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PREDICTION OF CRACK INITIATION OF STAINLESS STEEL SUS316NG USING SCANNING ACOUSTIC MICROSCOPE

Islam Md. NURUL[1], Yoshio ARAI [2] Wakako ARAKI[3]

[1] Assistant Professor
Department of Mechanical Engineering, Rajshahi University of Engineering and Technology, Bangladesh.
[2] Professor
Department of Mechanical Engineering, Saitama University, Japan.
[3] Professor
Department of Mechanical Engineering, Saitama University, Japan
nurul93213@yahoo.com*, yarai@mech.saitama-u.ac.jp, araki@mech.saitama-u.ac.jp

***Abstract**- The objective of present study is to develop a prediction method of fatigue crack initiation of cyclically loaded austenitic stainless steel (SUS316NG) using ultrasonic wave. Optical microscopy and scanning acoustic microscope have been used to study the surface slip bands and back reflection intensity from these bands. Ultrasonic data is recorded as a function of the number of cycles and compared with the length of the slip band measured optically. Optical observation of microstructure and back reflection intensity by scanning acoustic microscopy revealed that with increasing the number of fatigue cycle the slip band density increased and the amplitude of back reflection intensity gradually decreased before the slip band length increases. Cyclic loading results the increase in dislocation density along persistent slip bands (PSBs). The dislocation segments vibrate in response to ultrasonic stress and absorb the wave energy. Attenuation is caused by the movement of dislocation and this mechanism was considered.*

Keywords: Ultrasonic method, Back reflected intensity, Crack initiation and Austenitic stainless steel.

1. INTRODUCTION

It is necessary to develop a technique of detecting or estimating the process of fatigue crack initiation of cyclically deformed material in order to predict the residual fatigue life. The PSBs development as well as extrusions and intrusions are formed in the surface grain in case pure metal and some alloys [1-5] as a result of irreversible glide of dislocations due to cyclic loading. The potential sites for fatigue crack initiation such as PSBs, extrusions or intrusions with continuing cyclic straining are considered. The relationship between strain amplitude, the behavior of cyclic stress-strain and the evolution of dislocation structure has been studied for steels [6-7], nickel [8]. Material damage evaluation by ultrasonics, attenuation coefficient change with increasing the number of fatigue cycle by measuring the acoustic signal on polycrystalline aluminum, steel and copper were reported [9-14]. The acoustic attenuation and velocity change on the dislocation mobility was found by Granato and Luicke [15,16] in their string model of dislocation vibration.

In the previous research, a method for evaluating low-cycle fatigue crack growth using ultrasonic back reflection intensity and the dependency of plastic strain range on the evolution of PSBs were proposed [17]. Crack growth starts to take place from a specific location without affecting the other region. In such case, the local measurement of fatigue damage plays an important role to predict the remaining life. In this research we measure the changing behavior of ultrasonic back reflection intensity during fatigue process using two different in-plane incident angles in order to predict the crack initiation.

2. MATERIALS AND METHOD

An austenite stainless steel (JIS-SUS316NG) [18] was used in this study. The chemical compositions and mechanical properties are given in Tables 1 and 2, respectively. Specimen configuration is shown in Fig.1. The microstructure of the test specimen is shown in Fig. 2 and the average grain diameter is 100 μm (by linear intercept method). The specimen was deformed cyclically in an electro-hydraulic material testing machine (MTS810), at a room temperature in air. Test specimen is subjected to a plane bending load whose strain amplitude was 1200×10^{-6}. The stress ratio was -1, and loading frequency was 1 Hz. Ultrasonic measurements were carried out using immersion method. Fig 3 shows the propagation path of ultrasonic wave.

