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Procedia Engineering 101 (2015) 552 – 560

Procedia Engineering

www.elsevier.com/locate/procedia

3rd International Conference on Material and Component Performance under Variable Amplitude Loading, VAL2015

Mechanical property change in the region of very high-cycle fatigue

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Abstract

Very high-cycle fatigue behaviour of type 316L austenitic stainless steel, which is used as the structural material of the pulsed spallation neutron sources, was investigated through the ultrasonic fatigue test with the strain rate of 10^2 1/s. Cross-sectional hardness distributions of the fatigue-failed specimens for solution annealed (SA) and cold worked (CW) 316L were measured to understand the cyclic hardening or softening in the very high-cycle fatigue region. In addition, the tensile tests of the fatigue-failed specimens were performed at room temperature. Furthermore, the nonlinear ultrasonic system was used for evaluating the dislocation density variation during plastic deformation. The results showed the cyclic hardening in the region of very high-cycle fatigue in the case of SA 316L. In contrast, in the case of 10% CW 316L, cyclic softening occurred when the number of cycles below 10^6 and followed by cyclic hardening. In the case of 20% CW 316L, cyclic softening was observed when the number of cycles below 10^7, while cyclic hardening occurred subsequently.

Peer-review under responsibility of the Czech Society for Mechanics

Keywords: Very high-cycle fatigue; Mechanical property; Ultrasonic fatigue test; Cyclic hardening; Cyclic softening; Stainless steel 316L; Dislocation density

1. Introduction

In modern industry, many mechanical components, such as turbine engine, railway, reactor and spallation neutron source, usually bear very-high cyclic loading (in excess of 10^8 cycles) with high frequency and low stress amplitude. Those components require not only high strength but also excellent fatigue properties. Many researchers have focused

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1877-7058
Peer-review under responsibility of the Czech Society for Mechanics
doi:10.1016/j.proeng.2015.02.066

on investigating the very high-cycle fatigue properties of the component structural materials. It was reported that the very high-cycle fatigue degradation behavior is different from that of the conventional fatigue up to million cycles, the fatigue crack initiation due to internal flaw and/or inclusion becomes dominant in the very high-cycle fatigue regime[1, 2]. Type 316L austenitic stainless steel has been used for the structural material of the enclosure vessel of liquid mercury target for the MW-scale spallation neutron source in the J-PARC (Japan Proton Accelerator Research Complex). The target vessel suffers cyclic loading during the operation and the total number of cycles in the service life is higher than 2×10^{8}, with a high strain rate of 50 1/s at maximum under intensive proton and neutron irradiation environments[3]. Therefore, the resistance to very high-cycle fatigue is an essential requirement to evaluate the structural integrity of the target vessel.

It is well-known that empirical relationships among the fatigue strength, the ultimate strength and the hardness are described as follows[4],

$$\sigma_w = C_1\sigma_u = C_2 H \qquad (1)$$

where σ_w, σ_u and H are the fatigue strength, ultimate tensile strength and hardness, respectively. C_1 and C_2 are the constants depending on the material. It is indicated that the fatigue strength of metals and their alloys is dependent on their ultimate tensile strength and hardness. There are many investigations on changes in mechanical properties during the cyclic plastic deformation [5-11]. The cyclic hardening for normal materials[5-6] and cyclic softening for the previously plastically-deformed materials[7-9] in the low cycle strain-controlled fatigue were observed. It was supposed that the cyclic behaviour, i.e. cyclic hardening or softening, is related to the dislocation density of the materials[10,11]. The storage-recovery model, i.e. the interaction between the plastic deformation induced dislocation generation and annihilation, was used to describe the dislocation density variation during the cyclic plastic deformation [11]. However, mechanical properties changes in the very high-cycle regime are rarely investigated.

In addition, ultrasonic diagnosis which has been used for evaluating the creep damage or cavitation damage[13,14], etc., is used to evaluate dislocation density by measuring the ultrasonic damping. The ultrasonic damping will occur due to the internal defects induced dissipated acoustic energy[13,14].

The main purpose of this paper is to study the mechanical properties in the very high-cycle regime. From this viewpoint, two parameters, micro-hardness and the residual strength, i.e. the ultimate tensile strength of the fatigue-failed specimens are measured to understand the change of mechanical properties during the cyclic plastic deformation. Additionally, the dislocation density variation during cyclic plastic deformation was investigated by using the nonlinear ultrasonic system.

2. Experimental procedures

2.1. Specimen

The type 316L austenitic stainless steel was used for the very high-cycle fatigue test. A part of as-received materials, which were heat-treated at 1055 ºC for 6 min with water quench (referred to SA), were subjected to different cold-rolled levels, i.e. 10% and 20% reduction of thickness (referred to 10% CW and 20% CW). The original ultimate tensile strength of SA, 10% CW and 20% CW are 649 MPa, 775 MPa and 882 MPa, respectively. The original universal hardness of SA, 10% CW and 20% CW are 2.44 GPa, 4.21 GPa and 5.31 GPa, respectively.

An hourglass shape specimen was selected for the test as shown in Fig. 1(a). In order to obtain the resonance frequency of the specimen at 20 kHz, the lengths of l and L were selected as 22.7 mm and 40 mm, respectively. The surface roughness R_Z (JIS-B6001 2001) of the as-received specimen is 2.4 μm, which is proved to have no effect on the fatigue strength[3].

2.2. Fatigue test

Fatigue tests were conducted by using an ultrasonic fatigue testing system (Shimadzu, USF-2000) as shown in