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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.

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).

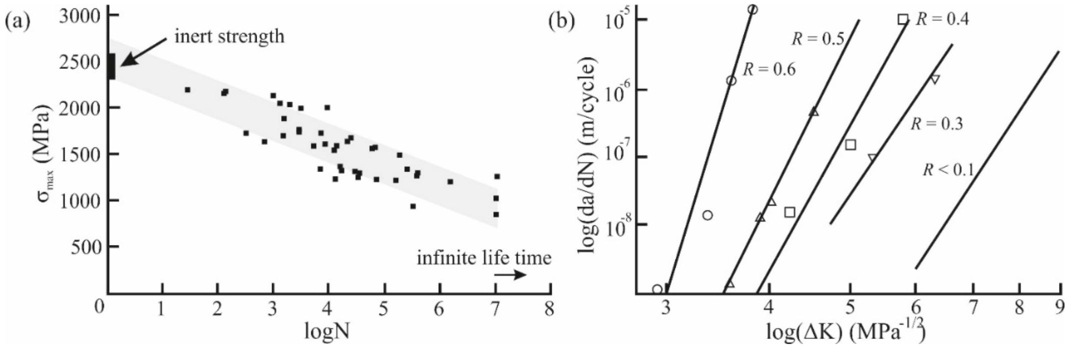

Fig. 1. (a) Typical Wöhler diagram for the hardmetals having high carbide fraction (in this example 86.5 wt. % WC) (after Schleinkofer et al. 1995) (b) typical FCG rate diagram for WC-Co having 90 wt. % WC under different load ratios (after Fry and Garret 1988).

Experimental work on fatigue crack growth rate studies highlight the importance of understanding microcrack growth in WC-Co. The early stage of fatigue in WC-Co, which is mainly dominated by the microcrack evolution, distinguishes the overall fatigue resistance of different grades at component scale. Most of the work conducted in literature pay minor attention to this fact and results are generally provided based on empirical generalizations.

A tool for predicting the fatigue performance of WC-Co based on microstructural features also does not exist. It is obvious that the development of such a tool would be an important contribution to the science of hardmetals. With such a tool, it is possible to virtually develop and experiment large variety of WC-Co grades and it is possible to have an early image of their fatigue performance at component scale. Such an approach would decrease the need for extensive and time demanding experimental work.

In this respect, previously a model based on a continuum damage mechanics approach together with an element elimination method was implemented in commercial finite element software Abaqus for simulating the crack propagation in hardmetals. In the current study, the model is further extended to artificially generated hardmetal microstructures in order to simulate and evaluate the overall fatigue crack growth performance of different hardmetal grades.

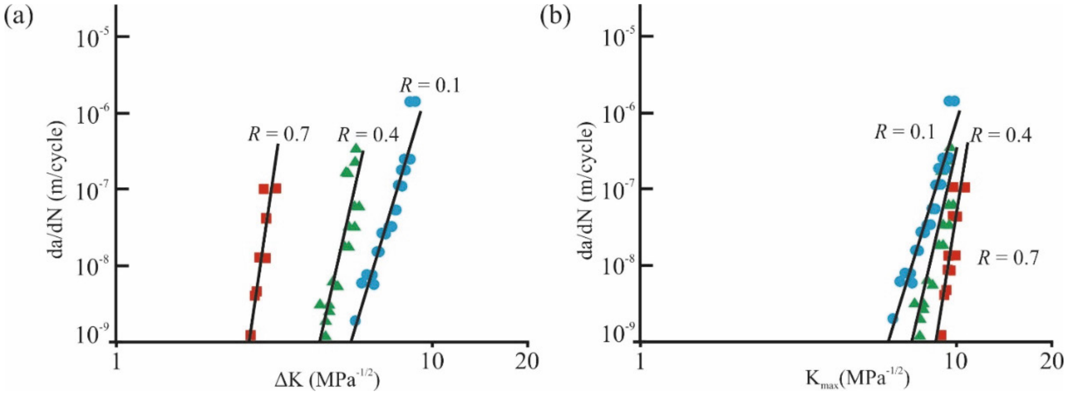

Fig. 2. FCG rate diagrams for 94 wt. % WC hardmetal, (a) as a function of ΔK, (b) as a function of K_{max} (after Llanes et al. 2002).

