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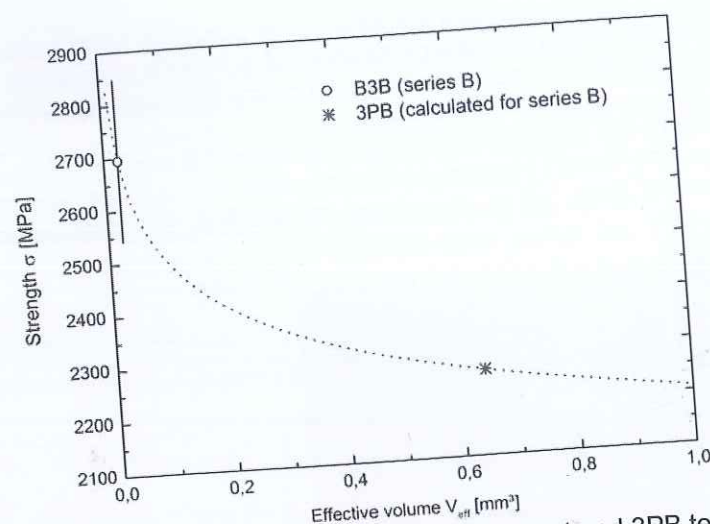
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**Figure 4:** Strength as a function of the effective volume for B3B test and 3PB test

#### 4. Conclusions

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The applicability of the ball on three balls test on hard metals was analysed using ultrafine WC-6 Co hard metal. It was discovered that the B3B test can be used for hard metals as an alternative strength measuring method to bending tests, which is confirmed by following results:

- The highest tensile stress appeared in the center of the sample on the opposite surface of the loading ball for all samples investigated.
- The probability of failure can be described using a Weibull distribution.
- A major advantage of the B3B test is its simple experimental procedure and the tolerance towards the deviations from the perfect disc-shaped sample geometry and the roughness of the sample surfaces. Especially Spark Plasma Sintered samples can be tested directly after the production without any machining. The highest Weibull modulus or rather the narrowest strength distribution could be observed for series A, where dense samples with an as-sintered surface were tested. Sintered components that have no special surface finishing can be easily and quickly tested with this method, for example as a quality control tool during production. The B3B test allows the use of specimens that are easy to manufacture and have no special requirement of surface and chamfer quality, as for bending test with rectangular bars.

## 5. References

- ## 5. References
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## Notch Effects on the Fatigue Endurance of Cemented Carbides

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## Abstract

Notch effects on the fatigue resistance of two microstructurally different WC-Co cemented carbides have been studied. Hardness, mechanical strength, fracture toughness and fatigue endurance corresponding to infinite fatigue life of  $2 \times 10^6$  cycles, have been evaluated in both smooth and notched specimens. Results indicate clear but inverse microstructural effects on intrinsic susceptibility to mechanical degradation and notch sensitivity under cyclic loads. The findings are discussed on the basis of the role played by the binder mean free path (key two-phase microstructural parameter), through its effective ductility in a constrained state, in toughening, fatigue and local plasticity development at the notch tip.

**Keywords:** Fatigue strength, notch influence, fatigue sensitivity, cemented carbides.

## 1. Introduction

WC-Co cemented carbides, usually referred to as hardmetals, are established materials for tools and wear parts with stringent requirements. As a consequence of its composite nature: hard, brittle carbides bound by a soft, ductile metallic phase, they exhibit an exceptional combination of strength, toughness and wear resistance (e.g. Refs. [1,2]). Through the years, implementation of cemented carbides has continuously risen not only in terms of market-share in conventional applications (based on their wear resistance) but also regarding its consideration as material option in other industrial sectors (e.g. metalforming, automotive, electronic, dental, etc.). Within this evolution trend, although its intrinsic "hard" nature is usually an attribute, most of the "emerging" and/or "to be consolidated" applications of cemented carbides require a higher relevance of toughness and fatigue resistance (with respect to that of hardness) for enhancing material performance. From this perspective, systematic experimental studies conducted by different research groups in the last three decades have provided extensive and enlighting information on microstructure-fracture-fatigue relationships for these materials (e.g. Refs. [1-8]). However, if technology development related to cemented carbides is to be optimized for engineering applications, existing information must be widened, targetting to several practical design issues: notch sensitivity (fatigue design of structural components), surface integrity effects associated with machining and shaping operations, and influence of service-induced changes on the basis of damage tolerance and reliability, among others. Following this idea, the work here presented aims to shed some light about notch effects on the fatigue endurance of cemented carbides.

