Multi-scale Model for Fatigue in Carbide-rich Tool Steel

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

von

Ngoc Anh Giang

Berichter: Univ.-Prof. Dr.-Ing. Christoph Broeckmann
Univ.-Prof. Dr.-Ing. Dr. h. c. (UA) Dieter Weichert

Tag der mündlichen Prüfung: 30. Oktober 2014

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

Band 6

Giang Ngoc Anh

Multi-scale Model for Fatigue in Carbide-rich Tool Steel

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, 2014)

Printed in Germany.

ISBN 978-3-8440-3748-7
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

Karbideiche Werkzeugstähle werden nicht nur in der Werkzeugindustrie, sondern auch für Maschinenelemente wie z.B. Lager, Dieselinjektoren und Verbindungselemente eingesetzt. Bauteile aus diesen Materialien sind häufig zyklischer Beanspruchung ausgesetzt. Ermüdung ist als wichtigste Versagensursache anzusehen, weil das Versagen ungefähr 90% aller metallischen Bauteile auf diese Fehlerursache zurückzuführen ist [1]. Werkzeugstähle sind ebenfalls empfindlich gegenüber schwingender Beanspruchung. Die Ermüdungsfestigkeit dieser Werkstoffe hängt zudem empfindlich von den mikrostrukturellen Eigenschaften wie der Form, dem Grössenverhältnis, dem Volumenanteil und der Verteilung von primären und eutektischen Karbiden ab. Deshalb, werden neben dem Lastkollektiv die mikrostrukturellen Eigenschaften als die wichtigsten Einflussfaktoren auf die Lebensdauer von Werkzeugkomponenten angesehen.

Es ist bekannt, dass die Lebensdauervorhersage von Karbidreichen Werkzeugstählen unter schwingender Beanspruchung keine einfache Aufgabe ist. Aus diesem Grund ist es wichtig eine Wissensbasis über die Einflüsse der mikrostrukturellen Eigenschaften der Werkstoffe auf das Versagensverhalten aufzubauen. Das Hauptziel dieser Arbeit besteht darin schrittweise ein einfaches Modell sowie einen Rahmen zur numerischen Untersuchung der Einflüsse der mikrostrukturellen Eigenschaften auf die Langzeitfestigkeit (HCF) zu erstellen.

Im Allgemeinen kann die Ausbreitung des Schwingbruchs in drei Stufen eingeteilt werden: Die anfängliche Rissbildung (Rissinkubation), Kurz- und Langrisswachstum. Diese drei Stufen des Risswachstums wurden von McDowell [2] erfolgreich in einem so genannten mehrskaligen Versagensmodell (MSF) abgebildet. Um das Ermüdungsverhalten von Karbidreichen Werkzeugstählen zu modellieren, wurde das Modell von McDowell modifiziert und weiterentwickelt, um drei Längenskalen in Betracht ziehen zu können und ein mehrskaliges Ermüdungsmodell zu erhalten. Zur Darstellung der anfänglichen Rissbildung und des frühen Wachstumsstadium, wurde ein hierarchischer Ansatz angewandt und die Verweildauer in diesen Stadien durch ein Repräsentatives Volumen Element (RVE) unter Einbezug der lokalen zyklischen Mikroplastizität abgeschätzt. Die Stufe des Kurzrisswachstums setzt sich aus dem mikrostrukturellen Kurzriss- (MSC) und dem physikalischen Kurzrisswachstum (PSC) zusammen. Für das Kurzrisswachstum wurde die zyklische Verschiebung an der Öffnung an der Rissspitze (ΔCTOD) als die treibende Kraft identifiziert. Von dieser Beziehung ausgehend wurde die Auswirkungen der mikrosturukturellen Ausprägung des Werkstoffs auf das zyklische Kurzrisswachstum explizit bestimmt. Zur Berechnung der Zeitdauer des Langzeitrisswachstums wurde ein Schadensakkumulationskonzept implementiert. Unter der Annahme, dass die Ausbreitungsrate des Langrisswachstums aus den Kennwerten zur Kurzeitfestigkeit (LCF) abgeleitet werden kann, welche sich aus den Ergebnissen von zyklischen Zugversuchen interpolieren lassen [3], konnten Zeitsparend die Parameter zur Lebensdauerberechnung bestimmt werden.

