensitivity of the studied Ni-base hardmetal is similar to that expected for a WC-Co grade with alike binder mean free path. Furthermore, it is also evidenced that p/q ratio of the studied WC-Ni grade fits the trend described by Llanes et al. for WC-Co cemented carbides [21]. Thus, it appears that Ni and Co binders exhibit a similar cyclic degradation of operative toughening mechanisms in corresponding hardmetals, although the nature of their plastic deformation mechanisms is different. In this regard, it should be recalled that plastic deformation mechanisms in the Ni binder include slip and twinning [25-27], also discerned in the Co-base binders, but not stress-induced phase transformation, as it is the case in WC-Co grades. Care should be taken on above statements as they are based on the results obtained for a single WC-Ni grade. Within this context, further research on additional WC-Ni hardmetals with different microstructural characteristics is recalled for sustaining these ideas.

### 3.5. Fatigue mechanisms: crack – microstructure interaction

After failure, the fracture surfaces of tested specimens were examined using FE-SEM. Clear differences are evidenced when comparing fractographic aspects corresponding to stable (**Figure 6**) and unstable crack growth (**Figure 7**). While in the former "step-like" fatigue damage features are discerned within the binder, in the latter the metallic binder exhibit well-defined dimples, suggesting a pure ductile fracture mechanism. Fracture under cyclic loading in the nickel binder follows a faceted, crystallographic fracture mode, as can be appreciated by the sharp angular facets localized within broken binder regions. This faceted, crystallographic fracture mode has been previously reported in WC-Co hardmetals subjected to cyclic loads [21,39,41-43], and has been ascribed to fatigue-induced phase transformation within the Co-base binder. Although such hypothesis could be supported by the observation of similar cleavage-like features in fracture surface of bulk cobalt-base alloys within the high cycle fatigue regime, it is not conclusive as morphologies of FCC (deformation) twins and HCP (phase transformation) lamellas exhibit similar morphologies, and phase transformation seems to be enhanced with applied maximum stress levels [44]. Within this context, very interesting is the fact that crystallographic stable crack growth paths have also been reported in Ni-base alloys (e.g. Refs. [45-47]) in the near-threshold FCG regime. In this case, and similar to the WC-Ni hardmetal grade here investigated, phase transformation mechanisms cannot be invoked at the binder phase; pointing out the step-like crack morphology to be rather a microstructure size scale effect. In this regard, it is well-known that the transition from the near-threshold regime to the intermediate stage: (i) is accompanied by a noticeable change from a microstructure-sensitive to a microstructure-insensitive fracture behavior; and (ii) occurs when the size of the cyclic plastic zone ($r_c$) becomes comparable to the characteristic microstructural dimension of the material under consideration [48]. When plane stress conditions are satisfied, the size of the cyclic plastic region can be approximated as

$$r_c \approx \frac{1}{\pi}\left(\frac{\Delta K_I}{2\sigma_y}\right)^2 \qquad (5)$$

where $\Delta K_I$ is the applied stress intensity factor range and $\sigma_y$ is the yield strength of the material. In cemented carbides, the high effective yield stress exhibited by the constrained binder (between 2 and 4 GPa [17]), together with the relatively low $\Delta K_I$ values at which stable crack growth takes place (between 4 and 10 MPam$^{1/2}$, **Figure 2**), yields a submicrometric plastic region ahead the crack tip, whose size is then comparable to the binder mean free path (**Figure 8**). Under these conditions, microscopic failure modes characterized by localized shear and zig-zag crack paths may be expected, as it is evidenced in this investigation too. Furthermore, as similar microstructure-plasticity scenario applies to WC-Co cemented carbides, the findings of this study raises the question on the speculated critical role played by the FCC to HCP phase transformation for rationalizing a relatively higher fatigue sensitivity of plain WC-Co hardmetals as compared to grades constituted by other alternative binders (e.g. Ref. [49]). Further research in this interesting issue is clearly required.

## Conclusions

The fracture and fatigue behavior of a fine grained WC-Ni hardmetal has been investigated and compared to that of Co-base cemented carbides with similar microstructural parameters. The following conclusions may be drawn:

1. The studied WC-Ni (with minor chrome addition) hardmetal exhibits similar hardness, transverse rupture strength and fracture toughness to those observed for a Co-base grade with alike binder mean free path. Within this context, the use of LEFM to rationalize the fracture behavior of Ni-base cemented carbides is also validated.