Reports on the fatigue behavior of cemented carbides involving notched geometries have been published by Roebuck and coworkers [9-12]. This team has proposed and validated the use of V-notched specimens as a testing protocol approach for assessing intrinsic microstructural influence, beyond possible processing/surface finish issues, on fatigue strength and sensitivity. On the other hand, notched specimens have also been employed in recent investigations by distinct research groups, although following different objectives: assessment of fatigue notch sensitivity of cermets [13], evaluation of high temperature fatigue strength [14], and analysis of microstructural effects on fatigue behavior [15]. However, none of the above studies has attempted to evaluate and analyze separate influences of microstructure on intrinsic fatigue sensitivity (data from unnotched specimens) and



fatigue notch sensitivity (data from notched samples). This is indeed the main aim of this study. It is a required exercise if structural design issues are to be considered for selecting cemented carbides with optimal microstructures towards enhanced mechanical performance.

## 2. Materials studied: microstructure, hardness and toughness

The study was conducted on two microstructurally different WC–Co cemented carbides. They correspond to experimental grades provided by Sandvik Hard Materials (Coventry, UK). Designation, binder content (%Co), mean carbide grain size ( $d_{wc}$ ), binder mean free path ( $\lambda_{co}$ ) and carbide contiguity ( $C_{wc}$ ) are listed in Table 1. Values for the two-phase microstructural parameters ( $\lambda_{co}$  and  $C_{wc}$ ) were estimated from best-fit equations, attained after compilation and analysis of data published in a large number of literature studies, on the basis of empirical relationships given by Roebuck and Almond [1] but extending them to include carbide size influence [16,17]. Hardness (HV30) and fracture toughness ( $K_{Ic}$ ) for the two hardmetal grades are also included in Table 1. Hardness was measured using a 30 kgf (294 N) Vickers diamond pyramidal indentation. Fracture toughness was evaluated following the single edge notched bend method. The sample geometry employed was a rectangular bar of 45×10×5 mm dimensions. A detailed description of the pre-cracking and fracture toughness testing procedure used has been reported elsewhere [18]. As it is expected, hardness and toughness exhibit an inverse dependence with binder mean free path.

Hardmetal grade	%Co (%wt)	$d_{wc}$ (μm)	$\lambda_{co}$ (μm)	$C_{wc}$	HV30 (GPa)	$K_{Ic}$ (MPa√m)
L22	6.2 ± 0.4	0.4 ± 0.2	0.14	0.57	16.9 ± 0.2	8.4 ± 0.3
M23	15.9 ± 0.4	1.1 ± 0.5	0.54	0.30	11.0 ± 0.1	16.1 ± 0.3

Table 1. Microstructural and mechanical (hardness and toughness) characteristics for the materials investigated.

## 3. Fracture strength and fatigue endurance testing of smooth and notched specimens

Fracture and fatigue strength were assessed under four-point bending, with inner and outer spans of 20 and 40 mm respectively. Prismatic specimens of 45×4×3 mm dimensions were employed. In the unnotched case, before testing the longitudinal section later subjected to the maximum stress in bending was ground and polished. On the other hand, a through-thickness slot was mechanically machined for evaluation of notch effects. Notch depth and root radius were set to 250 μm and 60 μm respectively, corresponding to a theoretical stress concentration factor ( $k_t$ ) of 4.22 [19]. Additionally, longitudinal edges of all the samples were beveled.