2. FE Modelling Approach

The main focus of the study is to simulate the microscale crack propagation in WC-Co under cyclic loads using finite element (FE) method. In this study, both binder and the carbide phases subject to fundamental continuum mechanics principles, and within this context, a damage model based on a continuum damage mechanisms (CDM), together with an element elimination based simulation technique was used to model the crack propagation in the material. In this respect, brittle and ductile damage laws were implemented for the WC and the Co phases respectively. Details on the modelling approach was provided elsewhere (Özden et al. 2014).

The material parameters for the WC are taken from literature. Meanwhile, to determine the material parameters for the binder, a particular model alloy has been produced to represent the composition of the binder based on the works of Almond and Roebuck (1988) (Table 1). Experimental investigations were carried out with this binder alloy to identify parameters for more accurate plasticity and damage parameters (Özden et al. 2015).

Table 1. Mechanical properties of the WC and CO phases used for the simulation.

Material	Elastic Modulus (GPa)	Poisson's Ratio (-)	Yield Strength (MPa)	Hardening Modulus (GPa)	Dynamic rate of backstress (-)	Maximum critical principal stress (MPa)	Critical damage parameter (-)
WC	700.00^{+}	0.240^{+}	-	-	-	4000	-
Co	227.28	0.300	683.07	52.379	151.638	-	$0.3^{\ddagger}$

$^{+}$Sadowski and Nowicki (2008), $\ddagger$ Lemaitre and Desmorat (2005).

In order to evaluate the predictive nature of the approach initially various numerical models based on real damaged microstructures were generated and the results of the studies were compared. Results from these studies indicated that, the damage model reflects good agreement in capturing the FCG characteristic of the real microstructures (Özden et al. 2014, 2015). As the next step, the model is further extended to artificial microstructures. Artificial models were generated based on user-defined criteria; therefore, have larger flexibility in generation in comparison to experimental models. In this respect, two artificial microstructures were generated and evaluated based on their FCG characteristics.

Initially a 3D representative microstructural model composed of 80 wt. % WC was generated by using commercial program Digimat-FE and from the front surface of this model, an ideal 2D model (reference) having 80 wt. % WC, was generated. The model was designed to have dimensions of 65x65x1 µm, considering the capacity of the program in generating such structures. The individual WC grains were assumed to have a grain dimension of 2 µm (Figure 3a). In order to create a notch like effect, similar to an experimental case, a few of the elements were manually removed from the upper edge of the model resulting in an initial crack of ~2.6 µm (Figure 3b).

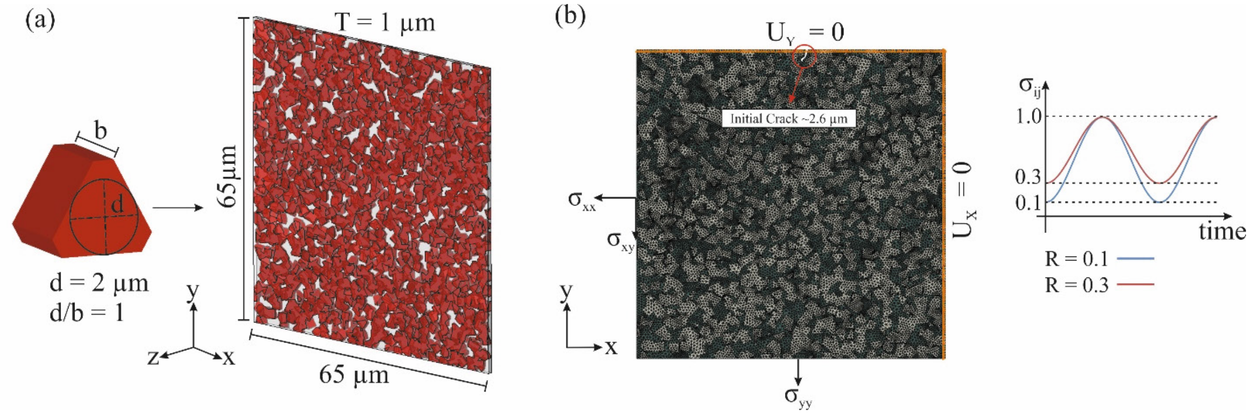

Fig. 3. (a) The WC inclusion geometry and the resulting 3D artificial microstructure (b) FE model for the simulation.

