Finite Element Simulation of Fatigue Crack Growth in Hardmetal

Von der Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Ingenieurwissenschaften genehmigte Dissertation

von

Utku Ahmet Özden

Berichter: Univ.-Prof. Dr.-Ing. Christoph Broeckmann

Prof. Luis Miguel Llanes Pitarch

Tag der mündlichen Prüfung: 9. Oktober 2015

Werkstoffanwendungen im Maschinenbau
hrsg. von Prof. Dr.-Ing. Christoph Broeckmann

Band 7

Utku Ahmet Özden

Finite Element Simulation of Fatigue Crack Growth in Hardmetal

Shaker Verlag
Aachen 2015

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: D 82 (Diss. RWTH Aachen University, 2015)

Printed in Germany.

ISBN 978-3-8440-4098-2
ISSN 2195-2981

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen
Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9
Internet: www.shaker.de • e-mail: info@shaker.de

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 Binderpahse 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.

Acknowledgements

This thesis work is the result of many nice coincidences in my life, which lead to me for a Ph.D. study in Germany. Coincidences alone however, would not help me accomplish this challenging task without the support of many valuable people, whom I would like to emphasize my thanks and gratitude.

First, I would like to thank my dear wife Mrs. Sibel Şener Özden for her intensive support and love towards me over the years. Without her encouragement and endless support, I would not find the motivation to pursue such a challenging task. Thank you Sibel, I am very lucky to have you in my life.

I would like to greatly acknowledge and thank Prof. Dr. –Ing. Christoph Broeckmann for his belief in my motivation and his long lasting guidance and support towards realizing this thesis. In this regard, I would as well like to thank my friend and my colleague Dipl. –Ing. Alexander Bezold, who was always there to help me, with whatever challenge I have encountered throughout my study in Germany.

This thesis would not be realized in the first place, if Dr. –Ing. Atılım Eser did not encouraged and supported me towards a Ph.D. study in Germany. From the first day my arrival to Germany, he was always there to support me. Therefore, I would like to thank my very best friend for his never-ending support along this way.

I had the opportunity to work with some very talented and hardworking individuals over the years. In this regard, I would like to thank my former assistants M.Sc. Geng Chen, M.Sc. Serhan Kurtaraner and especially M.Sc. Keng Jiang for their friendship and the great work they have conducted over the years.

I would like to give my special thanks to Prof. Luis Llanes for his willingness to serve on my thesis defense committee and for his support and guidance during the preparation of this work. In this regard, I would also like to acknowledge my colleagues Dr. Álvaro Mestra and M.Sc. Jose María Tarragó from CIEFMA UPC for their support with some of the experimental work conducted in this thesis.

Special thanks go to all my colleagues and staff members in IWM, for their kindness and support with many technical and administrative topics. It has been a great pleasure for me to work with such distinguished individuals.

I would like to thank the members of my family, without whom none of these would be possible. In this regard, I would like to thank my uncle Mr. Cihan Dağ, my aunt Mrs. Nuran Tanırcan, my grandmother Mrs. Hatice Dağ and my late father Mr. Hasan Özden for their endless support.

Finally, I see myself one of the luckiest individuals to have a great brother and a caring mother. In this respect, I would like to send my gratitude to my brother Mr. Ufuk Özden and my mother Mrs. Şükran Özden for their never-ending love and support through all stages of my life.

Table of Contents

List of Figures

List of Tables

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_ν	Triaxility function
s	Specific entrophy
S	Virgin area
$\bar{S}$	Resisting area
S_D	Damaged area
T	Period
T	Temperature
Ux,Uy,Uz	Displacement in the x, y and z directions
v	Frequency
V_{Co}	Volume fraction of the Co
W	Strain energy
Y	Geometric correction factor

Scalars –

Greek Symbols

ε_f	Rupture strain
λ_{Co}	Mean free path of the Co binder
σ	Stress
$\sigma_1, \sigma_2, \sigma_3$	Principal stresses
σ_H	Hydrostatic stress
σ_L	Fatigue strength
σ_R	Rupture stress
σ_y	Yield stress
σ_{y0}	Initial yield limit
ψ_T	Thermal state potential
ψ_e^*	Elastic specific free enthalpy
ψ_p	Plastic hardening
ψ_{pl}	Plastic dissipation
ΔK	Stress intensity range
Δl	Deformation
ΔK_{th}	Threshold stress intensity range
Γ	Energy density release rate
γ	Dynamic rate of backstress
ε	Strain
η	Stress triaxility
λ	Lame's first parameter
ν	Poisson's ratio
ρ	Density

ψ	Helmholtz free energy

Symbols – Matrices, Vectors, Tensors

$\boldsymbol{\alpha}$	Back stress tensor
$\boldsymbol{C}$	Elasticity matrix of moduli
$\boldsymbol{C}^{-1}$	Elasticity matrix of compliances
$\boldsymbol{\varepsilon}$	Strain tensor
$\boldsymbol{\varepsilon}^{el}$	Elastic strain tensor
$\boldsymbol{\varepsilon}^{pl}$	Plastic strain tensor
$\boldsymbol{s}$	Internal variables
$\boldsymbol{\sigma}$	Stress tensor
$\boldsymbol{\Sigma}$	Macroscopic (global) stress tensor
$\boldsymbol{\varphi}$	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