Strength tests under monotonic loading were conducted using a servohydraulic machine. On the other hand, fatigue tests were carried out in a resonant device at frequencies of about 150 Hz and load ratio of 0.1. Fatigue endurance was defined as the fatigue strength corresponding to an infinite fatigue life of  $2 \times 10^6$  cycles. It was determined following the staircase method [20], using at least 15 specimens per grade and testing condition.

## 4. Fatigue endurance and notch sensitivity

Fatigue experimental findings were attained from statistical analysis of up-and-down tests, as described above. An example of complete testing sequences for hardmetal grade M23, corresponding to smooth and notched specimens, is shown in Figure 1. Fatigue endurance results for both hardmetal grades studied are listed in Table 2. Fracture strength data are also included, for comparison

purposes. Several observations may be highlighted. First, fatigue resistance assessed on smooth specimens is significantly higher for the harder grade than for the tougher one, even though differences between their fracture strength levels are statistically negligible. Second, strength lessening effects affiliated to the notch are relevant, independent of hardmetal grade or loading condition under consideration. Third, and quite interesting, fracture and fatigue strength levels for notched specimens are quite similar to each other. However, special care should be taken on conclusions drawn from this finding, as experimentally measured fracture and fatigue strengths for notched specimens include both intrinsic (microstructural-related) and notch-like effects. This will now be analyzed and discussed.

Hardmetal grade	$\lambda_{co}$ (μm)	$\sigma_{r,smooth}$ (MPa)	$\sigma_{r,notch}$ (MPa)	$\sigma_{f,smooth}$ (MPa)	$\sigma_{f,notch}$ (MPa)
L22	0.14	3287 ± 473	1001 ± 82	2442 ± 40	672 ± 37
M23	0.54	2933 ± 176	1036 ± 110	1400 ± 17	610 ± 16

Table 2. Fracture strength ( $\sigma_r$ ) and  $2 \times 10^6$  cycles fatigue endurance ( $\sigma_f$ ) of smooth and notched specimens for the materials investigated.

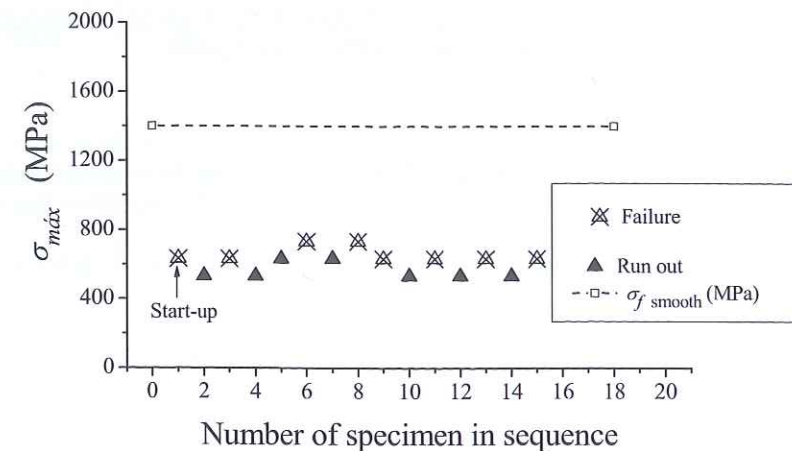
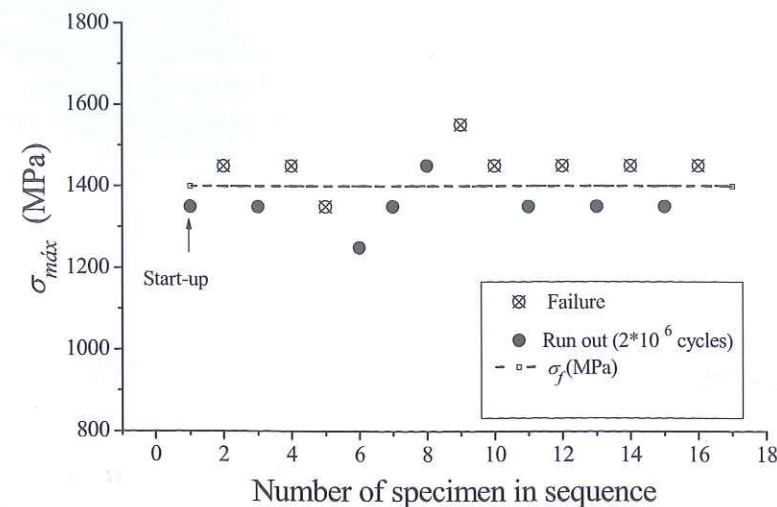
Table 3 summarizes the results attained under cyclic loading in terms of parameters defining intrinsic fatigue sensitivity ( $\delta_f$ ) and fatigue notch sensitivity ( $q$ ). The former is a direct index of the relative susceptibility to strength degradation when a material is subjected to repetitive loads. It is defined by the expression:

