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Fatigue testing and properties of hardmetals in the gigacycle range☆

Agnieszka Betzwar Kotas [a,*], Herbert Danninger [a], Brigitte Weiss [b], Ken Mingard [c], Jose Sanchez [d], Luis Llanes [e]

[a] *Technische Universität Wien, A-1060 Vienna, Austria*
[b] *Universität Wien, A-1090 Vienna, Austria*
[c] *National Physical Laboratory, Teddington, UK*
[d] *CEIT, San Sebastian, Spain*
[e] *Department of Materials Science and Metallurgical Engineering, Universitat Politècnica de Catalunya, Barcelona 08028, Spain*

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ABSTRACT

Hardmetal products are frequently fatigue loaded in service, such as e.g. cutting tools for milling or percussion drills. In the present work, the fatigue behaviour of hardmetals was investigated into the gigacycle range using ultrasonic resonance fatigue testing at 20 kHz in push-pull mode at $R = -1$. Liquid cooling was afforded using water with addition of a corrosion inhibitor. Hourglass shaped specimens were prepared, the surface being ground and polished with subsequent stress-relieving anneal to remove the high compressive residual stresses introduced during grinding. S-N curves with fairly low scatter were obtained, which indicates microstructure-controlled and not defect-controlled failure. Low binder content as well as fine WC grains were found to improve the fatigue endurance strength. In no case, however, a horizontal branch of the S-N curve was observed, i.e. there is no fatigue “limit” at least up to 10^{10} cycles. The initiation sites were in part difficult to identify; in such cases when the site was clearly visible, decohesion of the binder from large WC grains seems to have caused crack initiation. This further corroborates that microstructural features and not singular defects as e.g. inclusions are the initiation sites, which underlines the high purity of the hardmetal grades used. Based on fracture mechanical consideration a damage diagram was determined allowing to deduce critical defect sizes.

1. Introduction

Hardmetals can be regarded as the most important tool materials in use today. For machining of metals, wood cutting, rock drilling etc., hardmetals, mostly WC-Co type, are indispensable. One main reason is the wide range of properties attainable by varying parameters such as binder content, carbide grain size and carbide type. Production is estimated at 75,000 tons per year worldwide.

In many applications, hardmetal tools are subjected to cyclic loading. This may be interrupted cut in metal shaping, such as e.g. milling, or sawing of metals or wood, or percussion drilling of rock or concrete. The cycle numbers may vary widely but frequently exceed 10^6, which means that the “very high cycle fatigue” range is entered. In addition to mechanical cycling, also thermal cycling causes damage through mechanical stresses.

The extensive studies for characterization of hardmetals included mechanical testing both in monotonic and in cyclic loading [1–9]. It is difficult to test fairly brittle materials in push-pull mode, since even a slight misalignment results in incorrect data. Therefore, bending has been commonly preferred, which is easier to perform but results in a small loaded volume of the specimen. In particular cases when singular defects play a major role, testing small volumes may result in erroneous results [10].

In most cases, the tests were done up to 10^7 cycles maximum. This agrees with the N, numbers of loading cycles mostly encountered in practice. On the other hand, testing up to much higher N, in the gigacycle range, enables elaborating the fatigue behaviour and in particular the crack initiation process much more clearly.

1.1. Crack initiation in fatigue loading

If failure of materials is described, microstructure controlled and defect controlled initiation can be distinguished. For metals this holds mostly for fatigue loading. On the other hand, for brittle materials such as e.g. ceramics, also monotonic loading can result in defect-controlled failure. In practice, if components and not materials are studied, of course also geometrical effects such as notches, cross holes, machining marks etc. have to be considered. “Microstructural control” is characterized by initiation at one of numerous microstructural constituents. Typical examples are cold work tool steels of 1.2379/AISI D2 type which contain a huge amount of coarse carbides. In such cases the probability that a crack initiating constituent – a large carbide or carbide

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☆ Dedicated to Prof. Wolf-Dieter Schubert at the occasion of his 65th birthday.
* Corresponding author.

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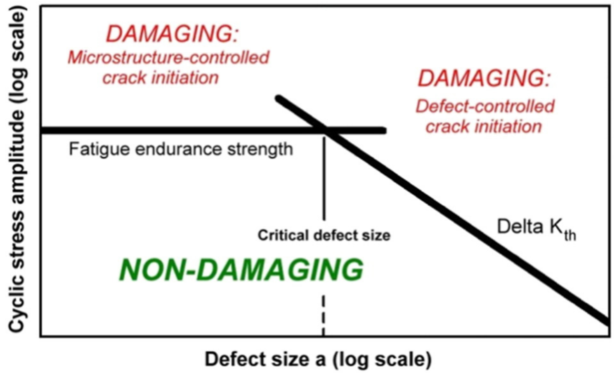

Fig. 1. Kitagawa-Takahashi- fatigue damage diagram (schematic).

cluster – is present in the loaded volume is very high [11], and therefore the scatter of the individual data is usually low.

Defect controlled initiation, in contrast, starts from very rare microstructural constituents. Examples are oxidic, carbidic or nitridic inclusions in high purity bearing or spring steels [12,13] or slag inclusions in PM tool steels [14]. This type of fatigue failure of metals corresponds to the static failure of high performance ceramics, the strength of which is typically governed by the largest defect present in the loaded volume. It can thus be derived that in case of gigacycle fatigue loading, also metallic materials show "ceramic-like" behaviour.