2. As previously observed for plain WC-Co grades, the WC-Ni hardmetal studied exhibits a large-power dependence of FCG rates on both $\Delta K$ and $K_{max}$, as well as subcritical crack growth at $K_{max}$ values lower than $K_{Ic}$. Moreover, values of fatigue sensitivity and FCG kinetics parameters determined for the WC-Ni grade are in satisfactory agreement with those estimated from microstructure – FCG behavior trends proposed from fatigue data gathered from WC-Co cemented carbides.

3. A fatigue mechanics analysis allows to estimate the fatigue limit of the WC-Ni hardmetal investigated on the basis that $K_{th}$ is the effective toughness under cyclic loads.

4. Stable FCG for the hardmetal studied is characterized by faceted, crystallographic features within the binder, different from the ductile dimples evidenced in the region of unstable propagation. Such fatigue failure mode is postulated to be a direct consequence of the comparable size length scales of microstructure and cyclic plastic zone in front of the crack tip. The facts that

both fractographic scenario during stable FCG and fatigue sensitivity (for a given binder mean free path) are similar for Ni-base and Co-base hardmetals raises then the question on the speculated role played by the FCC to HCP phase transformation as a critical fatigue micromechanism in WC-Co cemented carbides.

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**Figure 3.** Normalized FCG rate as a function of $K_{max}$.

**Figure 4.** Up-and-down fatigue test used to determine mean fatigue limit for the WC-Ni cemented carbide studied.

**Figure 5.** Fatigue sensitivity (left and dashed lines) and modified Paris law exponents ratio ($q/p$) (right and solid line) as a function of binder mean free path for the WC-Ni hardmetal studied (orange) as well as for the WC-Co grades investigated by Llanes et al. [21].

**Figure 6.** Scanning electron micrographs corresponding to stable crack growth ($R=0.1$) for the WC-Ni hardmetal investigated. Fatigue facets are neatly discerned in the metallic constitutive phase.

**Figure 7.** Scanning electron micrograph corresponding to unstable crack growth for the WC-Ni hardmetal studied. Ductile dimples are evidenced within the binder.

**Figure 8.** A schematic representing cyclic plastic zone - microstructure length scales existing at the crack tip during stable FCG in cemented carbides.

**Figure 1.** Example of critical flaw (binderless carbide agglomerate) that originates fracture in the WC-Ni hardmetal investigated.

