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主　論　文　の　要　旨

論文題目　A study on restoration of fatigue damage in stainless steel by high-density pulse current（高密度パルス電流によるステンレス鋼における疲労損傷の修復に関する研究）

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論　文　内　容　の　要　旨

Fatigue fracture is generally considered to be the most serious type of fracture in machinery parts because fatigue fracture can occur in normal service, without excessive overloads, and under normal operating conditions. Fatigue occurs when a material is subjected to repeat loading and unloading. Fatigue fractures are serious due to the insidious, which are frequently sneaky and can occur without warning anything to be amiss. In materials science, fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading.　Fatigue damage is an important phenomenon associated with the degradation of the mechanical properties of a material due to cyclic loading and represents a fundamental aspect of the overall evaluation of the remaining life of machine parts and components in service. The relative cost of these failures constitutes an amount of waste of the source. Consequently, it is essential to improve the long-time durability and reliability of materials by extending their fatigue lifetime.

The prevention of fatigue fractures in metal materials is an effective way to prolong their service life. To improve fatigue strength, various surface engineering techniques have been developed, such as high-frequency quenching, carburizing, nitriding and shot peening. Pretreatment on the material surface is effective for the suppression of crack initiation. However, once a fatigue crack is initiated during service, the reliability of the structure is severely impaired and the mentioned methods are inefficient for delaying the progress of fatigue failure. Therefore, a technique to heal the fatigue damage caused by fatigue crack initiation during service and recover the fatigue strength at the healed zone would be very desirable in terms of structural integrity.

In the past fifty years, the applications of electric current, as an instantaneous high energy input method, have been widely developed in the fields of materials science and engineering. It has been found that the application of electric current can have significant effects on the improvement of mechanical properties of metals, such as plastic deformation, recrystallization and fatigue behavior. Although the increased the fatigue life of metallic materials due to the applying an electric current has been studied, the mechanism of the effect of electric current on the fatigue behavior is still unclear. On the other hand, considering the persistent slip bands (PSBs) play an important role in the fatigue crack initiation, these interfaces between the PSBs and the matrix serve as preferential sites for fatigue crack initiation in general. Hence, the locally vanishing of the PSBs can decrease the possibility of the fatigue crack initiation. Unfortunately, the effect of electric current on the fatigue crack initiation has not been investigated till now. Moreover, during the fatigue loading process, the primary emphasis is that the fatigue crack initiation is caused by accumulation of micro-defects, such as dislocations in the material. However, the quantitative evaluation of the effect of electric current on the recovery of dislocations has been few studied and the relationship between the dislocation density and the crack initiation has not been established.

This dissertation aims to establish a method to delay the fatigue failure. In this study, the application of high-density pulse current (HDPC) was carried out to restore the fatigue damage. It is essential to clarify the mechanism of the effect of electric current on fatigue damage restoration. On the other hand, it can be considered that the delaying fatigue crack initiation due the electric current is an important way to extend the fatigue lifetime. It is important to build the relationship between the dislocation density and the delaying fatigue crack initiation and to evaluate the delaying effect of the crack initiation due to the application of HDPC.

Chapter 1 is the introduction of the research background, such as the fatigue fracture and fatigue crack initiation. The method to delay the fatigue fracture was reviewed. The application of electric current on the mechanical properties of metals was discussed. Additionally, the application of electric current on the fatigue behavior was summarized. Meanwhile, the motivation of this study was represented.

Chapter 2 introduces the experimental material and methods used in this study. The SUS316 austenite stainless steel was used as the experimental material. The experimental method which is used to evaluate the healing effect due to the application of HDPC was also described. (e.g. measurement of atomic force microscope (AFM), the digital image correlation (DIC) method, measurement of Vickers microhardness (HV), and observation of transmission electron microscopy (TEM)). Additionally, experimental condition, procedure and the preparation of TEM sample were described.

In chapter 3 we represent the results of HDPC on fatigue behavior. The fatigue crack initiation was delayed successfully by the application of HDPC. The delaying effect was different depending on the timing of the application of HDPC. The reason of the delaying fatigue crack initiation was due to the restoration of fatigue damage. To clarify the effect of HDPC on the healing of fatigue damage, the recovery of residual strain and microhardness at the root of the notch tip were evaluated. On the surface of specimen, the locally disappear of slip bands and the decrease of the height of slip bands were found. It is the important reason for the delaying effect on fatigue crack initiation. Moreover, it was found that the residual strain was recovered after the application of HDPC. The strain hardening was also recovered. The recovery of residual strain and strain hardening indicates the decrease of fatigue damage.

Chapter 4 describes the dislocation structures before and after the application of HDPC. The recovery of dislocation due to the effect of HDPC was observed and the mechanism of healing effect on fatigue damage in the microstructure was discussed. After the application of HDPC, the dislocation pile-ups disappeared and the dislocation density decreased. The motion and annihilation of dislocations is an important mechanism of damage recovery. When the HDPC was applied upon unloading, the reverse motion of dislocation was improved due to the effect of electron wind force. In addition, the application of HDPC causes a high-rate heating. It is thought that joule heating is a side effect.

In chapter 5, to establish the relation between the delaying fatigue crack initiation and the dislocation structure, a model of fatigue damage parameter is proposed based on the fatigue crack initiation model in which the accumulation of the dislocation density was considered. The proposed model was evaluated against experimental data. The predication of the delaying effect on the fatigue crack initiation can be carried out by the decrease of dislocation density caused by the application of HDPC. According to the physics of the fatigue crack initiation, the delaying fatigue crack initiation is due to the improved reverse of dislocation.

Chapter 6 is the conclusion of this thesis. The fatigue crack initiation was delayed by the application of HDPC. It was found that the delaying effect was due to the restoration of fatigue damage (e.g. healing of slip bands, recovery of residual strain and strain hardening). In the microstructure, the recovery of dislocation was the essential for the restoration of fatigue damage. Furthermore, the relationship between the delaying fatigue crack initiation and the dislocation density were built by the proposed fatigue damage parameter based on the fatigue crack initiation model.

The application of HPDC presented in this dissertation is an effective way to delay the fatigue crack initiation by restoration of the fatigue damage. The development of this technique will bring a dramatic improvement in the long-term reliability of structures, with the effect of reducing their maintenance costs and the environmental load.