Der wichtigste Beitrag dieser Studie besteht in der Simulation und Modellierung der Einflüsse von Karbiden auf die Mechanismen der Ermüdungsrissausbreitung auf drei unterschiedlichen Längenskalen. Das vorgeschlagene Modell wird als starkes Werkzeug angesehen, um sowohl die Lebensdauer von Werkzeugstählen als auch von partikelverstärkten Kompositwerkstoffen und anderen heterogenen Materialien vorherzusagen. Auf Basis des in der Studie vorgestellten Modells kann eine Optimierung der mikrostrukturellen Eigenschaften der o.g. Materialklassen durchgeführt werden. Die Optimierung kann in einer Erhöhung der Betriebszeiten resultieren.

ABSTRACT

Title: Multi-scale model for fatigue in carbide-rich tool steel

Carbide-rich tool steel is most commonly used not in the tooling industry, but also in engine parts, e.g. springs, bearings, diesel injections, connecting rods etc.. Components made from this kind of material are often subjected to cyclic mechanical stresses. Fatigue is important as it occupies the largest cause of failure in metal, approximately estimated 90% of all metallic failures [1], tool steels are also susceptible to this type of failure. Fatigue resistance of this material strongly depends on the microstructural features including shapes, shape ratio, volume fractions, and distributions of primary and eutectic carbides. Thus, besides loading condition microstructural features are considered as the main factor which influences lifetime of tool components.

It is known that the lifetime prediction of carbide-rich tool steel in alternating applied stress is not an easy task to perform. Therefore, gaining knowledge about the effects of microstructural features on the fatigue behavior of this material is necessary. Subsequently, the main objective of this research is to develop a simple model as well as a computational framework to quantify the influence of these microstructural features on the fatigue behavior of the material in the high cycle fatigue (HCF) regime.

In general, fatigue crack mechanisms can be divided into 3 stages: initial crack formation (crack incubation or nucleation), short crack and long crack growth, which have successfully been established by McDowell [2], in a so-called multistage fatigue model (MSF). To model fatigue behavior of carbide rich tool steel, McDowell's model was modified and developed at three length-scale levels, resulting in a multi-scale fatigue model. For fatigue crack formation and early growth, a hierarchical approach was used, and lifetime of this stage was estimated based on local cyclic micro plasticity within a representative volume element (RVE). The short crack stage consists of microstructurally short crack (MSC) and physically short crack (PSC) growth in which short crack driving force was determined from the process zone at the crack tip, so-called cyclic crack tip opening displacement (ΔCTOD). From this relation, the effects of microstructural features on the cyclic short crack growth were explicitly identified. For long crack growth, an accumulated fatigue damage concept was implemented to calculate the lifetime of this stage. Based on that relation, the long crack growth rate was easily derived from low cycle fatigue (LCF) properties because it is believed that LCF test is easy to calibrate and it may be interpolated from monotonic tensile test [3], which results in saving time and cost for fatigue prediction.

The most important contributions of this study are to simulate and model the influence of carbides on three different length scales of fatigue crack mechanisms in tool steels. The proposed model is considered as a powerful tool for lifetime prediction not only in tool steels, but also in particle reinforced composites and other heterogeneous materials. Moreover, optimization process on microstructural features can be done based on the results of this study. Consequently, the in-service life of materials may be improved.

Keywords: High Cycle Fatigue, Tool Steel, Fatigue Crack Incubation, Short Crack, Long Crack, Multi-scale Fatigue Model.