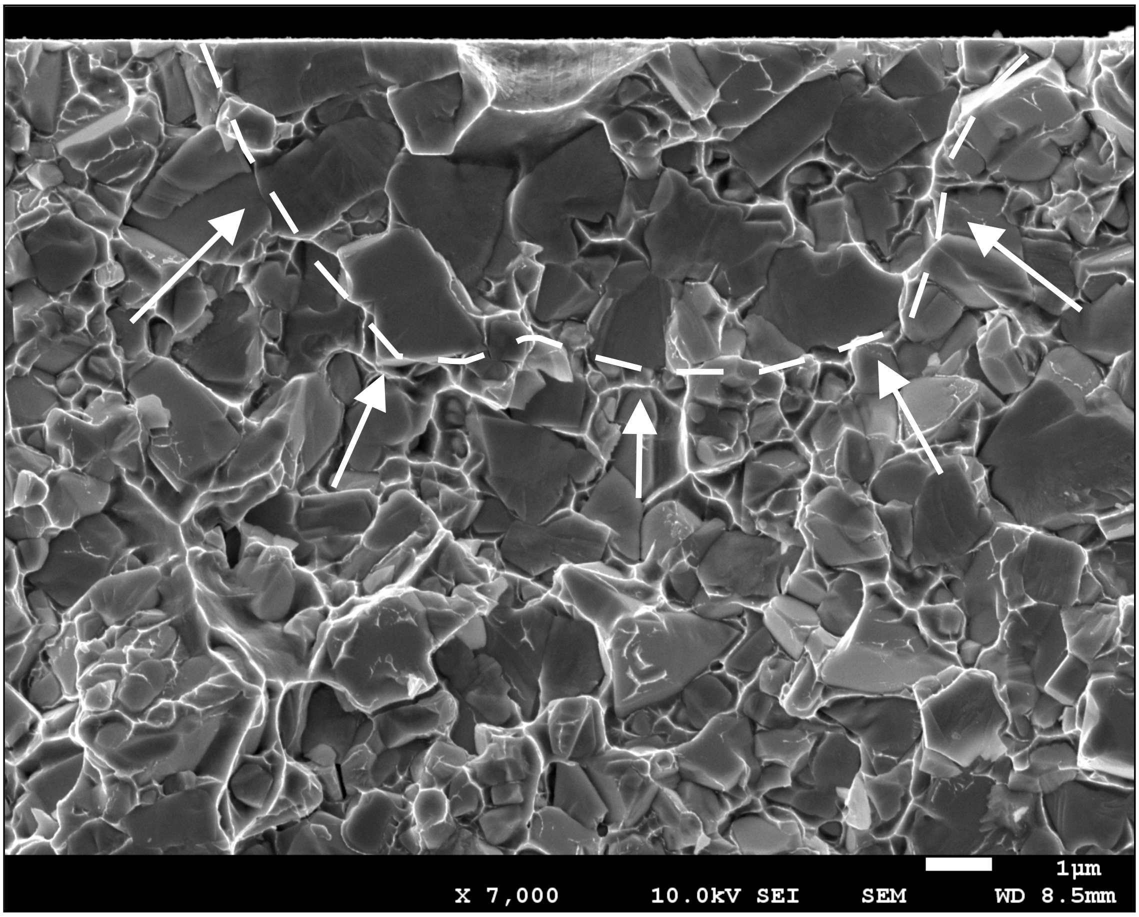

**Figure 2.** da/dN behavior vs. (a) ΔK, and (b) $K_{max}$, for each load ratio studied.

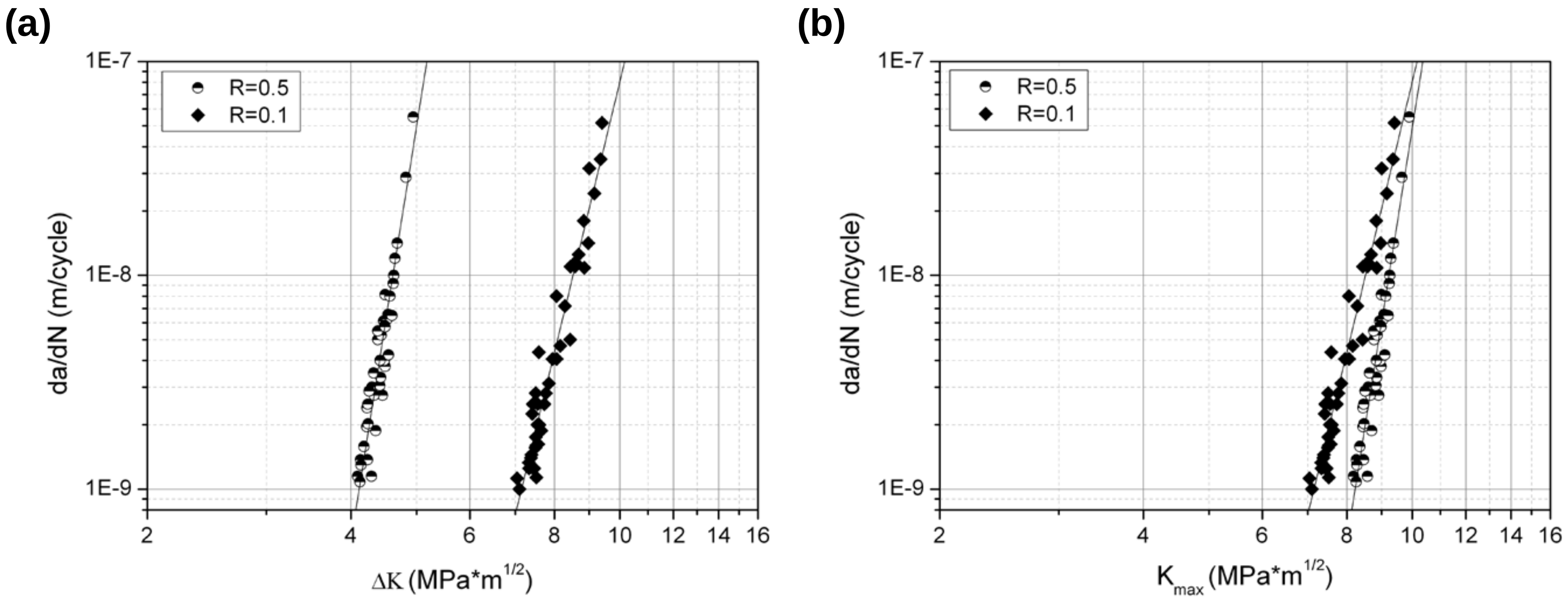

**Figure 3.** Normalized FCG rate as a function of $K_{max}$.

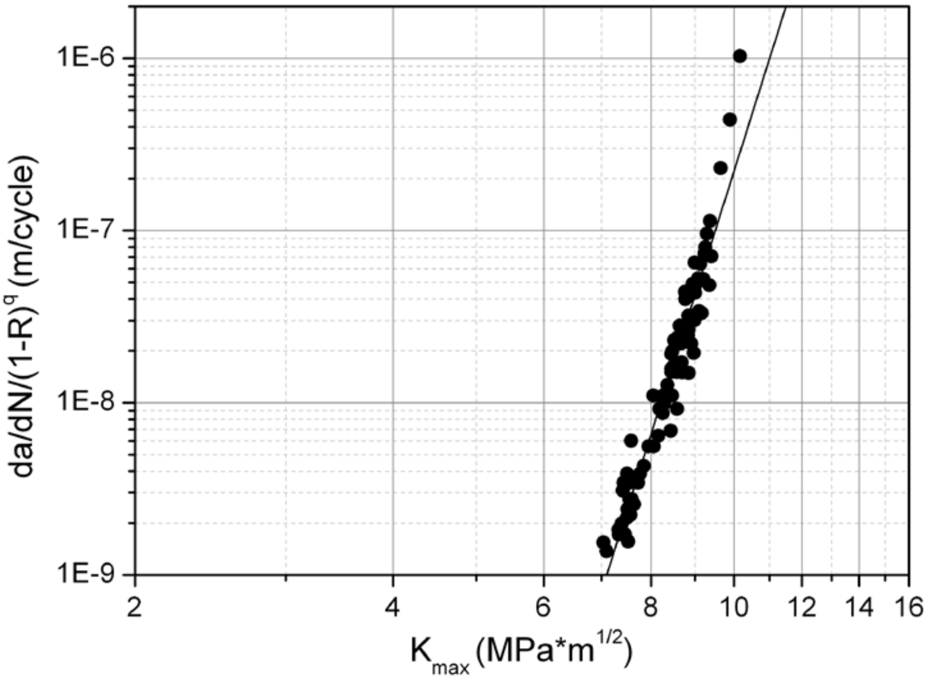

**Figure 4.** Up-and-down fatigue test used to determine mean fatigue limit for the WC-Ni cemented carbide studied.