For assessing the fatigue initiation behaviour, Kitagawa-Takahashi-diagrams, also called "fatigue damage diagrams", can be used [15], as schematically depicted in Fig. 1. The fatigue endurance strength (or the static strength (UTS), see [16]) is plotted against the defect size in log-log scale. Up to a certain defect size, the defects are irrelevant for damage, and the strength is controlled by the microstructure. Above this critical defect size, initiation occurs at the largest defect in the loaded volume, and the fatigue (or static (UTS)) strength of the material is the lower, the larger the defect size is. For plotting such a diagram, the fatigue strength of the defect-free material is required as well as the "effective threshold stress intensity factor" ΔK_{theff}, that defines the onset of crack growth. The Kitagawa-Takahashi diagram thus only depends on properties that are relevant for fatigue and does not require properties that are at least not directly correlated to fatigue, such as the hardness as e.g. in Murakami's approach [17].

However, it has to be considered that such a Kitagawa-Takahashi fatigue damage diagram holds for a given maximum loading cycle number, since true fatigue limits do not exist for technical materials [18] and also since the sensitivity to singular defects increases with higher N.

The present study describes the fatigue behaviour of WC-Co hardmetals in the gigacycle range, i.e. up to $N > 10^9$ cycles, ultrasonic testing being performed. Main topics were the initiation mode – microstructure- vs. defect controlled – , the existence of a true fatigue limit and the effect of parameters such as carbide grain size and binder content.

1.2. Testing procedure

The principle of the testing done here is ultrasonic resonance fatigue loading, a method known for many decades. The development of high frequency testing methods dates back to the beginning of the 20th century. Already in 1911, Hopkinson [19] introduced the first electrodynamic resonance system operating up to 116 Hz. In 1929 Jenkin and Lehman [20] used a pulsating air resonance fatigue testing system operating at frequencies up to 10 kHz. In the 1950s, Mason [21] introduced an ultrasonic fatigue testing system operating at 20 kHz. 10 years later, Neppiras [22] presented the basic principles and the mathematical equations for the design of a resonance system. Since then, the ultrasonic resonance test system has been successfully applied by various groups for the determination of S-N curves, fatigue crack growth and corrosion fatigue measurements. Based on extensive studies of Stickler and Weiss [23] on the applicability of the system for fatigue testing of various materials [24–26] these authors started around 1975 to investigate the fatigue response of PM materials.

The main benefit of ultrasonic testing is the chance to get into the gigacycle range within reasonably short times. At 20 kHz, attaining 10-^{10} cycles takes about 5 days as compared to 8 years at standard servohydraulic testers. This enables checking if a true fatigue limit exists, i.e. a horizontal branch of the S-N curve. Furthermore, the method enables finding the last remaining defects in a material, as stated above [12,13]. For crack growth studies, ultrasonic testing enables very low da/dN, to $<10^{10}$ m/cycle, which means that real threshold values are obtained. For hardmetals, ultrasonic testing should enable verifying Llanes and coworkers' hypothesis that toughening by ductile bridging reinforcement is either degraded or even inhibited during cyclic loading [27–30].

In classical ultrasonic push-pull testing the specimen is fixed on one end and the other resonates freely. This is particularly advantageous for brittle materials for which clamping at both ends easily results in axiality problems. Compared to bending tests, the loaded volume is much larger, this being critical in the case of defect-controlled initiation [10].

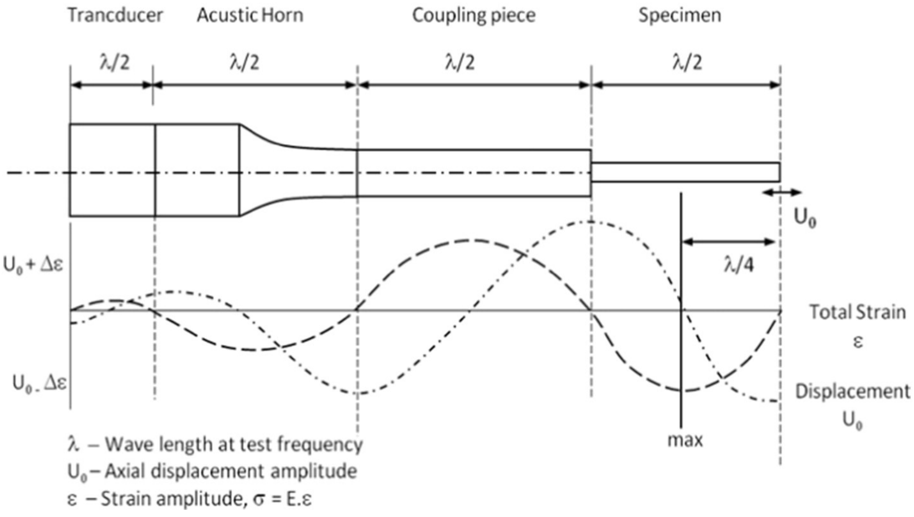

Fig. 2. Ultrasonic resonance tester (schematic).

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