

# **Finite Element Simulation of Fatigue Crack Growth in Hardmetal**

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# Zusammenfassung

Die mikromechanischen Mechanismen der Rissausbreitung unter statischer Belastung in WC-Co (Hartmetallen) sind bereits ausgiebig untersucht und verstanden worden. Untersuchungen zur Rissausbreitung unter schwingender Beanspruchung werden hingegen vorwiegend auf experimenteller Basis auf Bauteilebene und selten unter Berücksichtigung der mikrostrukturellen Einflüsse auf die Mechanismen der Rissausbreitung in Hartmetallen durchgeführt. Weiterhin werden selten numerische Studien zur Rissausbreitung unter zyklischer Beanspruchung durchgeführt.

Experimentelle Beobachtungen weisen darauf hin, dass sich das Schädigungsverhalten von Hartmetallen aus den frühen Stufen der Mikrorissausbreitung ableiten lässt. Unter Berücksichtigung dieser Erkenntnis wurde eine numerische Methode zur Untersuchung der Rissausbreitung in Hartmetallen unter schwingender Beanspruchung entwickelt.

Auf Basis dieses Hintergrunds wurde ein kontinuumsmechanisches Schädigungsmodell in Kombination mit einer Technik zur Element Elimination in ein kommerzielles Finite-Elemente-Programm implementiert, um die Rissausbreitung in WC-Co-Hartmetallen zu simulieren. Hierzu wurden unterschiedliche Schädigungshypothesen, welche auf der Annahme von sprödem Versagen und Werkstoffermüdung beruhen, zur Beschreibung des Werkstoffverhaltens der einzelnen Werkstoffphasen WC und Co eingesetzt. Die Materialparameter für die Karbidphase wurden aus der Literatur entnommen, wo hingegen die Parameter für die Binderphase experimentell an einem Modellbinderwerkstoff auf Co-Basis bestimmt wurden, dessen Zusammensetzung als repräsentativ für die Binderphase in kommerziell erhältlichen Hartmetallen angesehen werden kann.

Zur Verifikation des numerischen Ansatzes wurden numerische Modelle basierend auf realen (vorgeschädigten) und künstlichen Mikrostrukturen erstellt. Als Ergebnis wird festgehalten, dass das Modell die Rissausbreitung in WC-Co-Hartmetallen unter zyklischer Beanspruchung in zufriedenstellender Übereinstimmung mit experimentell beobachteten Rissverläufen vorhersagen kann.



## Abstract

WC-Co cemented carbides (hardmetals) are a group of composite materials exhibiting outstanding combinations of hardness and toughness. As a consequence, 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 is 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.

Within this context, 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 the material. Separate damage laws, based on brittle failure and fatigue, were used for describing the mechanical response of WC and Co phases, respectively. Material parameters for the carbide phase were taken from literature, whereas those for the metallic phase were experimentally determined in a model binder-like Co-base alloy, i.e. one with a composition representative of the binder phase within a commercial hardmetal grade.

In order to validate the approach used, numerical models based on both the real (damaged) and artificial microstructures was generated. It is found that, proposed model is capable of capturing damage evolution with cyclic loading in WC-Co, as numerical results reflect satisfactory agreement with real crack pattern resulting from experiments.





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# Nomenclature

## Scalars –

### Alphabetical Symbols

$a$	Crack length
$A$	Area
$c$	Contiguity
$C$	Kinematic hardening modulus
$C_p$	Material constants for crack growth
$da/dN$	Crack velocity
$d_{wc}$	Average WC grain size
$D$	Damage indicator
$\bar{D}$	Damage flag
$E$	Elastic modulus
$F$	Force
$G$	Shear modulus
$G_I$	Strain energy release rate
$h$	Unified damage law exponent
$H$	Energetic damage law parameter
$I_1, I_2, I_3$	Invariants of the Cauchy stress
$J_1, J_2, J_3$	Invariants of the deviatoric Cauchy stress
$k$	Thermal expansion coefficient
$k$	Yield stress in pure shear
$K_I$	Stress intensity factor
$K_{Ic}$	Fracture toughness
$l$	Length