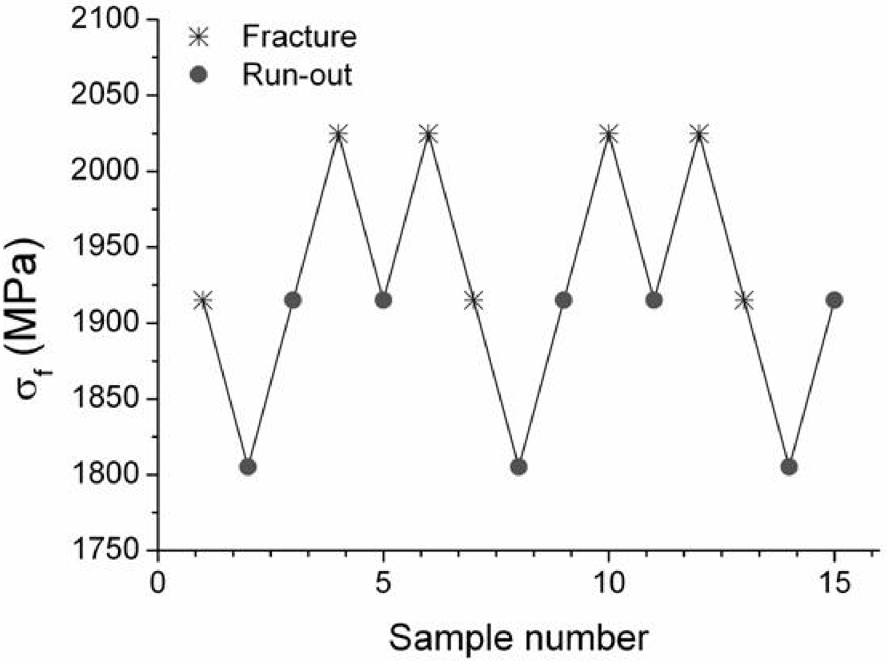

**Figure 5.** Fatigue sensitivity (left and dashed lines) and modified Paris law exponents ratio (q/p) (right and solid line) as a function of binder mean free path for the WC-Ni hardmetal studied (orange) as well as for the WC-Co grades investigated by Llanes et al. [21].

