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主　論　文　の　要　旨

論文題目　**Strain hardening relief and crack initiation delay of Ni-based superalloy Inconel 718 induced by high-density pulsed electric current**

（高密度パルス電流によるNi基超合金インコネル718のひずみ硬化の緩和とき裂発生の遅延）

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論　文　内　容　の　要　旨

Metal forming is the essential method in the manufacturing industry to shape metals by plastic deformation. However, the cold-formed pieces tend to possess high strength but low ductility, the so-called strain hardening, which requires the high forming forces and weakens the life of equipment and molds. Typically, the intermediate annealing is conducted during the processing of pieces to restore the ductility loss. However, intermediate annealing is usually performed at a high temperature for a long time to realize the strain-hardening relief, which is laborious and low-efficient. Therefore, the research objective of this study is to propose a low-cost and high-efficient method, i.e., high-density pulsed electric current (HDPEC) treatment, to relieve the strain hardening and establish the microstructure-mechanical properties relationships of HDPEC-treated pieces. A systematic and detailed investigation was carried out on the strain-hardening relief of deformed Ni-based superalloy Inconel 718 (IN718) with various HDPEC treatment conditions and the mechanism of strain-hardening relief induced by HDPEC was clarified.

Although many studies on strain-hardening relief caused by electric current treatment, coupled with the effects of thermal (Joule heating) and athermal (electron wind force, EWF), have been reported, some issues regarding the mechanisms are unclear. For example, how the microstructure changes (e.g., dislocation motion and grain boundaries evolution) in the material during HDPEC treatment, and what's the difference between HDPEC treatment and the traditional heat treatment in strain-hardening relief, need to be clarified. Therefore, this study aims to reveal the microstructure changes induced by HDPEC and clarify the effects of thermal and athermal on the microstructure evolution. Some specially-designed experiments were carried out to address the above issues, and the mechanisms regarding the microstructure evolution induced by HDPEC were revealed.

In addition, the fatigue fracture of engineered components or structures is a significant phenomenon in materials science, even though they work within the safe load. Since the intrinsic defects (e.g., porosity and impurity) or geometric discontinuity (e.g., joint, notch, and welding) in materials caused the stress concentration, the crack initiated near the plastic zone ahead of the defects or discontinuity and finally caused the failure. In recent years, the electric current method has been used to enhance the fatigue life of metallic materials, and fruitful achievements have been obtained. However, almost all the studies are focused on fatigue life enhancement via crack healing induced by electric current treatment. The effect of electric current on the plastic zone ahead of defects or discontinuity before crack initiation is still rarely studied. Hence, another research objective of this study is to heal the plastic zone or plastic deformation ahead of the notch and to examine the enhancement of crack initiation life of notched samples utilizing HDPEC. Numerous fatigue tests under various HDPEC treatment conditions were carried out, and the microstructure characterization was also conducted by EBSD measurement to reveal the mechanism.

The main content and results of this thesis are described in each of the following chapter:

Chapter 1 presents the general introduction of the research background of metal forming and fatigue fracture, while the effect of HDPEC on metallic materials was summarized. The potential problems and unclear issues regarding the effect of HDPEC on strain-hardening relief and microstructure evolution were pointed, and the research objectives of this study were presented.

Chapter 2 introduces the material and experimental method of this study. The experimental conditions of the tensile and fatigue test were presented, and the application conditions of HDPEC were also given. To evaluate the effect of HDPEC on the sample, the finite element method (FEM) simulation involving the electric field analysis, thermal field analysis, and stress field analysis was described. The FEM procedure was self-developed on the commercial software MATLAB, and the graphical user interface (GUI) was also presented. In addition, the evaluation methods of the changes in mechanical properties and microstructure, such as hardness test, residual stress and dislocation density analysis carried out by X-ray diffraction (XRD) measurement, local deformation and crystallographic properties analysis conducted by electron backscatter diffraction (EBSD) measurement, and surface morphology and fractography observation performed by scanning electron microscope (SEM) measurement, were introduced.

In Chapter 3, the effect of HDPEC on the strain-hardening relief of deformed IN718 under various HDPEC treatments was investigated. First of all, the temperature rise of the sample during HDPEC treatment was measured using thermal sensors, and the simulation result was also presented for comparison. The mechanical properties and microstructure evolution of the HDPEC-treated samples were investigated. The results show that the strain hardening was successfully eliminated by HDPEC treatment, and the ductility was also recovered. In addition, the dislocation elimination induced by HDPEC was the dominant reason, while grain size and texture evolution were the side effects in strain-hardening relief. The microstructure characterization indicates that the grain morphology of the HDPEC-treated samples tends to possess random orientation and equiaxed morphology.

Chapter 4 presents some specially-designed experiments to reveal the mechanisms of strain-hardening relief induced by HDPEC. First of all, the quasi-in-situ EBSD observation was conducted in this study to investigate the microstructure evolution caused by HDPEC. The dislocation motion and elimination induced by HDEPC were directly observed. Two ways of dislocation elimination caused by HDPEC as reported in previous studies, i.e., the combination of dipole dislocations and absorption in grain boundaries, were observed and confirmed. In particular, a new way for dislocation elimination, via EWF-driven dislocations entangled at the previous dislocation walls (i.e., sub-grain boundaries) and then forming new grain boundaries, was found in this study. Moreover, a designed experiment with several equivalent samples was also conducted to illuminate the contributions of thermal and athermal effects on strain-hardening relief induced by HDPEC. The results demonstrated that the athermal effect is more significant in strain-hardening relief than the thermal effect. Additionally, the high electric current is more effective in reducing dislocation density and relieving the strain hardening, which attributes to the large EWF (high current density) that helps dislocation overcome resistance to motion and thus realizing the annihilation. Most importantly, the difference between HDPEC treatment and traditional heat treatment in strain-hardening relief was elucidated in this study. Generally, the microstructure recovery induced by traditional heat treatment mainly relies on recrystallization, which involves thermally-activated dislocation climb. In contrast, the effect of HDPEC treatment on strain-hardening relief is related to the EWF-induced dislocation glide, which has been demonstrated to be a more efficient way in dislocation motion.

Chapter 5 presents the enhancement of the crack initiation life of the notched IN718 induced by HDPEC. First of all, the current density field, thermal field, and stress field ahead of the notch are presented using the self-developed FEM procedure. The enhancement of crack initiation life induced by HDPEC at different stress levels was investigated. The results show that the crack initiation life was highly enhanced by HDPEC treatment, and the maximum increase rate reached 108.3% at the fatigue stress of σ_{max} = 250 MPa after multi-HDPEC treatment. The microstructure characterization shows that the fatigue-introduced plastic zone only affected ~2-grain area ahead of the notch root, and the dislocations at the plastic zone were evidently removed by HDPEC treatment.

Chapter 6 presents the conclusions and original contributions of this dissertation. A summary of future work was proposed.