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Use of ultrasonic back-reflection intensity for predicting the onset of crack growth due to low-cycle fatigue in stainless steel under block loading

Md. Nurul Islam [a,*], Yoshio Arai [b], Wakako Araki [b]

[a] Department of Mechanical Engineering, Rajshahi University of Engineering and Technology, Rajshahi 6204, Bangladesh
[b] Department of Mechanical Engineering, Saitama University, Japan

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ABSTRACT

The present study proposes the use of ultrasonic back-reflected waves for evaluating low cycle fatigue crack growth from persistent slip bands (PSBs) of stainless steel under block loading. Fatigue under high-low block loading changes the back-reflected intensity of the ultrasonic wave that emanates from the surface. Measuring the change in ultrasonic intensity can predict the start of crack growth with reasonable accuracy. The present study also proposes a modified constant cumulative plastic strain method and a PSB damage evolution model to predict the onset of crack growth under block loads.

1. Introduction

While structural components in practical engineering applications are nearly always subject to stresses under variable amplitude loading (VAL), most fatigue data measured in the laboratory has been obtained under cyclic loads with constant amplitude. Theoretical and experimental studies have recently been carried out on cumulative damage or fatigue crack growth under VAL [1–9]. To maintain and extend the operating life of machines subjected to cyclic loads, it is important to predict the propagation of fatigue cracks which have been initiated in grains. Techniques based on dislocation damping, which decreases the vibration responses, have been investigated quite intensively [10–19]. Fatigue cracks typically originate from a specific location, and the fatigue life consists of initiation and propagation periods. To detect fatigue damage before the fatigue crack starts propagating, local nondestructive measurement is crucial. An example of such a measurement method is the high-frequency focused-beam ultrasound technique, developed in our group, which enables us to detect dislocation damping in a specific grain from the grain-by-grain decrease of the ultrasonic back-reflection response [20,21]. Macroscopic cracks reflect ultrasonic waves and increase the back-reflection intensity. Nurul et al. [22] have elucidated the effect of plastic strain range on the ultrasonic back-reflection intensity under constant plastic strain range of low cycle fatigue in the stainless steel JIS-SUS 316NG [23].

This study evaluates the effect of variation of plastic strain range on the ultrasonic back-reflection response during initiation and propagation of low-cycle fatigue cracks in stainless steel SUS 316NG. We also propose methods to predict the remaining life of the stainless steel sample in terms of the onset of crack growth.

2. Materials and methods

2.1. Materials

The material used in this experiment was an austenite stainless steel (JIS-SUS316NG) [23]. Its chemical composition and mechanical properties are given in Tables 1 and 2, respectively. The specimen shape, its dimensions is shown in Fig. 1. To observe the slip band as well as initiated crack by optical microscope, polishing was done using different fine grade emery paper and finally buffing was done on the center portion of the test piece with 0.1 μm alumina powder. Fig. 2 shows the microstructure of the test specimen.

The average grain diameter found using linear intercept method is 100 μm [22].

* Corresponding author. Tel.: +880 0721 750 319, mobile: +880 01191 637268; fax: +880 0721 750 319.
E-mail address: nurul93213@yahoo.com (M.N. Islam).

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2.2. Fatigue testing

Strain-controlled plane bending fatigue tests were performed using a hydraulic material testing machine (MTS810). Under block loading conditions, the high plastic strain range $\Delta\varepsilon_p^h$ was applied with N^h cycles, followed by cyclic loading of the low plastic strain range $\Delta\varepsilon_p^l$ until the start of crack growth and throughout the crack propagation. The loading sequence is shown in Fig. 3 and the detailed block loading conditions are listed in Table 3.

2.3. Measurement of ultrasonic back-reflection

To measure the ultrasonic back reflection intensity from the material surface, water immersion method was used with a high frequency (100 MHz) point-focused transducer, whose focal length was 12.5 mm, at an incidence angle of 30° to generate surface wave. Fig. 4a shows a diagram of the measurement system and Fig. 4b shows the propagation path of the ultrasonic wave. The induced surface wave is reflected by the grain boundary as well as propagate on the surface. The back reflected wave was received by the transducer as shown in Fig. 5 as a typical wave form. The ultrasonic parameter A_{max}/A_0 (normalized value of back-reflection intensity) was measured. The back-reflection intensity A_{max}/A_0 is defined as the normalized value of the intensity, where A_{max} is the peak value of intensity during fatigue at specific locations from the initiation point of the crack, and A_0 is the maximum value of back-reflection intensity before loading of the corresponding location ($N = 0$).

