Journal of Nuclear Materials xxx (2017) 1–7

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Temperature measurement for in-situ crack monitoring under high-frequency loading

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ARTICLE INFO

Article history:
Received 19 January 2017
Received in revised form
13 November 2017
Accepted 11 December 2017
Available online xxx

Keywords:
Gigacycle fatigue
High-strain rate
Crack propagation
Temperature
Thermography
Non destructive inspection

ABSTRACT

A liquid mercury target vessel, composed of type 316L stainless steel and used in a pulsed spallation neutron source, suffers not only from proton and neutron damage but also cyclic impact stresses caused by proton beam-induced pressure waves. In a previous study, we carried out an ultrasonic fatigue test to gigacycles and observed that the specimen surface temperature rose abruptly just before failure. To understand the mechanism of this temperature rise, the temperature distribution of the specimen surface was measured using a thermography instrument during an ultrasonic fatigue test. The result showed that the temperature rose locally, especially at the crack tip, and the peak position moved with crack propagation. Furthermore, nonlinear structural analysis by LS-DYNA was performed to clarify the mechanism of this temperature rise. The analytical results showed that the heat due to plastic deformation at the crack tip is the dominant factor underlying the temperature rise rather than friction between crack surfaces.

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1. Introduction

A pulsed spallation neutron source, which generates neutrons by injecting high-intensity pulsed proton beams into liquid mercury, is installed at the Materials and Life science experimental Facility (MLF) in Japan Proton Accelerator Research Complex (J-PARC). A mercury enclosure vessel composed of type 316L stainless steel (316L SS), a so-called target vessel, suffers not only proton and neutron irradiation damage but also cyclic impact stress caused by proton beam-induced pressure waves [1]. The target vessel undergoes more than 2×10^8 cycles over its designed service life of 2500 MWh and/or 5 dpa (displacement per atom) which is decided temporally based on ductility under irradiation [2]. Furthermore, the strain rate at the beam window of the target vessel reaches approximately 50 1/s at the maximum. Fig. 1 shows the time responses of the stress and strain rate at the center of the beam window of the mercury target vessel at 1 MW in J-PARC, as obtained from numerical simulation. The strain rate is much higher than that of conventional fatigue loading of ~10^{-1} 1/s.

It was reported that the fatigue strength in the gigacycle region is different from conventional fatigue strength up to millions of cycles. For example, internal nonmetallic inclusions lead to internal fracture, so-called fish-eye, at more than 10^7 cycles for high-strength steels, and it is difficult to define the fatigue limit using fatigue data for up to 10^7 cycles [3]. By contrast, in the austenitic stainless steels used as structural materials for nuclear components, fatigue data for cycle counts higher than 10^7 is insufficient [4]. It was reported that fatigue failure originating from the surface (surface fracture) is dominant in solution-annealed 316NG, whereas fish-eye fracture originating from the inclusion of pre-strained material occurred in only one case [4,5]. A remarkable reduction in the total elongation due to the nonmetallic inclusions was observed in a few 316LN specimens in a quasi-static tensile test involving post-irradiation examinations of the mercury target vessel used in the Spallation Neutron Source at Oak Ridge National Laboratory (ORNL) [6].

In previous studies, an ultrasonic fatigue test, which is one of the accelerated test methods that uses ultrasonic-resonance, was performed to investigate the gigacycle fatigue strength of 316L SS. The result showed that fatigue failure due to surface cracking occurred when the number of cycles was higher than 10^7, and obviously, the fatigue limit of up to 10^9 cycles was not reached. Furthermore, specimen temperature rose abruptly just before failure, accompanied by surface oxidation [7,8]. Change in specimen temperature

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https://doi.org/10.1016/j.jnucmat.2017.12.019
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Please cite this article in press as: T. Naoe, et al., Temperature measurement for in-situ crack monitoring under high-frequency loading, Journal of Nuclear Materials (2017), https://doi.org/10.1016/j.jnucmat.2017.12.019

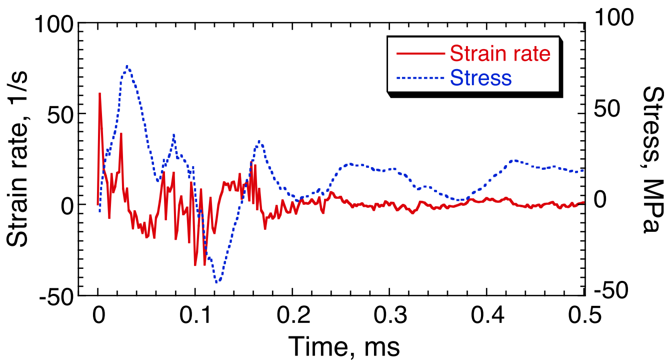

Fig. 1. Time responses of stress and strain rates of beam window for mercury target vessel at beam power of 1 MW.

during fatigue testing has been reported in many studies. For example, Sakagami et al. developed self-reference lock-in thermography, in which a reference signal was constructed from sequential data on the thermoelastic temperature change, for remotely and non-destructively detecting the fatigue cracking [9]. Luong proposed a prediction method for detecting the fatigue limit in a low-cycle fatigue test by analyzing the temperature change due to irreversible energy dissipation obtained from infrared thermography [10]. This method was based on the detection of inflection point of the dissipated energy, which increases with stress amplitude. Akai et al. confirmed the applicability of that prediction method for the fatigue testing of 316L SS at 5 Hz from the viewpoint of change in the dissipated energy as a function of stress amplitude [11].