Table 1 Chemical compositions [wt.%]

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

Table 2 Mechanical properties

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

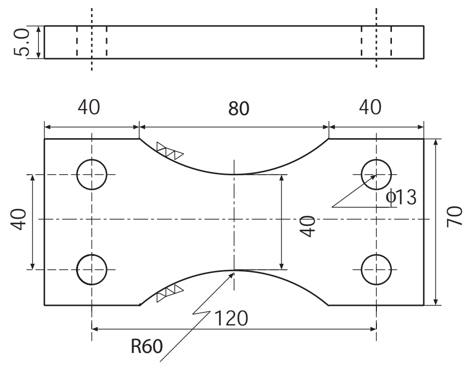

Fig. 1: Specimen configuration [unit: mm]

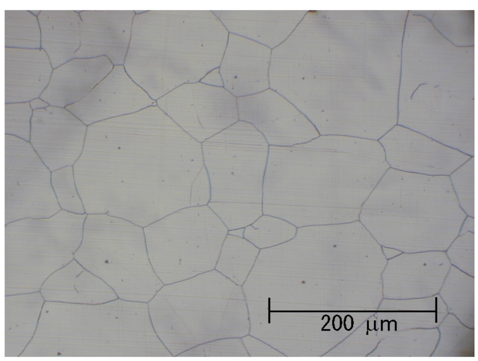

Fig. 2 Microstructure of tested material

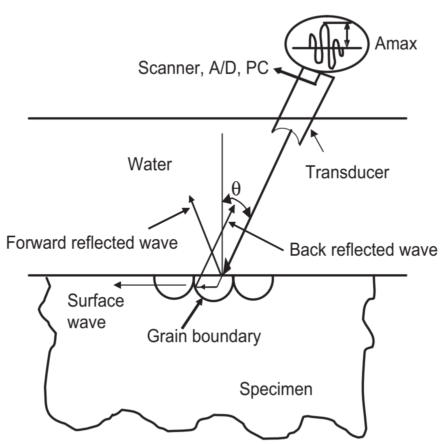

Fig.3: Propagation of ultrasonic wave

The leaky reflected surface wave by the grain boundaries was received by the same transducer. The transducer receives the ultrasonic back-reflected wave from the reflection off the crystal grain boundary. The maximum intensity A_{max} of the back-reflected wave is normalized by the initial value A_0 as the reference value and the ratio A_{max}/A_0 is used to monitor changes in back-reflection intensity, which is attributed to fatigue. The in-plane incident angle for 0^o and 80^o is shown in Fig.4. The reference direction (zero degree) is in the stress direction as shown in Fig.4.

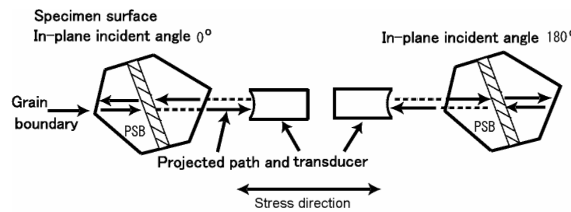

Fig.4: In-plane orientation measurement direction

3. EXPERIMENTAL RESULTS AND DISCUSSION

Fig.5 shows the scanning acoustic microscope image at crack initiated location on 0º and 180º measurement direction. The number 1, 2, 3 and 4 at the end of arrow mark on this image indicate four selected location from where start of crack growth occurred. Fig.5 contain five images, (a) and (b) before loading (N=0), (c) and (d) at start of crack growth (N=1800) and (e) shows the decreasing behavior of ultrasonic on 180º measurement direction where 0º direction measurement doesn't show this behavior. Inhomogeneous distribution of brightness in the ultrasonic microscope images indicates the back reflection intensity from grain boundaries. From previous results [17] it was known that the location which includes high brightness of back reflection intensity is favored for measuring decreasing behavior if a crack is initiated from the location. Before loading (N=0) the back reflection intensity at the center of rectangular mark region (location1, end point of pink color arrow) show low brightness (difficult to measure ultrasonic decreasing behavior) on 0º and it shows high brightness on 180º measurement direction. On rectangular mark region among two different measurement directions, we are able to catch the decreasing behavior of ultrasonic from early stage of fatigue life just before the start of crack growth on 180° measurement direction. Fig.5 (e) shows the decrease in back reflection intensity before the start of crack growth for location 1 at 180º measurement. One example of optical and corresponding scanning acoustic microscope image which shows the decreasing behavior of ultrasonics is shown in Fig.6 at location 1 in Fig.5 (b). From this result, a decrease in brightness at rectangular mark location appears with increase in fatigue cycle and large decrease appears at crack initiation and same time the length of the slip band start to increase.

