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EVALUATION OF CRACK INITIATION OF SUS316NG UNDER VARIABLE LOADING USING ULTRASONIC BACK REFLECTION

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ABSTRACT

A change in ultrasonic back reflection intensity is used to predict the crack initiation life of austenitic stainless steel in its early stage of fatigue life due to variable loading. Behavior of back reflection intensity from the surface of the material due to fatiguing was measured. Due to the formation of persistent slip bands (PSBs) as well as increasing the average dislocation density, with increasing the number of fatigue cycle back reflection intensity was decreased before the crack initiation on that specific crystal grain where crack was initiated. The attenuation of ultrasonic back reflection intensity is due to the vibration of dislocation was considered.

Keywords: Back reflected Intensity, Attenuation, Crack Initiation.

1. INTRODUCTION

In practical application, many structural components are subjected to stresses of variable amplitude loading (VAL). Most of the fatigue data have been obtained due to cyclic loads under constant amplitude but in almost all engineered systems the operating condition leads to variable amplitude loading [1-3]. It is suggested by number of author’s that variable stress cycle could be more damaging than constant stress cycle. Prediction a start of fatigue crack which has been initiated in a grain starts propagating is important for the life maintenance of machines subjected to cyclic loads. Techniques based on dislocation damping which decreases the vibration responses have been investigated quite intensively [4-13]. Fatigue fracture originate from a specific location including initiation and propagation periods. The detection of fatigue damage before fatigue crack development using nondestructive technique, local measurement plays an important role. In the previous research, a method for evaluating low-cycle fatigue crack growth using ultrasonic back reflection intensity on the evolution of PSBs were proposed [14] and also authors made clear the effect of plastic strain range on the ultrasonic back reflection intensity behavior under constant plastic strain range condition of low cycle fatigue in stainless steel of nuclear grade SUS 316NG [15]. Crack growth starts to take place from a specific location without affecting the other region.

In the present study, the dependence of ultrasonic back-reflection on variable loading at the location where fatigue crack growth starts in stainless steel was evaluated and different method to predict the remaining life for start of crack growth were proposed.

2. MATERIALS AND METHOD

The material used in this experiment was an austenite stainless steel (JIS-SUS316NG) [16]. The chemical composition and mechanical properties are given in Tables 1 and 2, respectively. Specimen configuration is shown in figure 1. Figure 2 shows the microstructure of the test specimen and the average grain diameter is 100 μm (by linear intercept method).

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

Strain-controlled fatigue tests were performed using a hydraulic material testing machine (MTS810) applying plane bending loading. The stress ratio was -1, and loading frequency was 1 Hz. In order to evaluate the change in ultrasonic back reflected wave from the boundary of crystal grain, the ultrasonic wave which is generated from the pulser impinges the material surface at an angle larger than the critical angle. The transducer was used in this study has a central frequency of 100 MHz of focal length is 12.5mm in water, the scan pitch 5 µm, and the angle of incidence 30°. The outline of ultrasonic apparatus and propagation path are shown in Fig. 3 and Fig. 4 respectively. The leaky reflected surface wave by the grain boundaries was received by the same transducer as shown in Fig.4. 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.

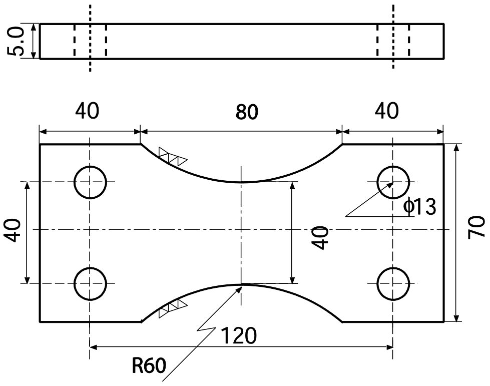

Fig 1. Specimen configuration [unit: mm]

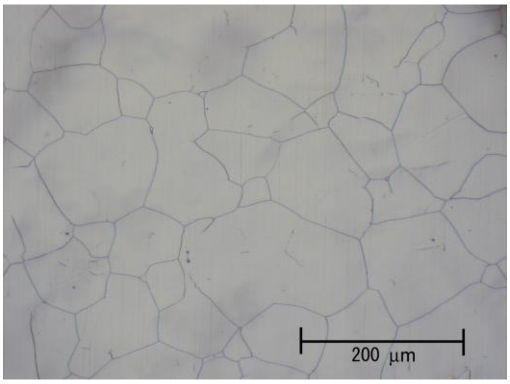

Fig 2. Microstructure of tested material

Under variable loading condition, the high plastic strain range $\Delta\varepsilon^h{}_p$ is applied with N^h cycles followed by cyclic loading of the low plastic strain range $\Delta\varepsilon^l{}_p$ until fracture. The detailed variable loading conditions are listed in Table 3.