It was crucial to generate the second model directly based on this reference model, due to the overall mesh dependency of the technique. In this respect, a practical approach was to use the same reference mesh generated from the 3D model, and vary the percent composition of the WC and Co phases in the model. This was achieved practically by assigning each time adjacent elements from the boundaries between the two phases from one to another. Although such an approach does not end up in perfectly realistic geometries, it is the best way to ensure the use of similar mesh in all models. By doing so, a second model was generated (Fig. 4). Based on the comparison between the phase ratio and by linear averaging from the reference model, the second model was calculated to be composed of approximately 90 wt. % WC. For simplicity, the models were designated with the names 80WC and 90WC.

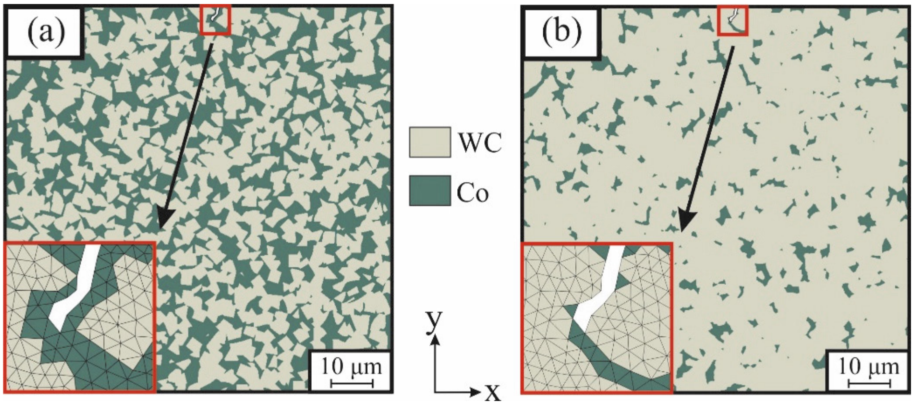

Fig. 4. FE models for hardmetals with artificial microstructure (a) 80WC (Reference), (b) 90WC.

3. Results and Discussion

Both models were subjected to multiaxial loading conditions much like in a real fatigue experiment and a load ratio R = 0.1 and 0.3 were implemented (see Fig.3b). In each case, the maximum loads were kept constant in order to investigate the load ratio effects. Plane stress elements are suitable for simulating the surface cracks (Antretter and Fischer 1998, Schmauder 2001), therefore in this study these type of elements were used. A visual representation of the FCG evolution for the 80WC and 90WC under R = 0.1 are provided in Fig.5 and Fig.6.