$$\delta_f = 1 - \frac{\sigma_f}{\sigma_r} \quad (1)$$

such that the material becomes more immune to fatigue, as  $\delta_f$  decreases (within the 0 to 1 range). On the other hand, the latter is a parameter indicative of the effective lessening influence of a notch on the fatigue strength ( $k_f$ ), with respect to the one implied by the theoretical stress concentration factor ( $k_t$ ). It is given by the equation:

$$q = \frac{k_f - 1}{k_t - 1} \quad (2)$$





**Figure 1.** Up and down fatigue test sequence used for determining the  $2 \times 10^6$  cycles fatigue endurance of hardmetal grade M23: a) smooth, and b) notched specimens.

such that the material exhibits less sensitivity to notch effects under cyclic loading, as  $q$  gets lower (within the 0 to 1 range).

Taking into consideration the physical meaning of  $\delta_f$  and  $q$  parameters, as described above, it may be pointed out that the similar value measured for the  $2 \times 10^6$  cycles fatigue endurance of L22 and M23 notched specimens is a consequence of different phenomenological responses. Thus, the tough-like grade is intrinsically more susceptible to fatigue degradation because the higher effective ductility

Hardmetal grade	$k_t$	$k_f$	$\delta_f$	$q$
L22	4.22	3.63	0.26	0.82
M23	4.22	2.30	0.52	0.40

**Table 3.** Notch stress concentration factor ( $k_t$ ), notch fatigue factor ( $k_f$ ), microstructural-related fatigue sensitivity ( $\delta_f$  – estimated from  $\sigma_f/\sigma_r$  ratio measured in smooth specimens) and notch fatigue sensitivity ( $q$  – measured by relative comparison of theoretical  $k_t$  and experimental  $k_f$ ).

associated with its less constrained binder [8]. However, such enhanced ductility also favors local plasticity at the notch tip, diminishing then the theoretical stress rising effect. Such reasoning applies for the harder (brittle-like) material too, but here trends are inversed with respect to those described for M23 grade.

The concept of local plasticity breaking the linear increase of the applied stress at the edge of the stress concentration, up to the theoretical value given by  $k_t$  (4.22 in this study) is also validated by the relatively high fracture strength values determined for the notched specimens. Furthermore, its higher prominence in the tough-like material is also supported by the relative differences found for the hardmetal grades studied: about 50% and 30% higher than expected for M23 and L22 materials, respectively. Although the reliability of these fracture strength values may be questioned, because they have been determined on the basis of linear elasticity, the experimental findings may be taken as real trends, i.e. higher levels of local plasticity developed at the notch tip of M23 specimens, as compared to L22 grade.

## 5. Summary and final remarks

The fatigue behavior of two microstructurally different WC-Co cemented carbides has been investigated. The study has been aimed to evaluate and analyze the individual influence of microstructure on intrinsic fatigue sensitivity (smooth specimens) and fatigue notch sensitivity (notched samples). It is concluded that fatigue susceptibility rises as the effective ductility of the constrained binder increases. However, higher toughness levels also yield a lower severity of the stress concentration effect under cyclic loading. Accordingly, a complex effect of microstructure on the fatigue endurance of notched hardmetals is identified, pointing out the need for simultaneous consideration of both intrinsic (microstructure – fatigue sensitivity) and notch-related influence, if their fatigue performance wants to be enhanced. In this regard, compromising microstructure arrangements, similar to those defined on the basis of mutual accounting of hardness and toughness as critical design parameters, should be tailored. In order to validate these ideas, further research in this field is clearly required.

