Contents

Foreword *VII*

Preface *IX*

Symbols and Abbreviations *XV*

1 Introduction *1*

2 Basic Concepts of Metal Fatigue and Fracture in the Engineering Design Process *3*

2.1 Historical Overview *3*

2.2 Metal Fatigue, Crack Propagation and Service-Life Prediction: A Brief Introduction *10*

2.2.1 Fundamental Terms in Fatigue of Materials *12*

2.2.2 Fatigue-Life Prediction: Total-Life and Safe-Life Approach *15*

2.2.3 Fatigue-Life Prediction: Damage-Tolerant Approach *19*

2.2.4 Methods of Fatigue-Life Prediction at a Glance *24*

2.3 Basic Concepts of Technical Fracture Mechanics *25*

2.3.1 The *K* Concept of LEFM *27*

2.3.2 Crack-Tip Plasticity: Concepts of Plastic-Zone Size *31*

2.3.3 Crack-Tip Plasticity: The *J* Integral *34*

3 Experimental Approaches to Crack Propagation *39*

3.1 Mechanical Testing *39*

3.1.1 Testing Systems *39*

3.1.2 Specimen Geometries *43*

3.1.3 Local Strain Measurement: The ISDG Technique *46*

3.2 Crack-Propagation Measurements *48*

3.2.1 Potential-Drop Concepts and Fracture Mechanics Experiments *49*

3.2.2 *In Situ* Observation of the Crack Length *54*

3.3 Methods of Microstructural Analysis and Quantitative Characterization of Grain and Phase Boundaries *56*

3.3.1 Analytical SEM: Topography Contrast to Study Fracture Surfaces *56*

3.3.2 SEM Imaging by Backscattered Electrons and EBSD *58*
3.3.3 Evaluation of Kikuchi Patterns: Automated EBSD *62*
3.3.4 Orientation Analysis Using TEM and X-Ray Diffraction *63*
3.3.5 Mathematical and Graphical Description of Crystallographic Orientation Relationships *65*
3.3.6 Microstructure Characterization by TEM *70*
3.3.7 Further Methods to Characterize Mechanical Damage Mechanisms in Materials *72*
3.4 Reproducibility of Experimentally Studying the Mechanical Behavior of Materials *74*

4 Physical Metallurgy of the Deformation Behavior of Metals and Alloys *75*
4.1 Elastic Deformation *76*
4.2 Plastic Deformation by Dislocation Motion *80*
4.3 Activation of Slip Planes in Single- and Polycrystalline Materials *90*
4.4 Special Features of the Cyclic Deformation of Metallic Materials *94*

5 Initiation of Microcracks *99*
5.1 Crack Initiation: Definition and Significance *99*
5.1.1 Influence of Notches, Surface Treatment and Residual Stresses *100*
5.2 Influence of Microstructual Factors on the Initiation of Fatigue Cracks *101*
5.2.1 Crack Initiation at the Surface: General Remarks *101*
5.2.2 Crack Initiation at Inclusions and Pores *102*
5.2.3 Crack Initiation at Persistent Slip Bands *104*
5.3 Crack Initiation by Elastic Anisotropy *107*
5.3.1 Definition and Significance of Elastic Anisotropy *107*
5.3.2 Determination of Elastic Constants and Estimation of the Elastic Anisotropy *109*
5.3.3 FE Calculations of Elastic Anisotropy Stresses to Predict Crack Initiation Sites *113*
5.3.4 Analytical Calculation of Elastic Anisotropy Stresses *116*
5.4 Intercrystalline and Transcrystalline Crack Initiation *119*
5.4.1 Influence Parameters for Intercrystalline Crack Initiation *119*
5.4.2 Crack Initiation at Elevated Temperature and Environmental Effects *123*
5.4.3 Transgranular Crack Initiation *126*
5.5 Microstructurally Short Cracks and the Fatigue Limit *127*
5.6 Crack Initiation in Inhomogeneous Materials: Cellular Metals *129*

6 Crack Propagation: Microstructural Aspects *135*
6.1 Special Features of the Propagation of Microstructurally Short Fatigue Cracks *135*
6.1.1 Definition of Short and Long Cracks *136*

6.2 Transgranular Crack Propagation *139*
6.2.1 Crystallographic Crack Propagation: Interactions with Grain Boundaries *139*
6.2.2 Mode I Crack Propagation Governed by Cyclic Crack-Tip Blunting *145*
6.2.3 Influence of Grain Size, Second Phases and Precipitates on the Propagation Behavior of Microstructurally Short Fatigue Cracks *149*
6.3 Significance of Crack-Closure Effects and Overloads *153*
6.3.1 General Idea of Crack Closure During Fatigue-Crack Propagation *153*
6.3.2 Plasticity-Induced Crack Closure *156*
6.3.3 Influence of Overloads in Plasticity-Induced Crack Closure *160*
6.3.4 Roughness-Induced Crack Closure *161*
6.3.5 Oxide- and Transformation-Induced Crack Closure *162*
6.3.6 $\Delta K^*/K^*_{max}$ Thresholds: An Alternative to the Crack-Closure Concept *163*
6.3.7 Development of Crack Closure in the Short Crack Regime *164*
6.4 Short and Long Fatigue Cracks: The Transition from Mode II to Mode I Crack Propagation *171*
6.4.1 Development of the Crack Aspect Ratio a/c *173*
6.4.2 Coalescence of Short Cracks *179*
6.5 Intercrystalline Crack Propagation at Elevated Temperatures: The Mechanism of Dynamic Embrittlement *181*
6.5.1 Environmentally Assisted Intercrystalline Crack Propagation in Nickel-Based Superalloys: Possible Mechanisms *181*
6.5.2 Mechanism of Dynamic Embrittlement as a Generic Phenomenon: Examples *187*
6.5.3 Oxygen-Induced Intercrystalline Crack Propagation: Dynamic Embrittlement of Alloy 718 *192*
6.5.4 Increasing the Resistance to Intercrystalline Crack Propagation by Dynamic Embrittlement: Grain-Boundary Engineering *197*

7 Modeling Crack Propagation Accounting for Microstructural Features *207*
7.1 General Strategies of Fatigue Life Assessment *207*
7.2 Modeling of Short-Crack Propagation *211*
7.2.1 Short-Crack Models: An Overview *211*
7.2.2 Model of Navarro and de los Rios *218*
7.3 Numerical Modeling of Short-Crack Propagation by Means of a Boundary Element Approach *226*
7.3.1 Basic Modeling Concept *226*
7.3.2 Slip Transmission in Polycrystalline Microstructures *230*
7.3.3 Simulation of Microcrack Propagation in Synthetic Polycrystalline Microstructures *232*
7.3.4 Transition from Mode II to Mode I Crack Propagation *236*

7.3.5 Future Aspects of Applying the Boundary Element Method to Short-Fatigue-Crack Propagation *239*
7.4 Modeling Dwell-Time Cracking: A Grain-Boundary Diffusion Approach *242*

8 Concluding Remarks *251*

References *255*

Subject Index *281*