CONTENTS

DECLARATION

I, Giang Ngoc Anh, declare that this thesis titled: 'Multi-scale model for fatigue of carbide-rich tool steel' and the work presented in it are my own. I confirm that:

- This work was done mainly while in candidature for a research degree at IWM-RWTH Aachen and no portion of the work referred to in this thesis has previously been submitted for a degree or any other qualification at other university or at any other institution.
- Any material previously published or written by another person that is always clearly attributed in the text.
- I have acknowledged all main sources of help. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

____

Date: October 30, 2014

ACKNOWLEDGEMENTS

This work was created during my research at the institute for Materials Applications in Mechanical Engineering (IWM) of RWTH Aachen, Germany.

There are many people who have made this work possible. First of all, I am truly grateful to my thesis advisor, Prof.Dr.-Ing: C.Broeckmann, head of the above institute for his patience, guidance and great support doing this work. He provided me with this opportunity to pursue a Ph.D. at the IWM of RWTH Aachen. He has influenced my career by teaching me work ethics and responsibilities, along with research skills, which are required of a good researcher.

I would also like to thank Prof. D. Weichert for his willingness to serve on my thesis defense committee and for his valuable comments and suggestions.

Secondly, I would like to thank Mr. A.Bezold for his help, advice, discussions, and also technical input in my Ph.D. work.

I further acknowledge the help of Mr. S. Kempen in proofreading and for his valuable advice.

Thirdly, I want to thank the Vietnam Forestry University, where I work, which helped and gave me a chance to study in Germany. The financial support of the work by the Ministry Of Education and Training of Vietnam (MOET) and DAAD is also gratefully acknowledged.

I wish to acknowledge all my colleagues at IWM for their help and for their contribution to a warm working environment at the institute.

Furthermore, I want to thank to my family and especially my lovely wife, Thuy Anh, for her support in all circumstances in my life, her endless energy, encouragements and sympathy throughout my involvement with the work.

Lastly, I cannot leave behind all the people who helped me in my academic work. Special thanks to all the friends who encouraged and helped me achieve this goal...

Giang Ngoc Anh
Aachen, Germany, October 30, 2014

NOMENCLATURES

1. List of Abbreviations

AISI	American Iron and Steel Institute
BCC	Body Center Cubic
CTOD	Crack Tip Opening Diplacement
DIN	Deutsches Institut f*ü*r Normung
DS	Directionally Solidified
expt	Experiment
ε-N	Strain - Number of cycles
FEA	Finite Element Analysis
FEM	Finite Element Method
FDZ	Fatigue Damage Zone
FS	Fatemi-Socie parameter
GBF	Granular Bright Face
GO	Grain Orientation
GS	Grain Size
HCF	High Cycle Fatigue
HIP	Hot Isostatic Pressing
HP	Hard Phase
HSS	High Speed Steels/Carbide-rich Tool Steel
HWS	Hot Work tool Steels
INC	Incubation
JIS	Japanese Industrial Standard
LC	Long Crack
LCF	Low Cycle Fatigue
LEFM	Linear Elatic Fracture Mechanics
LENS	Laser Engineered Net Shaping
M3:2	M3 class 2
MMC	Metal Matrix Composite
MP	Matrix Phase
Mo-alloys	Molybdenum alloys
MSC	Microstructurally Small/Short Crack
MSF	Multi-Stage Fatigue
PBCs	Periodic Boundary Conditions
PSBs	Persistent Slip Bands
PEEQ	Equivalent Plastic Strain

PM	Powder Metallurgy
PSC	Physically Small/Short Crack
RVE	Representative Volume Element
sc	short crack
SCG	Short Crack Growth
SEM	Scanning Electron Microscope
SF	Spray Forming
S-N	Stress - Number of cycles
SWT	Smith-Watson-Topper parameter
th	threshold
VHCF	Very High Cycle Fatigue
w.%	Weight percentage