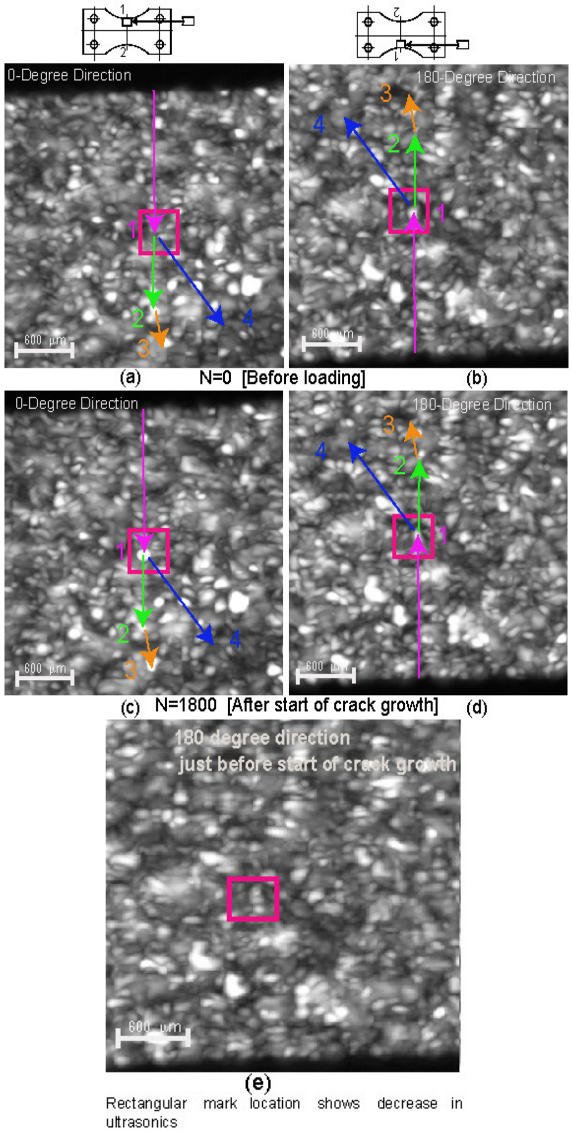

Fig.5: Change in back reflection intensity on 0° and 180° in plane orientation direction measurement

In order to predict the crack initiation life, we assume a damage evolution model [17] in a crystal grain that includes PSBs relating D_{PSB} with plastic strain range and number of fatigue cycle.

$$D_{PSB} = \bar{D}_{PSB}\left[\left\{1-\exp(-\kappa_\varepsilon \Delta\varepsilon_p)\right\} + \left\{1-\exp(-\kappa_N.\frac{N}{N_f})\right\}\right]$$

$$N > 0 \qquad (1)$$

where $\bar{D}_{PSB}$ is half the saturated value of D_{PSB}, κ_ε is a coefficient shows the dependency of D_{PSB} on the plastic strain amplitude, and κ_N is a coefficient shows the dependency of D_{PSB} on the number of cycles. The average dislocation density in the crystal grain including PSBs becomes

$$\Lambda_{av} = \Lambda_{PSB} \times D_{PSB} + \Lambda_0 \qquad (2)$$

where Λ_{PSB} is the density of movable dislocations in PSBs and Λ_0 is the initial dislocation density of the grain. Using the value of Λ_{av} from Eq.(2), we can estimate the attenuation of ultrasonic in the grain including PSBs and the back-reflection intensity from the grain using [15,16]

$$\alpha = C_1 \Lambda_{av} L^4 f^2 \qquad (3)$$

$$\frac{A_{max}}{A_0} = \exp\{-2(\alpha_1 - \alpha_0)H\} \qquad (4)$$

where C_1 is the material constant, L is the dislocation loop length, f is the frequency of the ultrasonic wave, α_0 and α_1 are coefficients of attenuation for the initial and current states, respectively, and H is the radius the of crystal grain.