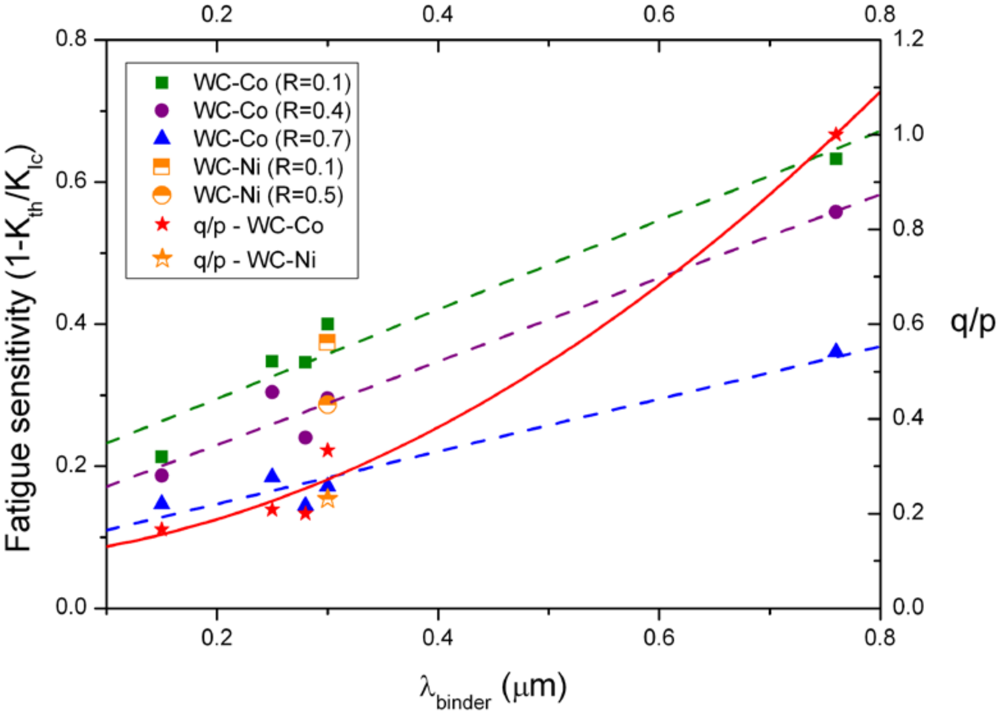

**Figure 6.** Scanning electron micrographs corresponding to stable crack growth (R=0.1) for the WC-Ni hardmetal investigated. Fatigue facets are neatly discerned in the metallic constitutive phase.

