Numerical simulation of transformation-induced microscopic residual stress in ferrite-martensite lamellar steel

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Abstract. The effect of transformation-induced microscopic residual stress on fatigue crack propagation behavior of ferrite-martensite lamellar steel was discussed. Fatigue tests of pretrained and non-pretrained specimens were performed. Inflections and branches at ferrite-martensite boundaries were observed in the non-pretrained specimens. On the other hand, less inflections and branches were found in the pretrained specimens. The experimental results showed that the transformation-induced microscopic residual stress has influence on the fatigue crack propagation behavior. To estimate the microscopic residual, a numerical simulation method for the calculation of microscopic residual stress induced by martensitic transformation was performed. The simulation showed that compressive residual stress was generated in martensite layer, and the result agree with the experimental result that inflections and branches were observed at ferrite-martensite boundaries.

1. Introduction

Mechanical properties of steel plate are controlled by microstructure. Recently, an improvement in fatigue strength was achieved by introducing lamellar structure of ferrite and martensite by controlling rolling and cooling condition. Shown in figure 1 is the microstructure of ferrite-martensite lamellar steel.

Figure 1. Microstructure of ferrite-martensite lamellar steel.
steel [1]. The ferrite-martensite lamellar steel has the yield stress of 520 MPa and the tensile strength of 581 MPa. Detailed observation of fatigue crack propagation paths showed that inflections and branches were observed at boundaries of ferrite and martensite. For the reason of the inflections and branches, the following two major points related to martensite phase might be considered: (1) the hardness of martensite as secondary phase, (2) microscopic compressive residual stress caused from transformation expansion of martensite. The schimatic illustration is shown in figure 2. In this paper, the effect of microscopic residual stress due to martensitic transformation expansion on fatigue strength is discussed.

2. Fatigue crack propagation behavior in ferrite-martensite lamellar steel
First, fatigue tests were performed in order to clarify the effect of microscopic residual stress. The steel plate with ferrite-martensite lamellar microstructure as shown in figure 1 was 1% prestrained along rolling direction. The prestrained and non-prestrained specimens were used in the fatigue tests. The fatigue tests were carried out with three-point bending under following conditions: $\Delta K$ increase, stress ratio $R = 0.1$, repetition frequency $f = 10$ Hz. Then the observation of fatigue crack propagation paths was performed. Inflections and branches at ferrite-martensite boundaries were observed in the non-prestrained specimens. On the other hand, less inflections and branches were found in the prestrained specimens. As a result, fatigue crack growth rate $da/dN$ was higher in 1% prestrained specimens than that in 0% prestrained specimens. It could be expected that microscopic compressive residual stress would be changed when specimens were prestrained, microscopic residual stress have some effect on the inflections and branches of fatigue crack propagation. Therefore a numerical simulation was performed to estimate the distribution of transformation-induced microscopic residual stresses.

![Figure 3](image3.png)

Figure 3. Fatigue crack growth rate of ferrite-martensite lamellar steels with and without prestrain.

3. Numerical simulation procedure of microscopic residual stress distribution
A numerical simulation was performed to calculate the microscopic residual stress in ferrite-martensite lamellar structure. A numerical simulation model of ferrite-martensite lamellar structure was generated as shown in figure 4. The geometrical parameters, such as the thickness and length of martensite, the distance between martensite phases, etc., were determined based on the experimental results of the observation of microstructure as shown in figure 1. The volumetric expansion and change in mechanical properties due to phase transformation was taken into consideration to calculate the transformation-induced microscopic stress distribution [2]. The transformation expansion curves during cooling process used in the numerical simulation are shown in figure 5. Figure 6 shows the temperature dependency of yield stress ($\sigma_y$) and Young’s modulus ($E$). The curves and transformation temperatures were selected from database. The data to use were determined based on the chemical composition measured by EPMA analysis of ferrite and martensite.
The simulation model was cooled from 900°C to 20°C: from the fully austenite condition to room temperature. The boundary conditions for the model was free to expansion and contraction. The microscopic residual stress is generated during the cooling process due to the difference in the transformation temperature and mechanical properties between ferrite and martensite.

**Figure 4.** Numerical simulation model for transformation induced microscopic residual stress.

**Figure 5.** Transformation expansion curves used in the numerical simulation.

**Figure 6.** Temperature dependency of yield stress and Young’s modulus used in the numerical simulation.

4. **Microscopic residual stress distribution in ferrite-martensite lamellar steel**

A result of the numerical simulation of transformation-induced microscopic residual stress is shown in figure 7. The distribution of residual stress along the direction of martensite layer $\sigma_y$ over the simulation model is shown in figure 7(a). In addition, figure 7(b) shows the distribution of $\sigma_y$ along the black line shown in figure 7(a). As seen from these figures, the microscopic stress distribution induced by transformation expansion of martensite is compressive in martensite and tensile in ferrite. From the viewpoint of the fatigue crack propagation behavior, when the residual stress in martensite was compressive, the penetration of the crack through martensite would be difficult. This agrees with the experimental result of the observation of fatigue crack path in non-prestrained ferrite-martensite lamellar steel.
5. Summary
In this study, the effect of microscopic residual stress on fatigue crack propagation behavior of ferrite-martensite lamellar steels was discussed. A numerical simulation method for transformation-induced microscopic residual stress was proposed. The following results were obtained.

- The fatigue test results of prestrained and non-prestrained specimens of ferrite-martensite lamellar steel showed that microscopic residual stress have some effect on the inflections and branches of fatigue crack propagation.
- The microscopic stress distribution induced by transformation expansion of martensite is compressive in martensite and tensile in ferrite.

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References
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