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Evaluation of Fatigue Crack Growth Performance in different Hardmetal Grades based on Finite Element Simulation

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Abstract

Hardmetals (WC-Co) are a group of composite materials exhibiting outstanding combinations of hardness and toughness. Therefore, they are extensively used for highly demanding applications, such as cutting and drilling tools, where cyclic loading is one of the most critical service conditions.

The micromechanics of fracture in hardmetals under static loads is well investigated and understood. Studies regarding failure by fatigue on the other hand, is mainly limited to experimental investigations conducted at a component scale and seldom refer to the influence of microstructure on the failure mechanism. Moreover, numerical studies evaluating the mechanisms of fatigue crack growth in hardmetals are also scarce.

Experimental observations indicate that, the overall fatigue performance of hardmetals can be predicted from the early stages of the microcrack evolution. Taking this into consideration, a numerical methodology for evaluating the fatigue crack propagation in hardmetals was developed. In this respect, previously a model based on a continuum damage mechanics approach together with an element elimination method was implemented in a commercial finite element software for simulating the crack propagation in hardmetals. In the current study, the model is further extended to artificially generated hardmetal structures in order to simulate and evaluate the overall fatigue crack growth performance of different hardmetal grades.

Fatigue crack growth rate diagrams based on the simulations were plotted for different hardmetal grades and the results showed good agreement in comparison to experimental observations. Such an approach is helpful for designing hardmetals at a microstructural scale without going through extensive experimental work.

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Keywords: Hardmetal, WC-Co, Fatigue, Crack, Simulation, FEM

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1. Introduction

Hardmetals or also referred as cemented carbides, are a group of composite materials which have the typical properties of high hardness and toughness. Hardmetal components are produced by powder metallurgy and the simplest and oldest form is the tungsten carbide-cobalt (WC-Co). From the date when it was first produced almost a hundred years ago, as a die tool for drawing tungsten wires, WC-Co is still one of the most used materials in industrial applications where hardness and wear resistance are crucial.

Composite materials are produced in an attempt to combine and superimpose the unique and desirable properties of some already existing materials under a unified microstructure. In the case of WC-Co, its initial phase (constituent) tungsten carbide (WC) provides the high hardness. The major drawback of WC is its brittleness. Therefore, Co as the second phase in the composite provides the necessary toughness (Exner, 1979). As a consequence, WC-Co is widely used in the machining, mining, forming and similar industries mainly as a tool for cutting, drilling, grinding, and similar applications in which a high hardness and wear resistance are mandatory (Exner, 1970).

Due to its utilization in such a wide range of different applications, WC-Co is subjected to almost all types of physical damage including static, cyclic, impact and wear. Therefore, over the years many researchers investigated the nature and mechanics of such deformation process in WC-Co. However, the abundant work was conducted mostly regarding the performance under static or monotonically increasing loads. Only within the last thirty years or so, there is an increasing trend for understanding and evaluating the fatigue performance of WC-Co, which is related to their increasing usage as wear parts and structural components dominated by cyclic loads.

1.1. Fatigue properties of hardmetals

Evans and Linzer (1976) were one of the first researchers who indicated strong cyclic effects associated with hardmetals. Today there is a common agreement in literature that the hardmetals exhibit high fatigue sensitivity and the fatigue effects of hardmetals, as well as the ductile failure mechanisms, occur predominantly in the binder phase (Schleinkofer et al. 1997, Sailer et al. 2001)

Regarding the lifetime investigations in industrial hardmetal grades, a generalization can be made based on literature data. In this regard, based on the works of Schleinkofer et al. (1996,1997) and later by others (Klaasen et al. 2006, Nakajima et al. 2007), it can be concluded that, in hardmetals at infinite life time, general flattening of the Wöhler diagram like in classical metals is not observed; hence a real fatigue limit for the hardmetals does not exist (Fig. 1a). Moreover, even with the latest ultrasonic fatigue studies conducted at the gigacycle range (10^8-10^{10} cycles), a continuous decrease in S-N curve was realized up to 10^{10} cycles (Betzwar Kotas et al. 2013). These most recent findings once again validate that a real fatigue limit (strength) does not exist for the hardmetals and the failure mechanism is mainly microstructure controlled.

The Paris relationship is frequently addressed by researchers and is important for evaluating the fatigue resistance of a component. Similarly beginning from the early work of Roebuck and Almond (1988) and later followed by others (Torres et al. 2001, Llanes et al. 2002, Hiroko et al. 2014) and similar to the Wöhler diagrams, an ideal fatigue crack growth (FCG) is not observed for the industrial grades. Generally, there is a scatter of the experimental data, which can be idealized under a linear trend. Hence, the FCG rate diagrams for the hardmetals are composed of linearized curve fits and it is almost impossible to distinguish between different stages of crack growth (Fig. 1b). Based on these results, it can be easily argued that, following the initiation phase the crack propagation in the hardmetals develops rapidly under increasing velocity followed by the instantaneous failure. Based on their study, Fry and Garret (1988) also report that, time dependent crack growth does not occur in hardmetals during fatigue, since crack velocity (da/dN) is also independent of the frequency of the loading.

Moreover, in many of the studies where hardmetals were investigated with respect to different load ratios (R), the dominance of the maximum stress intensity (K_{max}) over the stress intensity range (ΔK) was highlighted (Fry and Garret 1988, Torres et al. 2001, Llanes et al. 2002) which is generally typical for brittle materials such as ceramics or intermetallics (Llanes et al. 2014) (Fig. 2). This can be easily recognized from the clustering of the FCG rate diagrams when plotted with respect to K_{max} instead of ΔK (Fig. 2b).