As for the ultrasonic fatigue test in which the strain rate is three orders of magnitude higher than that in the conventional fatigue test, Wagner et al. reported a rise in the temperature of cast aluminum-silicon alloys just before failure [12]. Krewerth et al. investigated crack initiation and crack propagation in AlSi7Mg steel by using thermography and concluded that infrared thermal measurements facilitate the exact detection of the initiation of internal, surface, and multiple cracks, as well as their propagation pass; the abrupt temperature rise due to crack propagation occurred at approximately 99% of the total fatigue life of the specimen [13]. Ranc et al. developed a thermomechanical model to investigate the relationship between thermal effects and crack initiation and propagation, and concluded that the temperature field of the developed model shows a good correlation with experiment results, and crack propagation constitutes a small part of the specimen lifetime [14]. In the case of the ultrasonic fatigue test, the mechanism of temperature change during the fatigue test seems to be different from the thermoelastic effect observed in conventional fatigue, because the temperature increase is much higher than that under conventional fatigue. Specifically, during the conventional low frequency fatigue test, it is possible to observe the thermoelastic effect which oscillate with a zero-mean value with cycle because the integration time of the infrared thermography is much smaller than the cycle period. However, for the ultrasonic fatigue test, the infrared thermography integrate during many cycles and is not able to detect the thermoelastic effect.

In this fundamental study on detecting the initiation and propagation of fatigue crack by remote and non-destructive measurement, with an aim to clarify the mechanism of temperature rise just before failure, measurement of surface temperature distribution on a 316L SS specimen during an ultrasonic fatigue test was performed using infrared thermography. Furthermore, nonlinear structural analysis was performed to clarify the mechanism of temperature rise, with a focus on plastic strain, friction, and beating of the fracture surface.

2. Experiment

2.1. Materials and specimens

Type 316L stainless steel, which is the structural material of the mercury target vessel, was used for the gigacycle fatigue test. As-received materials has been heat-treated by solution-annealing (SA) at 1120 °C for 7.5 min, followed by water quenching. A part of the SA plate was cold-rolled to 20% reduction in thickness for simulating irradiation-hardened material by increasing the dislocation density. This part is referred to as CW hereinafter.

Schematic drawings of the specimen designs are shown in Fig. 2. Two types of specimen were selected for the ultrasonic fatigue test an hourglass-shaped specimen and a notched plate specimen. The former was of the standard shape, the latter was selected to localize crack initiation location by notch and measure temperature distribution on a flat surface. The longitudinal direction of the specimen surface was set perpendicular to the working direction. Surface roughness of the specimens was as-machined ($Ra = 0.46$ μm) without any heat treatment. To obtain the resonance frequency of the specimen at 20 kHz, the lengths l and L of the hourglass specimen were selected according an empirical equation [4,15] as 22.7 mm and 40 mm, respectively. For the plate specimen, given that the shape has no empirical equation, l and L were selected as 23.5 mm and 41.07 mm, respectively, based on the result of resonance analysis by FE simulation.

2.2. Ultrasonic fatigue test

Gigacycle fatigue tests were conducted using an ultrasonic fatigue testing system (Shimadzu, USF-2000). Fig. 3 shows a photograph of the experimental setup. Ultrasonic oscillation at the rated frequency of 20 kHz was applied to the specimen through an ultrasonic horn fixed at one end of the specimen. The stress amplitude was controlled by changing the displacement amplitude of the free-end of the specimen. The specimen was loaded in tension-compression (ratio of stress $R = \sigma_{max}/\sigma_{min} = -1$). Fatigue failure in this study was defined as the point which the resonance frequency of specimen exceeded −0.5 kHz, because the resonance frequency decreases with fatigue crack initiation. Consequently, the specimen was not completely broken after the fatigue test. In

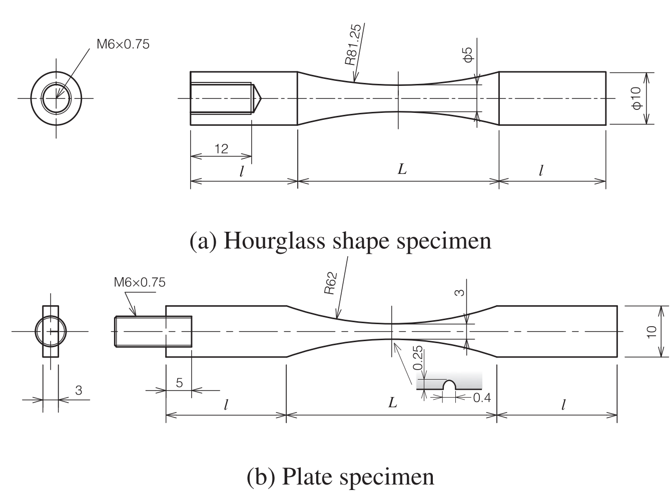

Fig. 2. Fatigue test specimens (Dimensions in mm).

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