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Introduction

One of my teachers in materials science once mentioned that the methodology of structural integrity belongs to the humanities rather than rational physics. Probably, there are only very few humanists interested in structural integrity. However, understanding materials fatigue and developing service-life prediction concepts became one of the major driving forces of the industrial and technological revolutions in the 19th and 20th centuries. Until today, choosing the right way in predicting a component's fatigue life is a matter of believing. Particularly in the high-cycle-fatigue (HCF) regime, there is mostly a factor of two and more between the predicted and the actual fatigue life. Even the question about the existence of a fatigue limit already raised 1860 by August Wöhler is not finally answered. Recent studies in the very-high-cycle-fatigue (VHCF) regime revealed that structures may fail well below the "fatigue limit" commonly defined as to occur at two millions of cycles (plain carbon steel).

The poor performance of fatigue-damage prediction methods is surprising when taking into account that elastic and plastic deformation of ductile materials is fairly well understood and that substantial progress has been achieved in the last twenty years in the fields of high-resolution materials characterization and powerful numerical simulation methods.

One of the central problems in structural integrity is the missing link between the microstructural dimensions of materials fatigue on the atomic length scale and the engineering design concepts for structures subjected to complex loading spectra. The moving together of design engineers and materials scientists is probably one of the main technical challenges of the 21st century. The steady need for smaller and lighter structures requires a reduction of existing safety factors and the revision of the total-life concept, which is based on the existence of a fatigue limit. It is the aim of this book to provide an overview of the general theoretical and experimental concepts of fatigue-life assessment and fracture mechanics (Chapters 2 and 3) as well as an insight into the fundamentals of elastic and plastic deformation (Chapter 4) and to review the current state in fatigue-crack-propagation research (Chapters 5 and 6). The focus is placed on a material's mesoscale, i.e., grain and phase distribution, and its interaction with crack initiation and propagation being responsible for the large scatter in fatigue life in the HCF and in the VHCF regimes. Depending on the material's strength, the phase of crack initiation and microcrack propagation determines up to 90% of fatigue life, while damage monitor-

ing using conventional nondestructive testing methods will not detect any technical cracks below 10^{-3} m dimension. It was shown that crack propagation on the micrometer scale is possible far below the threshold for long fatigue cracks. Hence, using conventional damage-tolerant life-prediction concepts based on fracture mechanics might be strongly nonconservative. Modern fatigue-damage simulation concepts accounting for the material microstructure and the transient development of crack closure effects (Chapter 7) can be considered as a baseline for the missing link between atomistic modeling and traditional concepts of engineering fatigue life assessment.

The situation becomes more complex when cycle-dependent fatigue damage is superimposed by time-dependent environmental effects, e.g., corrosion fatigue or stress-corrosion cracking. At elevated temperatures, interface diffusion of corrosive species becomes sufficiently fast to reduce the grain-boundary cohesion leading to intergranular crack propagation, when high tensile stresses act on the grain-boundary plane. This mechanism has been termed dynamic embrittlement and has been identified as a generic failure mechanism (Chapters 6 and 7).

Generally, fatigue damage is strongly dependent on local microstructural features like the grain size and geometry, the crystallographic orientation relationship, and the grain-boundary structure. This is proven and discussed by various examples and the implementation in numerical modeling concepts, which can be used not only for mechanism-based fatigue-life prediction but also for the derivation of trends for microstructure design, e.g., grain-boundary engineering.