2. Symbol

Symbol	**Description**
a	crack length
a_o	initial crack length/intrinsic crack
a_D	critical defect
a_{inc}	incubation crack length
a_f	final crack length
$A_{carbide}$	the area of a carbide
$A_{local\_plas\_zone}$	local plastic zone area
A_p	coefficient of Paris's law
a_{sc}	short crack length
b	fatigue strength exponent
c	fatigue ductility exponent
$\bar{c}$	kinematic modulus
$\bar{C}$	power law coefficient
$C_{I,II}$	coefficient of short crack growth
C_p	coefficient of Paris' law
c_s	surface crack
C_{sc}	coefficient of short crack law
C_ε	adhesive coefficient
D	square root of carbide area
$\bar{D}$	plasticity damage parameter
da/dN	crack growth rate
$da/dN\|_{msc/psc}$	msc/psc crack growth rate
$da/dN\|_{sc}$	short crack growth rate
$da/dN\|_{lc}$	long crack growth rate
D_c	size of cyclic plastic zone
$\bar{D}$	damage indicator
$\bar{D}_c$	critical damage indicator
DCR	cluster diameter of carbides

D_{cr}	critical size defect
D_{FDZ}	fatigue damage plastic zone or process zone
d	diameter of a specimen
D_m	size of monotonic plastic zone
d_g	autensitic grain size
d_o	characteristic length of dislocations
$\bar{D}_p$	average grain size
D_p	equivalent diameter of carbide
d_s	strongest microstructural barrier
D_{sp}	diameter of spherical carbide clusters
$\dot{\bar{D}}$	rate of plasticity damage parameter
E	Young's modulus
F	strengthening ratio
$\bar{F}$	coefficient of the cumulative distribution function
f^*	calculated void volume fraction
f	actual void volume fraction
f_c	void volume fraction at failure
f_{crit}	critical void volume fraction
h	length/height of carbide
$\bar{k}$	exponent of the cumulative distribution function
k_o	power law exponet
K^*	interaction coefficient of tension and torsion
K	hardening coefficient
K'	cyclic hardening coefficient
K_{max}	maximum applied stress intensity factor
K_{min}	minimum applied stress intensity factor
K_{op}	crack opening stress intensity factor
K_y	coefficient of Hall-Petch's equation
L	dimension of RVE model
l_s	characteristic length of microstructural features
m_p	exponent of Paris' law
m_{sc}	exponent of short crack law
$\bar{n}$	a certain number of critical defects
n	hardening exponent
n'	cyclic strain hardening exponent
N_f	number of cycles to failure
N_{inc}	number of cycles to fatigue crack incubation
N_∞	infinity life
$N_{smc/psc}$	number of cycles to microstructurally/physically small crack
N_{sc}	number of cycles to short crack growth
N_{lc}	number of cycles to long crack
N_o	number of cycles to failure to limit of LCF
N_T	total lifetime
N_{T^*}	transition lifetime
N^*	number of cycles to crack though the process zone

P_f	fracture probability
r	polar position from crack tip
$\bar{r}$	dynamic rate of back stress tensor
R	stress/strain ratio
R_ε	strain ratio
R_σ^*	stress/strain ratio in the process zone
$s = h/w$	shape ratio (length/width)
S	area of fatigue damage zone
S_p	mean free path of carbides
S_{ij}	deviatoric part of stress tensor
s_{sp}	striation spacing
V	unit volume
V_p	volume fraction of carbide
V_m	volume fraction of martensitic steel
U	load ratio function
$U_x\|_{appl.}$	applied displacement in X direction
$U_y\big\|_{appl.}$	applied displacement in Y direction
u_y	applied displacement in Y direction
Y	geometry correction factor
w	width (diameter) of carbide
α_{ij}	back stress tensor
α	fatigue crack incubation exponent
α'_{ij}	deviatoric part of back stress tensor
$\beta = -(b+c)$	fatigue power law exponent
χ	coefficient of msc/psc crack growth
δ	distance to free surface
Δa	crack length increment
$\Delta CTOD$	crack tip opening displacement
$\Delta CTOD_{th}$	crack tip opening displacement threshold
$\Delta\bar{D}$	increment of plasticity damage parameter
$\Delta\bar{D}_S$	increment of plasticity damage over stabilization cycle
ΔJ	cyclic J integral
ΔK	stress intensity factor
ΔK_{eff}	effective stress intensity
$\Delta\bar{K}_{eff}$	effective stress intensity in bulk composite
$\Delta K_{eff,th}$	effective threshold stress intensity factor
ΔK_{th}	threshold stress intensity factor
$\Delta K_{th,lc}$	threshold stress intensity factor for long crack
$\Delta K_{th,R}$	threshold stress intensity factor as a function of load ratio
$\Delta K_{th,sc}$	threshold stress intensity factor for short crack
ΔK_T	threshold stress intensity for transition region
$f\left(\sigma_{ij} - \alpha_{ij}\right)$	von Mises flow surface
$\varepsilon_{pl,n}$	normal plastic strain on a critical plane
$\Delta\varepsilon^I_{pl,ij}$	different plastic strain on the critical plane
$\Delta\varepsilon_{pl}$	plastic strain range

