Mechanisms, Metallurgical Factors and Mechanical Indices in the Damage Accumulation Mode of Fatigue Crack Propagation: A Case Study on 18% Ni Martensitic Steel

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（損傷蓄積型疲労き裂進展のメカニズムと冶金学的要因および力学的指標：18%Ni マルテンサイト鋼についての事例研究）

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論 文 内 容 の 要 旨

In order to prevent disasters caused by fatigue failure, the fatigue crack extension mechanism has been widely studied. The extension of fatigue crack mode is divided into plastic deformation (PD) mode and damage accumulation (DA) mode according to the mechanism, as recently proposed by the research team to which the author belongs. According to the crack extension behavior, it is further divided into two types. The mechanism theory and model of the PD mode have been established in detail. It is based on the alternating slip from the crack tip, and the crack is extended in one loading cycle due to the blunting and re-sharpening of the crack tip. Its driving force is the stress intensity factor range ΔK, and it can be used to predict the extension length per cycle of fatigue cracks. In the DA mode, the extension of the crack is carried out in the form of the nucleation of secondary cracks in front of the main crack and the coalescence with the main crack. A single slip in front of the main crack characterizes its extension behavior.

There are two differences between the two modes. First, at the microscopic scale, DA mode pays more attention to the metallurgical characters other than the high stress at the crack tip caused by the external force of PD mode. In other words, secondary cracks are formed by other activated dislocation sources, not the crack tip, such as grain boundary, Frank-Read source, and precipitation. Second, at the macroscopic level, the maximum shear strain that occurs during crack extension is not at the crack tip but at other locations where dislocation would accumulate in front of the crack tip. The non-propagation crack arrested under the PD mode mechanism can extend again after many cycles by DA mode because of the mode change. The damage accumulation can occur in front of the arrested crack tip, and a new crack can be initiated in front of the main crack. The main crack can coalesce with the new crack, and the main crack propagates. Suppose this phenomenon is evaluated using the characterization parameter K of PD mode of fatigue crack growth (PD-FCG). In that case, it will be very dangerous for engineering design because the crack will extend according to an unexpected mechanism and fail unexpectedly. Therefore, although the DA mode of fatigue crack propagation (DA-FCP) phenomenon seems very common, its principles differ from those of the PD mode. Under the definition of DA-FCP, appropriate evaluation methods can be analyzed to meet the safety design needs of actual engineering structures.

The significance of studying the DA model can be found above. However, from the current research, the understanding of DA mode is not comprehensive, and there are the following problems: the microscopic mechanism of secondary crack formation is still completely unclear; there are insufficient theoretical models and experimental verification; there is insufficient systematic research on the influence of artificial defects.

Therefore, in order to solve these academic problems, the fatigue crack extension mechanism under the DA mode in martensitic steel and its influence on fatigue strength will be clarified in this study. 18%Ni non-aging martensite was used as the target material for the study. This material is famous for its hierarchical microstructure and high dislocation density. Dislocation shielding of the main crack and strain localization are thought to be prone to occur in this material. Consequently, DA-FCP is considered highly likely to appear in this material, making it the target material for this study. The specific content consists of five chapters:

Chapter 1 describes the introduction and background of this dissertation. This chapter reviews traditional PD-FCG in sequence and then discusses its limitations. Subsequently, DA-FCP is introduced, highlighting its necessity and the current issues that must be addressed. Next, the characteristics of the material used in this study and its suitability for DA-FCP are presented. Finally, this dissertation's research objectives are outlined, including refining the micro-mechanism of DA-FCP and conducting quantitative mechanical characterization studies.

In Chapter 2, the mechanism of DA-FCP was explained. Rotating bending fatigue tests were performed. Moreover, the fatigue crack behavior was observed on the specimen surface, the fracture surface morphology was analyzed, and the plastic strain distribution near the crack tip was analyzed. These results revealed two fatigue crack extension modes dependent on the mechanical and metallurgical conditions. Besides, the unique *S-N* diagrams and the prediction method with material indices for the fatigue life were proposed for martensitic steels based on the existence of the two modes.

In Chapter 3, the metallurgical factor of DA-FCP was analyzed. A material index representing the steels and a new fatigue strength evaluation was proposed. DA mode of fatigue crack growth (DA-FCG) and DA-FCP appeared as new extension mode types, with DA-FCP dominating the fatigue limit. In this type, the block size in the microstructure is proposed as the material index of martensitic steel, and the fatigue limit equation is presented in conjunction with the material index.

In Chapter 4, the mechanical factor of DA-FCP was analyzed. As the mechanical index for the DA mode is still unclear, martensitic steel exhibited DA mode and remains unsolved. Fatigue tests were conducted for two shapes of micro-stress concentration sources (notches) to obtain fatigue crack extension properties. The specimens with two notch shapes, having the equivalent dimensions for fatigue limits, obtained unequal fatigue limits with significant differences. The two-notch shapes hold different stress states, resulting in different crack extension mechanisms of the material with different notch shapes, affecting the crack non-propagation mechanism and ultimately causing different fatigue strengths. It is concluded that the stress state, plane stress/strain, is considered one of the mechanical factors affecting the DA mode.

In Chapter 5, general conclusions were summarized, and an outlook was proposed. This chapter summarized the discussed content, including the fatigue crack extension mechanism, extension mode type, and the factors influencing DA mode. Moreover, based on the DA mode's fatigue crack extension mechanism obtained in this dissertation, many concrete topics to be studied were presented.