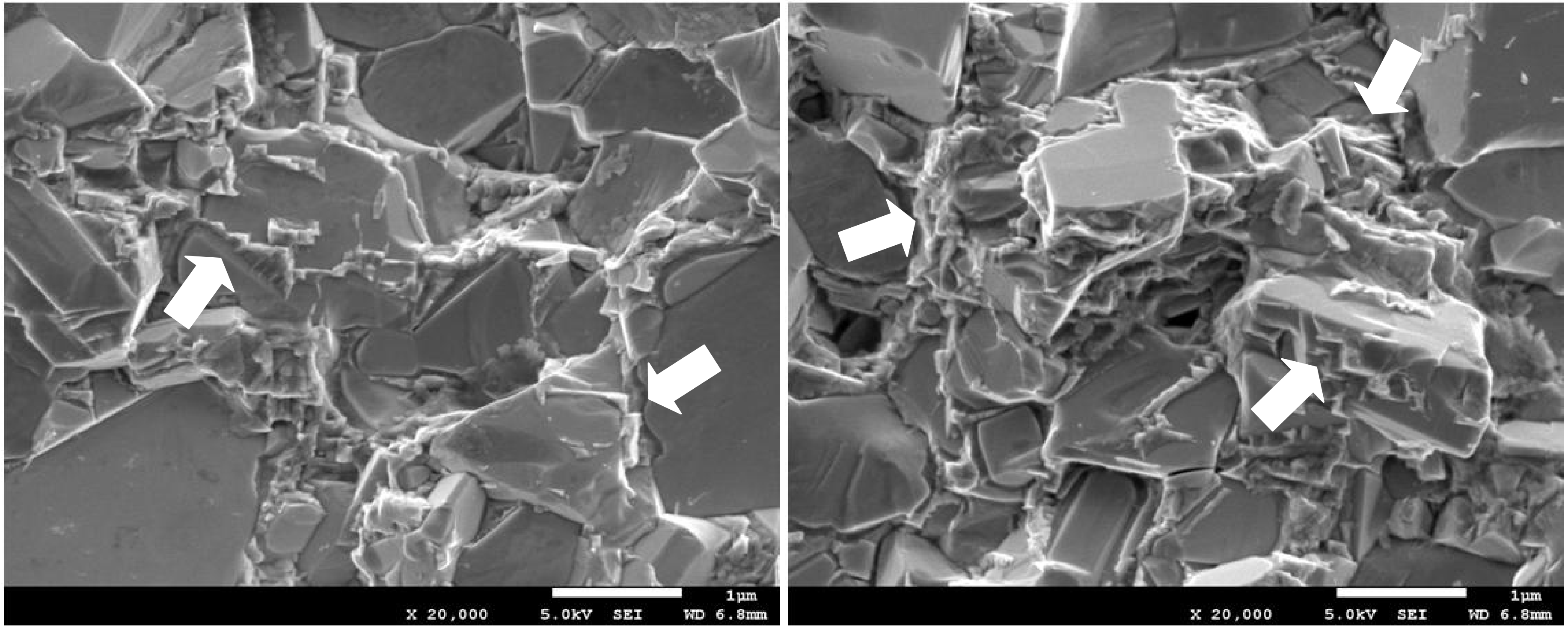

**Figure 7.** Scanning electron micrograph corresponding to unstable crack growth for the WC-Ni hardmetal studied. Ductile dimples are evidenced within the binder.

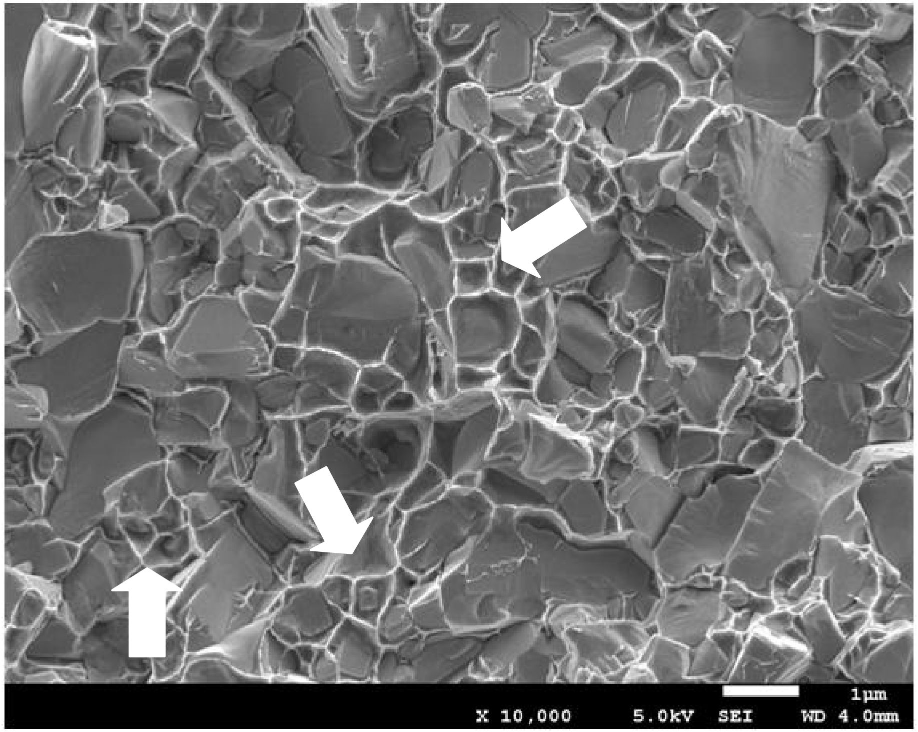

**Figure 8.** A schematic representing cyclic plastic zone - microstructure length scales existing at the crack tip during stable FCG in cemented carbides.