$\gamma_{pl,n}$	plastic shear strain on a critical plane
$\Delta\Gamma$	Fatemi-Socie parameter
Γ_{ij}	boundary of RVE (i,j =1,2)
$\frac{\Delta\gamma^{p*}_{max}}{2}$	maximum cyclic plastic shear strain range
$\left.\frac{\Delta\gamma^{p*}_{max}}{2}\right\|_{macro}$	remote applied plastic shear strain range
ε_a	remote strain amplitude
ε_C	equivalent plastic strain at initial damage
ε'_f	fatigue ductility coefficient
ε_R	equivalent plastic strain at final failure
$\dot{\varepsilon}^{pl}_{eq}$	rate of equivalent plastic strain
$\varepsilon_{pl,ij}$	plastic strain tensor
ε^*_{pl}	plastic strain over fatigue damage zone
ε^{pl}_{eq}	equivalent plastic strain
φ	angle of critical plane
$\varphi(f)$	function of void volume fraction
θ	polar angle in the cyclic plastic zone
ℓ	square root of local plastic zone area
κ	flow stress exponent
$\bar{\lambda}_c$	an expected number of critical defects
λ	correction factor
η	stress triaxiality
ω	frequency of applied loading
Ω	volume of local plastic zone
Π	potential energy per unit volume
Π_{int}	interaction energy per unit volume
Φ	von Mises plastic flow
ψ	correction factor of cyclic J integral
ρ_c	radius of crack blunting
$\Delta\sigma$	stress range
$\Delta\sigma_o$	stress threshold range
$\Delta\sigma^I_{ij}$	different stress on the critical plane
σ_a	remote stress amplitude
σ_{eq}	equivalent stress (von Mises stress)
σ'_f	fatigue strength coefficient
$\sigma^{carbide}_f$	fracture strength of a carbide
σ_f	strength (flow stress) of a fiber/particle
σ_H	hydrostatic stress
σ_I	instantaneous principle stress
σ_{ij}	stress tensor
σ_∞	coefficient of flow stress
σ_{iso}	flow stress
σ_{max}	maximum stress in the process zone
σ_{min}	minimum stress in the process zone

$\sigma_{max}^{carbide}$	maximum stress within a carbide
σ_m	strength (flow stress) of matrix phase
σ_m^*	mean stress within process zone
σ_n^{max}	normal stress on a critical plane
$\Delta\sigma_{ult}$	range of fracture strength
$\Delta\sigma_{ult}$	range of fracture strength
$\Delta\hat{\sigma}$	equivalent applied stress range
$\sigma_{p,C}$	strength of bulk composite
$\sigma_{p,M}$	strength of the matrix phase-soft phase
$\sigma'_{p,C}$	cyclic yield strength of composite material
σ^o	initial yield strength of material
σ_y	yield strength of bulk material
σ'_y	cyclic yield strength of bulk material
$\sigma'_{p,M}$	cyclic yield strength of the matrix phase
σ_{ult}	ultimate tensile stress