To calculate the attenuation using equation (3), we assume L, $\bar{\Lambda}_{PSB}$ and Λ_0 are 160 nm, $6.0\times10^{15}\,m^{-2}$ and $1.0\times10^{12}\,m^{-2}$ [19-21] respectively. The critical value of A_{max}/A_0 is assumed as the average amount of decrease in A_{max}/A_0 over several PSBs from where the crack growth starts in the experiment. The experimental and predicted value start of crack growth using D_{PSB} model is shown in Fig. 7 and it is found that predicted value is close to the experimental value.

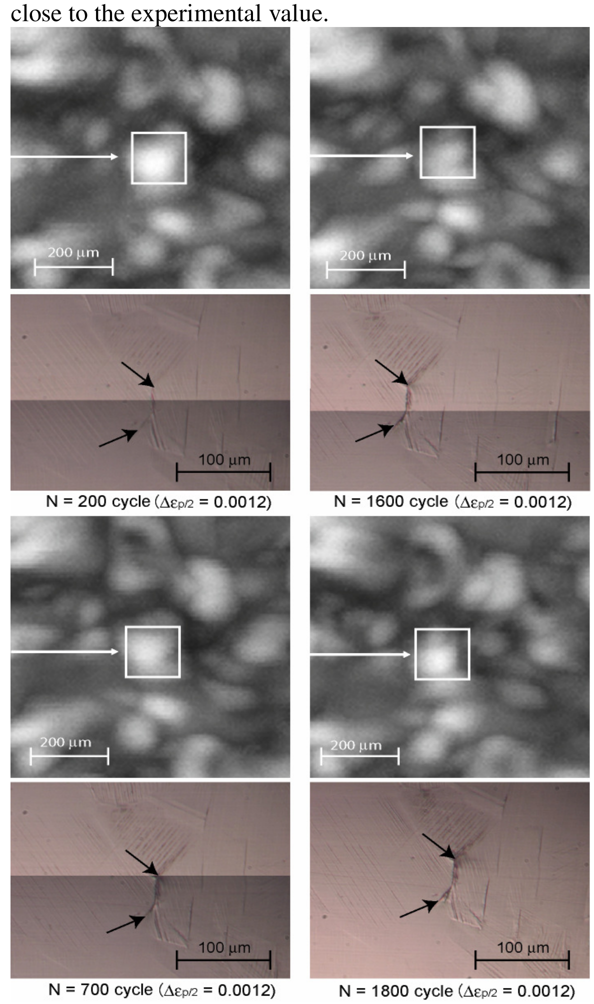

Fig.6: Ultrasonic and corresponding optical microscope image showing the change in length at the crack initiation.

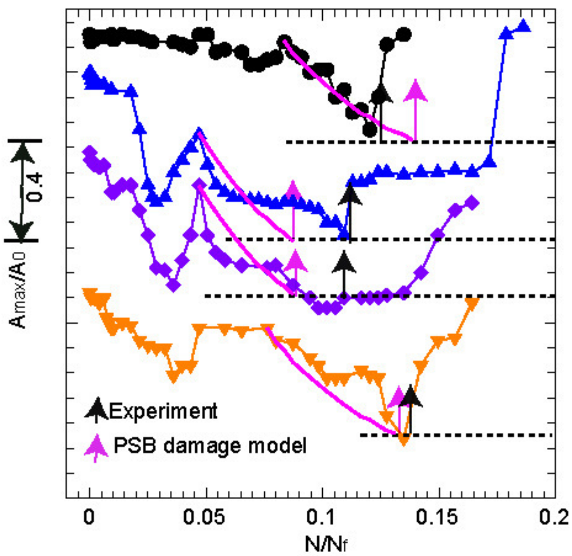

Fig.7: Relationship between back reflection intensity and fraction of fatigue life, $\Delta\varepsilon_p / 2 = 0.0012$

4. CONCLUSION

(1) PSB damage evolution model can be used in order to predict the fatigue crack initiation life.

(2) The number of location detection from where decreasing behavior of back reflection intensity observed was increased using different in-plane orientation direction measurement.

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