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主 論 文 の 要 旨

論文題目 A Study on Improvement of Tensile and Fatigue Properties of Type 316 Austenitic Stainless Steel by High−Density Pulsed Electric Current

(高密度パルス電流によるタイプ 316 オーステナイト系ステンレス鋼の引張および疲労特性の改善に関する研究)

氏　　名 YOON　Sungmin

論 文 内 容 の 要 旨

Type 316 austenitic stainless steel is one of the widely used and most popular stainless steel owing to its excellent ductility and corrosion resistance. Containing a large amount of chromium gives a good ductility owing to the stabilization of austenite grains, and adding nickel promotes self-produced surface passive film for the role of anti-corrosion. Despite these advantages, there are weaknesses such as relatively low mechanical strength and intergranular corrosion caused by sensitization effect, thereby the application of this material is sometimes limited. Thus, the following issues have been required for the modification of the material.

First, low material strength and fatigue properties due to large grain size by austenitization, contrary to the good ductility, has been required to improve with any modification method. Improvement of mechanical responses under tensile and fatigue loadings means the satisfaction of essential properties of materials in the design of mechanical components. Second, sensitization induced by chromium-rich carbide has been issued because microstructural degradation caused by sensitization can significantly restrict environmental applications. For example, a susceptible intergranular structure response under corrosive environments can occur stress corrosion cracking, as well as, damaged intergranular zones can decrease the fracture properties of the material. As such, the drawbacks to be solved in this stainless steel are briefly described in the above.

The application of high-density pulsed electric current (HDPEC) in metals is a recently effective method to improve mechanical properties based on microstructural modifications of materials. The presence of two phenomena, such as electron wind force (EWF) and Joule heating, made it possible to purposely modify the microstructure subjected to tensile and fatigue loadings. Although many studies have been conducted on the consequences of material improvement due to the two phenomena, opinions were divided on what mechanisms exist in improving mechanical properties, under what current conditions can increase efficiency, and how they interact between EWF and Joule heating. In other words, it has been necessary to introduce major mechanisms for improving the mechanical properties of the material by modifying microstructure. It was mandatory to define how the presence of EWF participates in its improvement.

This thesis has been addressed to understand the effect of HDPEC and to evaluate tensile and fatigue properties using a theoretical framework of fracture mechanics. The characterized microstructure features derived through a series of mechanical and microstructural evaluations suggest a comprehensive mechanism for material strengthening that can be understood owing to the presence of EWF. A raised temperature due to Joule heating was controlled below a temperature that influences any microstructures. All of the current conditions presented in this thesis maximized the effect of EWF.

In summary, details are described in each of the following chapters:

1. In chapter 1, the background of the thesis was introduced based on literature surveys. After the introduction of general stainless steel and type 316 austenitic stainless steel concerned in this study, a series of mechanical and metallurgical issues of the material was provided. Theoretical frameworks for fracture mechanics and electric current were introduced. As an accessible solver for the issues, the HDPEC method is emphasized to replace conventional modification way.
2. Chapter 2 describes the experimental and simulation approaches. Tensile and fatigue tests are the main experimental approaches to evaluate mechanical properties depending on conditions and application manner of HDPEC. Procedures for observation of microstructure and formulation of finite element analysis were provided.
3. In chapter 3, based on a combination of fracture mechanics and finite element analysis, the improvement of tensile fracture properties was assessed. The application

of HDPEC could give advantages to resist crack propagation owing to the modified mechanical properties such as yield stress and strain hardening exponent. The improvements of local fracture strength near the crack tip, fracture toughness and critical crack profiles were successfully achieved under given HDPEC conditions.

4. Strengthening mechanisms of the material as the effect of HDPEC under controlled temperature rising was established in chapter 4. Modification of the grain boundary characteristics and the elemental kinetics were provided as microstructural evidence. The partial grain refinement and the dissolution of $Cr_{23}C_6$ could contribute to improving simultaneously the yield stress and strain at fracture. Breaking the strength-ductility trade-off was achieved as the effect of HDPEC under temperature-controlled HDPEC conditions.
5. The improvement of the low-cycle fatigue (LCF) life in the material was demonstrated in chapter 5. Multiple applications of HDPEC during fatigue crack propagation were the best approach for the improvement of LCF properties. The number of multiple HDPECs and controlling the application timing play an important role in the effectiveness in the improvement of the LCF life. More strong ductile striations in the fatigue fracture surface were revealed than those without HDPEC. It can be thought as the contribution to increase the degree of ductility owing to the annihilation of dislocations.
6. In chapter 6, the application manner under the temperature-controlled method was proposed to ensure high-quality fatigue crack healing. Such fatigue crack healing was achieved under specific HDPEC conditions and crack profiles. The shorter the crack length, the stronger the application condition of HDPEC is required, on the other hand, the longer the crack length, the weaker condition of HDPEC is recommended. The crack closure, the partial bridging, the secondary crack healing, the homogenization of slip bands and the filling material contribute to the fatigue crack healing. It is recommended that abruptly increased and rapidly cooled temperatures with a shape gradient will be expected as the effect of HDPEC application.

The lists above have been elaborated to prove the improvement of tensile and fatigue properties based on microstructural advantages. It can not only overcome the relatively low tensile strength, which is a typical disadvantage of this material, but also contributes to struggling microstructural disadvantages. This method has a good cost performance and can also be easily applied to the material. Further, it is a post-processing method that can use for running mechanical components. Through this research, the effectiveness of HDPEC is proved and it is demonstrated that HDPEC is a promising method for modifying purposely the mechanical and material properties.