3. Experimental result

3.1. Comparison of ultrasonic microscopy and optical microscopy results

Fig. 6 shows images of the same sample, taken with ultrasonic microscopy (upper image) and optical microscopy (lower image). The rectangular marks in the ultrasonic images, and the arrows in the optical images, correspond to the location of PSBs from where the crack initiated. In the ultrasonic images, the inhomogeneous distribution of brightness denotes the back-reflection intensity from the grain boundaries. In the optical images of the same location, and for the corresponding number of cycles, the black line represents the slip band and the rectangular area indicates the back-reflection intensity. The length of the slip band remains constant before the back-reflection intensity increases, (decreasing the intensity in rectangular mark location in Fig. 5 at $N = 800$ and $N = 1050$ cycle) and begins increasing when the back-reflection intensity also increases (at about 1100 cycles), indicating the start of crack growth from a crack initiated along a PSB. In ultrasonic microscope image the bright region is the reflected intensity from grain boundary and other region is inside the grain. Sometime crack initiated from the grain boundary and sometime in the grain. Before a crack start to grow the ultrasonic intensity decreases and at the start of crack growth the back reflection intensity increases. Similarly when a crack starts to grow in the grain, the nearest grain boundary reflection (bright region) affected. In both cases the effects of grain boundary were in consideration.

Fig. 7 shows the relationship between back reflection intensity, slip band length and number of fatigue cycles of the corresponding

Table 2
Mechanical properties.

E (GPa)	ν	$\sigma_{0.2}$ (MPa)	σ_B (MPa)
190	0.25	261	583

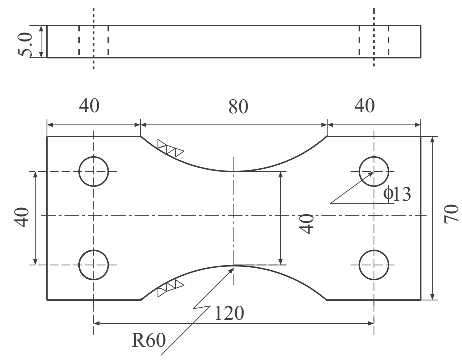

Fig. 1. Specimen configuration.

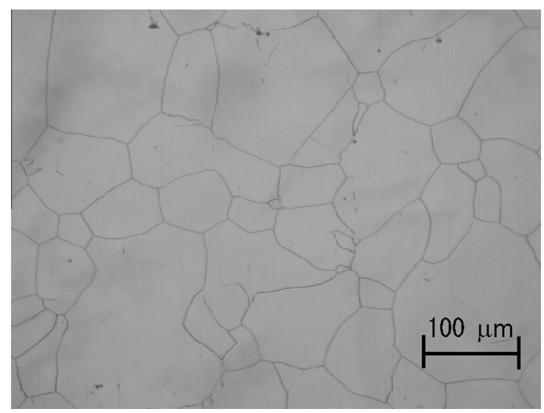

Fig. 2. Microstructure of the test specimen.

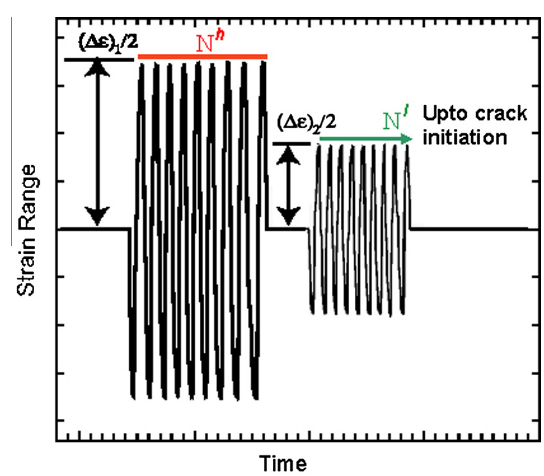

Fig. 3. Block loading.

Table 1
Chemical compositions (wt.%).

Cr	Ni	C	N	Mn	Si	S	P	Mo	Cu	B	Co	As	Fe
17.4	11.9	0.02	0.07	1.69	0.31	0.002	0.023	2.25	0.11	0.009	0.19	0.004	Bal