## Acknowledgements

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## Hardmetals with Alternative Fe/Co/Ni and Fe/Ni Binders A Study on Mo Doping, Mechanical Properties and Creep Behaviour

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Properties of hardmetals with a Fe/Co/Ni = 40/20/40 wt.% binder alloy were measured. Green bodies were prepared on a usual powder metallurgical route and sintered under vacuum conditions. The sintering behaviour of hardmetals in dependency on the binder content, and Mo-addition from various sources such as molybdenum nitride, molybdenum carbide and alloyed molybdenum was investigated by dilatometry. Microstructure analysis shows an improved grain-growth inhibiting effect of  $\gamma$ -MoN<sub>1-x</sub> as compared to both Mo<sub>2</sub>C and alloyed Mo. Hardness HV30, fracture toughness K<sub>1C</sub>, magnetic saturation and coercive force were determined as a function of the carbon content. The influence of WC grain-size on the creep behaviour was compared to cobalt containing and a cobalt-free Fe/Ni = 15/85 wt.% binder alloy by a three-point bending test under power-law conditions. From experimental data creep parameters such as Norton exponents ( $n = 3.7 - 8.7$ ) and activation energies ( $Q = 313 - 318$  kJ/mol) were estimated.

### Introduction

In the last decades several fundamental studies [1-6] on so-called alternative binder alloys for hardmetals have been published. They were driven by a possible improvement of the mechanical properties. It turned out that for particular properties and applications specific Fe/Co/Ni binder alloys perform equal or even superior as compared to cobalt, but do not reach its wide application range and combination of properties. Hence, the economic impact as well as the research activities were limited to specific fields of interest. Due to geostrategic and health concerns in recent years there is again an increasing interest on alternatives to cobalt, despite its outstanding mechanical properties [7].

In comparison to the well-developed Co-based hardmetals and despite some important works [1-12], the properties of hardmetals with Fe/Co/Ni binders are relatively unexplored. The purpose of the present work is to achieve a deeper understanding for the Fe/Co/Ni = 40/20/40 wt.% binder alloy, which was found to be suitable for metal tooling applications [9], i.e. to get more insight into (1) the sintering behaviour, (2) the dependency of the hardness, fracture toughness as well as the magnetic properties of a Mo<sub>2</sub>C, VC and Cr<sub>3</sub>C<sub>2</sub> doped hardmetal on the carbon content, (3) the influence of molybdenum as a grain-growth inhibitor added from different sources, (4) the creep behaviour as compared to cobalt and a cobalt-free Fe/Ni binder and (5) the influence of the WC grain size on the creep behaviour.

### Experimental

#### *Preparation and characterisation of samples*

The samples for investigation of the mechanical and magnetic properties, the sintering behaviour as well the influence of grain-growth inhibitors and molybdenum from different sources were prepared on a usual powder metallurgical route by liquid-phase sintering at 1440°C. A characterisation of the specimens is given in Tab. 1. The Ampersint® MAP A6050 (H.C. Starck, Fe/Co/Ni = 40/20/40 wt.%) alloy was used as binder, 4NP0 (H.C. Starck) was used as tungsten carbide powder. Hardness HV30 and fracture toughness K<sub>1C</sub> (Shetty), the magnetic saturation as well as the coercive force were measured by standard techniques. The microstructure was characterised using light-optical microscopy (LOM) and scanning electron microscopy (SEM). The linear-intercept method (ISO 4499-2:2009) was used to achieve grain-size distributions.

For creep test samples with three different binder systems as well as two different initial WC grain sizes were prepared and sintered by conventional industrial methods. The samples were doped with VC as well as Cr<sub>3</sub>C<sub>2</sub> for grain-growth inhibition (identical amount for all grades), the binder content was 16.3 vol.%. A characterisation of the creep-test samples is given in Tab. 2.