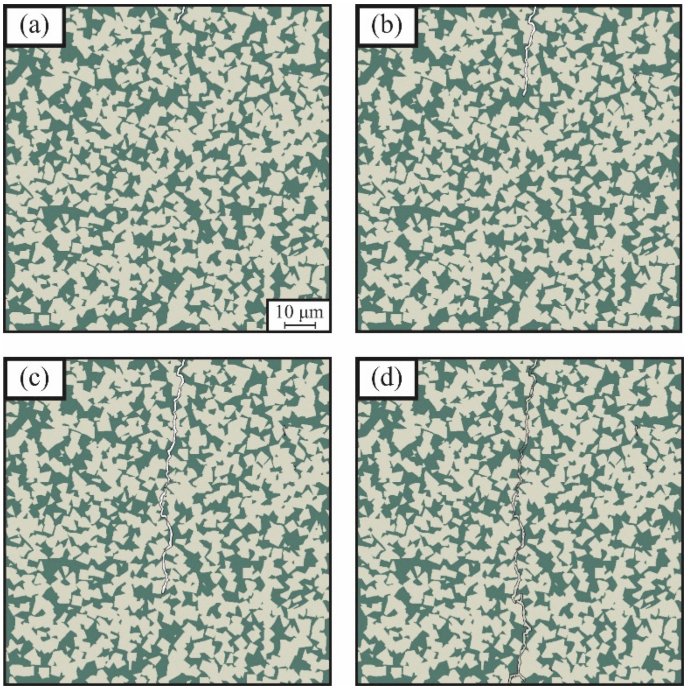

Fig. 5. Evolution of damage in the 80WC for R=0.1 at (a) 1000 cycles, (b) 2700 cycles, (c) 4335 cycles, (d) 4336 cycles.

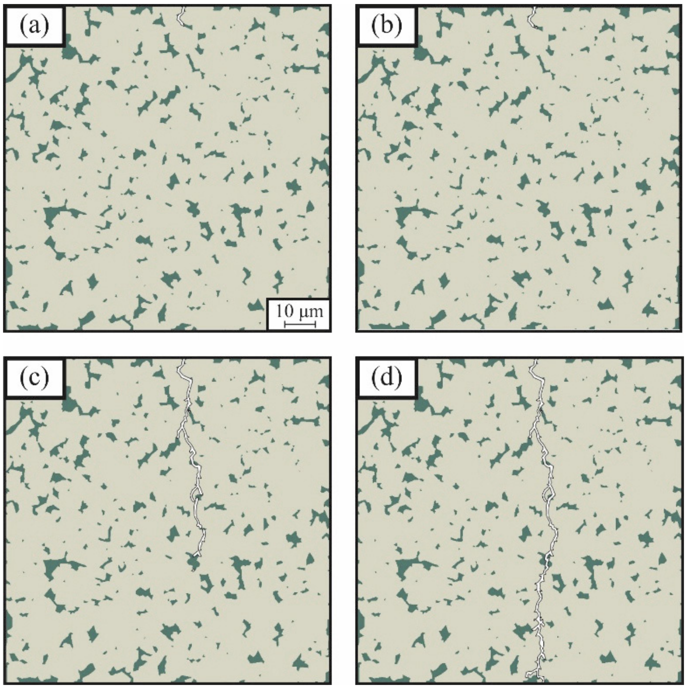

Fig. 6. Evolution of damage in the 90WC for R=0.1 at (a) 1000 cycles, (b) 1500 cycles, (c) 1658 cycles, (d) 1659 cycles.

In order to compare the results with respect to experimental observations a practical approach was followed. Assuming constant global stress components (Σ_{ij}) acting on each microstructure and the tensile (Mode I) failure mechanism, global maximum principal stress (Σ_{max}) was calculated for each model based on plane stress assumption. Then based on equation (1):

$$K_{\max} = \Sigma_{\max} \sqrt{\pi a} \tag{1}$$

and which takes the form

$$\Delta K = \Sigma_{\max} (1 - R) \sqrt{\pi a} \tag{2}$$

The maximum stress intensity factor (K_{max}) and the stress intensity range (ΔK) was calculated for each of the models and based on these calculations the FCG rate diagrams for each grade were plotted (Fig. 7 and Fig. 8).

Based on the experimental observations previously summarized, higher load ratios (R-values) generally result in FCG rate data at lower ΔK. However, such ratio effects are not particularly observed when the data is plotted with respect to K_{max} rather than ΔK (see Fig. 2), indicating the sensitivity of the hardmetals to the maximum applied load rather than the range. To a certain extent, such an effect is also captured by the models. As seen from the figures, for each microstructure when the data is plotted with respect to K_{max} clustering of the data is observed similar to the experimental observations (Llanes et al. 2002, Hiroko et al. 2014, Tarragó et al. 2015). Moreover, the power law dependence (m) of each curve was also determined based on the classical Paris law:

$$\frac{da}{dN} = C \Delta K^{m} \tag{3}$$

In this regard, for each model, the material parameter m was determined for each load ratio. Similar to the experimental work, the power law dependence of the FCG rate with respect to ΔK increases as the weight fraction of the WC increases (Torres et al. 2001, Llanes et al. 2002). The results indicate a strong dependence of the fatigue crack pattern on accumulated plasticity of the binder phase and the non-steady growth in the crack path. Both of these observations are also in accordance with the most recent findings on the FCG mechanisms in WC-Co (Tarragó et al. 2013, Mingard et al. 2013), indicating that physically accuracy of the model.

