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Fatigue crack resistance of hierarchical laminated transformation-induced-plasticity maraging steel

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論 文 名　: Fatigue crack resistance of hierarchical laminated transformation-induced-plasticity maraging steel

（階層的ラメラ組織を有する TRIP マルエージング鋼の疲労き裂進展抵抗）

区　　分　:　甲

論 文 内 容 の 要 旨

In this study, I focus on the effect of roughness-induced crack closure (RICC) on the fatigue resistance of a newly-developed high-strength alloy. Increasing small crack length enhances crack surface roughness and associated RICC, because plastic zone size approximate to single grain size activates single shear system. Simultaneously, threshold stress intensity factor range (ΔK_{th}) and associated plasticity-induced crack closure (PICC) effect are significantly increased during small crack evolving to long crack. Notably, ΔK_{th} for long crack is determined only by Young’s modulus and Poisson’s ratio, in other words, different metal materials have similar ΔK_{th} value under the long crack condition. In addition, oxide-induced crack closure (OICC) effect is inversely related to PICC effect. The fretting oxidation increases the thickness of oxide layer at crack tip with PICC effect and associated compressive stress increasing, that is, the OICC effect is negligible under the small crack condition. Therefore, understanding RICC effect on small crack behavior can contributes to material selection.

A type of transformation-induced-plasticity (TRIP) maraging steel (Fe-9Mn-3Ni-1.4Al-0.01C, wt.%) has great potential to be applied on present work, due to the maraging martensite/retained austenite laminated microstructure similar to bone, and exceptional tensile property achieving an ultimate tensile strength of approximately 920 MPa with a total elongation of about 30%. In addition, am mount of retained austenite can be obtained by controlling annealing time. One hand, the laminated microstructure is similar to that in pearlitic steels, which have superior low-cycle fatigue resistance due to the cementite/ferrite laminated structure contributing to zigzag crack propagation and associated RICC. Therefore, it is expected that TRIP-maraging steels has high fatigue performance from considering the Transformation-induced crack closure by TRIP and RICC. However, there is no fatigue data of TRIP-maraging and the fatigue mechanism has not been found. The structure of the dissertation is as follows.

Chapter 1 describes a general introduction of this work. The motivation of this research is based on the development and usage of high-strength steel to investigate RICC effect. The crack closure has been greatly developed, showing that crack closure is more effective in small crack propagation. Cyclic overload accelerates fatigue crack growth rate and enable to cause catastrophic failure. However, pearlitic steel with laminated microstructure shows superior low-cyclic fatigue resistance owing to RICC effect. Similar microstructure has been applied into a new alloy called TRIP-maraging steel, which has great potential in fields of the punch forming and structural lightweight design, because of the extraordinary balance between strength and elongation. Accordingly, this new alloy will be decided to investigate RICC effect on small crack in the present work.

Chapter 2 generally introduces fatigue properties of the new alloy, TRIP-maraging steel, which is invented under the inspiration of superior fracture resistance of bone. This steel is characterized by a hierarchically laminated austenite/martensite microstructure, and thus exhibits an outstanding fatigue life at each stress amplitude, compared with other conventional steels, such as dual-phase steel, pearlitic steel, 304 stainless steel, etc. This excellent performance stems from TICC and RICC.

Chapter 3 focuses on the effect of annealing time on the fatigue crack resistance of TRIP-maraging steel by observing the crack initiation site, propagation path and fracture surface. Our analyses show that annealing for a longer time increases austenite/martensite lamella size and connectivity of austenite. Simultaneously, increasing lamella size leads to a reduction in austenite hardness; higher austenite connectivity accelerates crack propagation. In addition, remarkable roughness on the crack surface associated with the laminated structure was observed in both steels, which caused roughness-induced crack closure.

Chapter 4 illustrates the mechanism of TRIP-maraging steels to explain its exceptional high cycle fatigue resistance. The TRIP-maraging steel with fine grained austenite was used. Our analyses revealed that soft austenite region acts as a preferential crack propagation path, but the plastic deformation during crack opening involves martensitic transformation, resisting subsequent crack growth via transformation-induced local hardening or crack closure. Moreover, crack growth along the laminates and across the block boundary forms a zigzag crack path, which would act as RICC. The combined effect of these factors plays an important role in resisting fatigue crack growth at high cycle fatigue and fatigue limit.

Chapter 5 presents results by serial sectioning characterization for assessing RICC in the TRIP-maraging steels. Microstructural morphology, which is dependent on the annealing time at 873 K, could influence RICC owing to the alteration of hardness and associated wear resistance. Serial sectioning was carried out to present the evolution of crack roughness. With exploring region close to the crack front, submicrometer-scale crack surface roughness progressively appears in the ‘hard’ steel annealed for 1 hour; in contrast, only micrometer-scale roughness presents in the ‘soft’ steel annealed for 8 hours. This fact verifies that stronger wear resistance enables to contribute a long-term effective RICC.

Chapter 6 summarized the results and proposed the outlook.