Macroscopic and Mesoscopic Quantitative Study for Damage-accumulation Mode of Fatigue Crack Propagation

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論 文 名　：Macroscopic and Mesoscopic Quantitative Study for Damage-accumulation Mode of Fatigue Crack Propagation（損傷蓄積モード疲労き裂伝ぱに関するマクロおよびメゾスコピック定量的研究）

区　　分　：甲

論　文　内　容　の　要　旨

The fatigue crack extension mechanism refers to the plastic deformation (PD) mode of fatigue crack growth (FCG) and the damage accumulation (DA) mode of fatigue crack propagation (FCP). The former is continuously extended by cyclic sharpening and blunting of the crack tip, which implies that the alternative dislocation emission and the maximum plastic strain occur at the crack tip. The latter is due to the occurrence of maximum plastic strain ahead of the crack tip, which is considered relevant to the dislocation emission and accumulation along a single slip plane. Such a continuous dislocation accumulation mechanism leads to the micro-voids' formation ahead of the crack tip and further discontinuous crack extension by the coalescence of these micro-voids. Due to the difference in the origin and extension modes of DA-FCP and PD-FCG, the corresponding retardation mechanism of crack extension is also considered different. If the fatigue crack extends as the PD-FCG, stress intensity factor range ΔK and the related fatigue limit prediction theory are considered to be still valid. However, if the crack extends as the DA-FCP, initiated as DA-FCP, then transformed into the PD-FCG and arrested as a non-propagating crack, then the theory based on the ΔK approach needs to be revised.

The occurrence of DA-FCP is considered to be due to the crack growth rate caused by the crack tip plastic deformation being slower than that of "damage" accumulation, crack initiation, and coalescence. In other words, DA-FCP tends to occur under conditions of low crack tip plastic deformation driving force, ΔK, such as in the near-threshold region. Therefore, the difference in fatigue crack extension resistance between DA-FCP and PD-FCG must affect the accurate prediction of fatigue limit. Moreover, the phenomenon of DA-FCP has been frequently observed in metals such as steels and other alloys mentioned above, including in the air and hydrogen environments. However, previous studies mainly describe DA-FCP behavior and discuss the corresponding micro mechanism. At the same time, it is still unclear which macroscopic or mesoscopic mechanical parameter is suitable for mechanically clarifying the difference between DA-FCP and PD-FCG. Therefore, studying the cyclic stress-strain behavior of DA-FCP under near-threshold conditions and further mechanical definition of DA-FCP is considered a significant work to fatigue design in engineering. The other study's purpose is to clarify the occurrence and the transition condition of DA-FCP for all metals, which is a prerequisite for accurately predicting the fatigue limit. The more forward-looking significance is to enable people to intervene or even manage such a fatigue crack extension behavior. This thesis consists of 5 chapters. The outline is as follows.

Chapter 1 described the general introduction of this thesis. First, a brief review of the fatigue crack extension modes and fracture mechanics-based mixed-mode fatigue research was introduced. After clarifying the mechanism-based fatigue crack extension modes, their corresponding retardation mechanisms of fatigue crack extension were pointed out, including a detailed introduction of measurement techniques. Then, the simulation techniques available for DA-FCP studies are discussed from micro- and meso-mechanics. Finally, the motivation of this study, namely, some quantitative mechanical characterization research for DA-FCP, was formed. The research focus and originality of each chapter were described.

Chapter 2 performed fatigue tests with an inclined notch, which predicts the fatigue limit with a mechanically long crack under fracture mechanics-based mixed modes condition. As a result, the damage accumulation (DA) mode of fatigue crack propagation was found to occur from the crack tip. In addition, the formation and coalescence of micro-voids cause the DA mode. Therefore, modifying the initial crack length by considering the DA mode crack propagation length has shown potential application in fatigue limit prediction. Moreover, a classification method of DA and PD modes is proposed.

Chapter 3 conducted crack closure measurement tests by an unloading elastic compliance method in inclined sharp notched specimens under cyclic tension-compression loading, which is to mechanically determine the transition between the damage accumulation (DA) and plastic deformation (PD) mode of fatigue crack extension. As a result, the fatigue crack extension evolution was characterized conclusively by three successive stages: 1) the DA stage, featuring continuously decreasing elastic compliances; 2) the mode transition stage, featuring almost cyclic plastic strain behavior; and 3) the PD stage, where the crack closure effect manifests. Moreover, a prediction method for DA fatigue crack propagation was proposed based on the local strain and grain size.

Chapter 4 conducted a crystal plasticity finite element method (CPFEM) simulation for polycrystalline. It was used to analyze the plastic normal strain localization, which is correlated with DA-FCP occurrence, ahead of the notch root. The CPFEM model quantitatively clarified the material and mechanical effects on DA-FCP. As a result, an equation of the critical grain size formulated by the Schmid factor, the misorientation angle, and the plastic zone size is proposed to characterize the critical condition for the occurrence of the DA-FCP. Moreover, a prediction method for DA-FCP region size is proposed.

Chapter 5 summarized general conclusions and proposed the outlook.