$m$	Material constants for crack growth
$n$	Material constants for crack growth
$N$	Number of cycles
$N_f$	Number of cycles for instability
$N_{WC/Co}$	Number of WC-Co interfaces
$N_{WC/WC}$	Number of WC-WC interfaces
$r$	Isotropic hardening variable
$R$	Isotropic hardening stress
$R$	Load (stress) ratio
$R_m$	Ultimate stress
$R_v$	Triaxility function
$s$	Specific entrophy
$S$	Virgin area
$\bar{S}$	Resisting area
$S_D$	Damaged area
$T$	Period
$T$	Temperature
$U_x, U_y, U_z$	Displacement in the x, y and z directions
$\nu$	Frequency
$V_{Co}$	Volume fraction of the Co
$W$	Strain energy
$Y$	Geometric correction factor

**Scalars –  
Greek Symbols**

$\varepsilon_f$	Rupture strain
$\lambda_{Co}$	Mean free path of the Co binder
$\sigma$	Stress
$\sigma_1, \sigma_2, \sigma_3$	Principal stresses
$\sigma_H$	Hydrostatic stress
$\sigma_L$	Fatigue strength
$\sigma_R$	Rupture stress
$\sigma_y$	Yield stress
$\sigma_{y0}$	Initial yield limit
$\psi_T$	Thermal state potential
$\psi_e^*$	Elastic specific free enthalpy
$\psi_p$	Plastic hardening
$\psi_{pl}$	Plastic dissipation
$\Delta K$	Stress intensity range
$\Delta l$	Deformation
$\Delta K_{th}$	Threshold stress intensity range
$\Gamma$	Energy density release rate
$\gamma$	Dynamic rate of backstress
$\varepsilon$	Strain
$\eta$	Stress triaxility
$\lambda$	Lame's first parameter
$\nu$	Poisson's ratio
$\rho$	Density

$\psi$  Helmholtz free energy

### **Symbols – Matrices, Vectors, Tensors**

$\alpha$  Back stress tensor

$\mathcal{C}$  Elasticity matrix of moduli

$\mathcal{C}^{-1}$  Elasticity matrix of compliances

$\varepsilon$  Strain tensor

$\varepsilon^{el}$  Elastic strain tensor

$\varepsilon^{pl}$  Plastic strain tensor

$s$  Internal variables

$\sigma$  Stress tensor

$\Sigma$  Macroscopic (global) stress tensor

$\varphi$  Kinematic hardening variable

### **Superscripts and subscripts**

$\tilde{x}$  Effective value of  $x$

$x_0$  Original value of  $x$

$x_C$  Critical value of  $x$

$x^D$  Deviatoric part of  $x$

$x_a$  Amplitude of  $x$

$x_{eng}$  Engineering value of  $x$

$x_{eq}$  Equivalent of  $x$

$x_{kk}$  Trace of  $x$

$x_m$  Mean value of  $x$

$x_{max}$  Maximum value of  $x$

$x_{min}$	Minimum value of $x$
$x_{ref}$	Reference value of $x$
$x_{true}$	True value of $x$
$x_{xx}, x_{yy}, x_{xy}$	Components of $x$

## Abbreviations

APT	Ammonium paratungstate
cBN	Cubic boron nitride
CDM	Continuum damage modelling
CT	Compact tension
CVD	Chemical vapor deposition
DCB	Double cantilever beam
f.c.c	Face centered cubic
FCG	Fatigue crack growth
FCGR	Fatigue crack growth rate
FEM	Finite element method
FGHM	Functionally graded hardmetals
h.c.p	Close-packed hexagonal
HCF	High cycle fatigue
HIP	Hot isotactic pressing
LCF	Low cycle fatigue
LEFM	Linear elastic fracture mechanics
MLZ	Multi ligament zone
PEG	Polyethylene glycol
PVD	Physical vapor deposition
SEM	Scanning electron microscope



SENB	Single edged notched beam
SHS	Self-propagating high-temperature synthesis
SPS	Spark plasma sintering
TRS	Transverse rupture strength
VUMAT	User defined material subroutine
wt.	Weight
XRD	X-ray diffraction