Overall, the modelling and simulation strategy showed promising results for reflecting the FCG in WC-Co. Although certain amount of simplifications were introduced, during both the modelling and implementation phases, in all different scenarios, cyclic evolution of the crack path through the microstructure, in general accordance with the experimental and published data was observed.

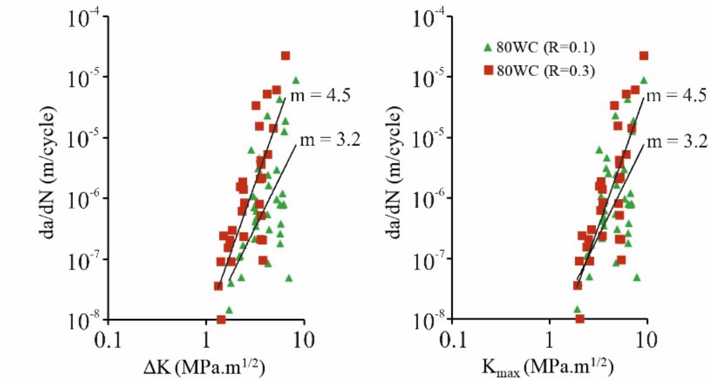

Fig. 7. Crack growth rate diagrams for 80WC at different load ratios (R) with respect to ΔK and K_{max}.

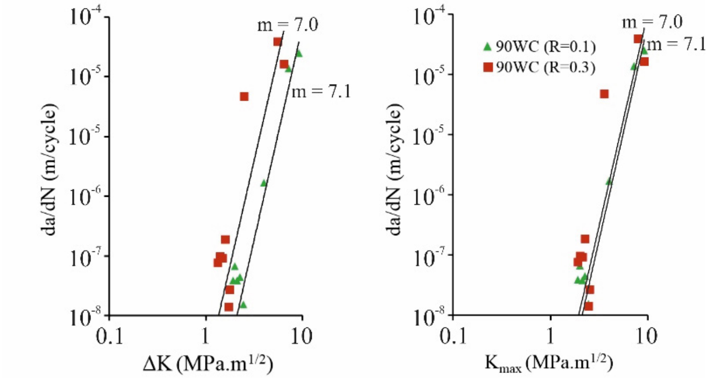

Fig. 8. Crack growth rate diagrams for 90WC at different load ratios (R) with respect to ΔK and K_{max}.

4. Conclusion

Experimental work on fatigue crack growth rate studies highlight the importance of understanding microcrack growth in WC-Co. The early stage of fatigue in WC-Co, which is mainly dominated by the microcrack evolution, distinguishes the overall fatigue resistance of different grades at component scale. Most of the work conducted in literature pay minor attention to this fact and results are generally provided based on empirical generalizations.

In this study, a previously generated damage model validated by the experimental studies was extended to investigate the fatigue performance of hardmetals based on artificial microstructures. In this regard, initially a three dimensional microstructure containing 80 wt. % WC was generated. From this reference model two grades of 80 and 90 wt. % WC containing WC-Co microstructures were prepared.

Both models were subjected to multiaxial cyclic loads and the evolution of the micro crack was observed. Based on the results of the simulations, fatigue crack growth diagrams similar to experimental studies were plotted. Although some discrepancies were observed, the results of the study showed generally good agreement with respect to experimental observations. The approach has the potential to generate a predictive tool for evaluating the performance of hardmetals at a microstructural scale. In the next phases, the approach will be further tested with additional microstructures.

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