Deformation-induced ε-martensitic transformation effect and fatigue crack growth mechanism on the low cycle fatigue in high-Mn austenitic alloys

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論 文 名　：Deformation-induced ε-martensitic transformation effect and fatigue crack growth mechanism on the low cycle fatigue in high-Mn austenitic alloys
（高 Mn オーステナイト系合金の低サイクル疲労における変形誘起ε-マルテンサイト変態効果と疲労き裂進展機構）

区　　分　：甲

論 文 内 容 の 要 旨

The main objective of this thesis is to investigate the fatigue crack growth mechanisms affected by ε-martensitic transformation. For this purpose, the low cycle fatigue tests were conducted in situ by optical microscopy and SEM to observe the crack growth behavior. The fracture surface and EBSD images were used for further discussion. The thesis consists of five chapters. All the chapters are arranged in order to achieve the main objective of the research work. The thesis is organized as follows:

Chapter 1 describes a general introduction of the research background and materials. The motivation of the research according to the current issues in engineering field particularly in the automotive industry is highlighted. Based on the current demand to reduce an weight and entry cost, high-Mn austenitic alloys, which show high strength and high ductility due to the effects of twinning-induced plasticity (TWIP) and transformation-induced plasticity (TRIP), are one of the good choices. In present thesis, the Fe-30Mn-6Al, Fe-30Mn-4Si-2Al and Fe-30Mn-6Si alloys were used to investigate the fatigue crack growth behavior. The plastic deformation modes of these alloys were controlled by stacking fault energy (SFE) decided by the chemical composition of Al, Si. In previous study, the Fe-30Mn-4Si-2Al alloy showed high low-cycle fatigue resistance. However, the fatigue crack growth mechanism was not investigated. Moreover, the Fe-30Mn-4Si-2Al alloy has long crack propagation life. Therefore, the effect of ε-martensitic transformation and the fatigue crack growth mechanism associated with ε-martensite should be investigated before the application.

Chapter 2 reports the macroscopic crack growth behavior of three alloys observed in situ by optical microscopy with fracture surface observations and EBSD measurements. The fatigue crack growth behavior associated with the microstructure changes were investigated at different fatigue crack length. The Fe-30Mn-6Al alloy showed the conventional crack growth behavior observed in Face-centered cubic metals without ε-martensitic transformation. The Fe-30Mn-4Si-2Al and Fe-30Mn-6Si alloys showed ε-martensitic transformation during the fatigue test. These two alloys showed a similar crack growth behavior which propagated along γ/ε interfaces in short crack region. However, the fatigue crack growth behavior of the two alloys changed as the fatigue crack length increased. The Fe-30Mn-6Si alloy, has highest volume fraction of ε-martensite, showed frequent subcrack formation and crack coalescence in front of crack tip. These behavior accelerated the fatigue crack growth rate. However, the Fe-30Mn-4Si-2Al alloy, has considerable volume fraction of ε-martensite, showed lowest fatigue crack growth rate than others tested. The reason that the Fe-30Mn-4Si-2Al showed low cycle fatigue resistance is considered due to the reverse transformation of ε-martensitic transformation. The reverse transformation suppressed strain localization, formation of persistent Lüders banding that stems from the accumulation of irreversible lattice defects.

Chapter 3 reports the fracture surface observations until 2 mm and corresponding grain reference orientation deviation (GROD) to evaluate the plastic deformation. The Fe-30Mn-6Al alloy is known to show the conventional fatigue crack growth behavior in chapter 2. The formation of PLB and ductile striations of the conventional crack growth behavior require a large plastic strain localization at the crack tip. In chapter 3, the Fe-30Mn-6Al alloy showed a large plastic strain localization near the fatigue crack path. Therefore, the conventional crack growth mechanism of the Fe-30Mn-6Al alloy observed in chapter 2 is demonstrated through the large plastic strain localization. The Fe-30Mn-4Si-2Al alloy showed striation-like patterns on fracture surface with the plastic strain localization at 1 mm length from the drill hole. However, the localized plastic strain was lower than the Fe-30Mn-6Al alloy. In addition, ductile striations were observed like the Fe-30Mn-6Al alloy at 2 mm from the drill hole. Therefore, it is supposed that the Fe-30Mn-4Si-2Al alloy has same crack growth behavior to the Fe-30Mn-6Al alloy. However, the behavior is delayed by reverse motion of dislocation, decreasing the plastic strain localization. From present results and assumption, the crack growth behavior of the Fe-30Mn-4Si-2Al alloy was proposed. The Fe-30Mn-6Si alloy showed lowest plastic strain near the crack path. Moreover, subcracks were observed on fracture surface until 2 mm from the drill hole. It has been reported that the Fe-30Mn-6Si alloy has pre-existing ε-martensite at initial state. Therefore, the pre-existing ε-martensite and ε-martensite transformed during the fatigue test coexist in the Fe-30Mn-6Si alloy. From the results, the subcrack formation and crack coalescence mechanism of the Fe-30Mn-6Si alloy was proposed.

Chapter 4 reports the microscopic fatigue crack growth behavior during one cycle to demonstrate the proposed crack growth mechanism in chapter 3. The Fe-30Mn-4Si-2Al alloy showed the crack deflections at annealing twinning boundaries (TB) and cracking along the annealing TB. Moreover, the fatigue crack growth was delayed while the fatigue crack penetrated the annealing TB. These behavior are results of dislocation dissociation and damage-accumulation described in chapter 2. Meanwhile, the Fe-30Mn-4Si-2Al alloy showed a large crack tip opening during one cycle. However, the fatigue crack did not propagate during three cycles. These behavior are related to the proposed crack growth mechanism of the Fe-30Mn-4Si-2Al alloy in chapter 3. The proposed crack growth mechanism described that dislocation is emitted from a crack wake when ε-martensite grow at the crack tip and reverse transformation suppresses the plastic strain localization. In the present chapter, the dislocation emission contributes to a large crack tip opening, but it does not contribute to the crack propagation because the dislocation emission from a crack wake and suppression of plastic strain localization inhibit the blunting and re-sharpening behavior. The Fe-30Mn-6Si alloy showed the frequent subcrack formation in front of the main crack tip. Moreover, a large crack tip opening was not observed. In chapter 3, the crack growth mechanism of the Fe-30Mn-6Si alloy was described as subcrack formation and crack coalescence with the main crack by pre-existing ε-martensite. From the results of chapter 4, the proposed crack growth mechanisms of the Fe-30Mn-4Si-2Al and Fe-30Mn-6Si alloys were demonstrated.

Chapter 5 summarizes the results obtained by the present studies, and all findings are described in the general conclusions.