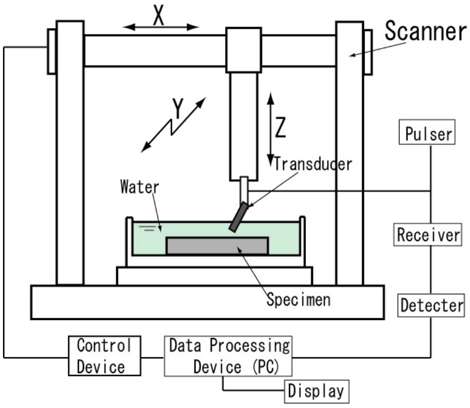

Fig 3. Ultrasonic apparatus

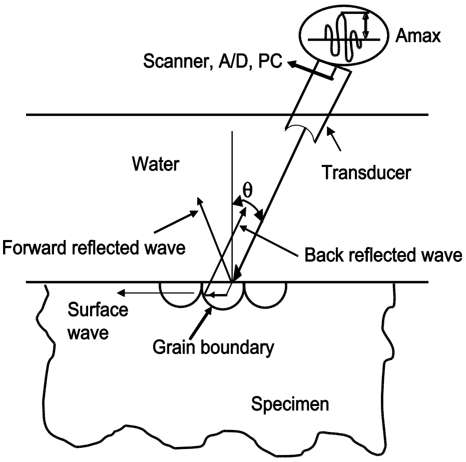

Fig 4. Propagation of ultrasonic wave

Table 3: Variable loading conditions

Specimen	$\Delta\varepsilon^h{}_p$	N^h	$\Delta\varepsilon^l{}_p$
1	0.0024	200	0.0019
2	.005	100	0.0024
3	0.0096	100	0.003

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 5 shows the decreasing behavior of brightness of the ultrasonic measurement and corresponding change in optical microscope image at crack initiated location. Inhomogeneous distribution of brightness in the ultrasonic microscope images indicates the back reflection intensity from grain boundaries. This figure shows the decrease in back reflection intensity before the start of crack growth. 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 which is the pin point of start of crack growth. From experiments result, it is shown that the number of cycles to start of crack growth is decreased compared with the result under the constant plastic strain range of $\Delta\varepsilon_p = 0.0019$ and $\Delta\varepsilon_p = 0.0024$ [15] which shows effect of high amplitude cycling.

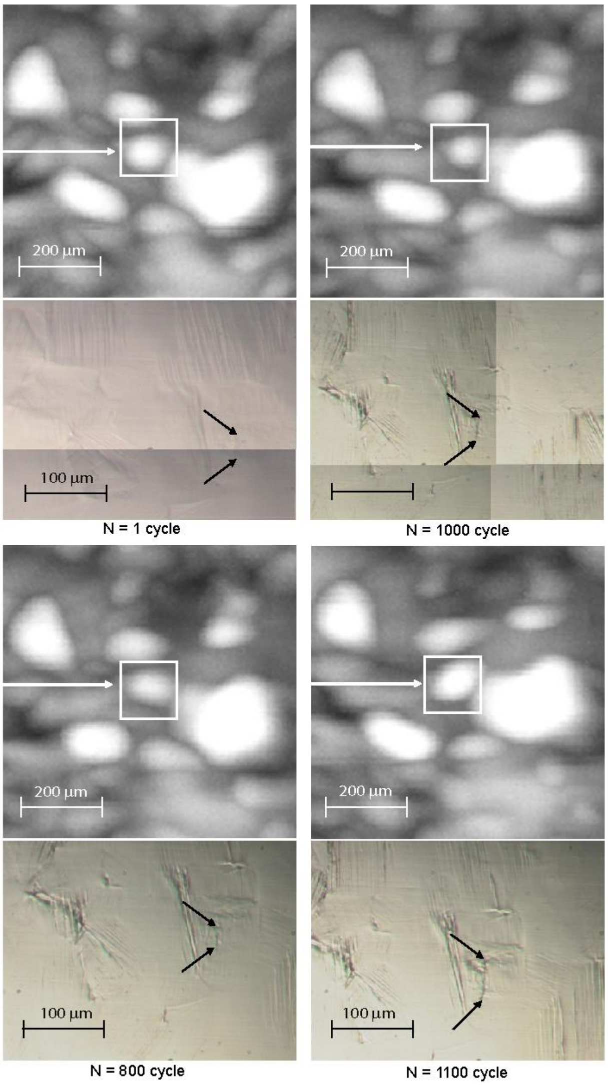

Fig 5. Ultrasonic and optical micrograph of slip bands, and growing crack from the crack initiated along the slip bands. The horizontal direction corresponds to the loading direction.

3.1 Prediction Methods of Start of Crack Growth

The number of cycles before the onset of crack growth can be predicted using

$$N_{SC} = N_{SU} + \Delta N_{SC} \text{...................}(1)$$

where N_{su} and N_{sc} are the number of cycles at start of decrease in ultrasonics and the number of cycles of start of crack growth respectively. N_{su} can be measured using the ultrasonic method, is the average number of fatigue cycle from where a decrease in ultrasonic starts and ΔN_{sc} can be calculated using one of the following three methods i.e. i) Linear approximation explained in details in previous work [14] , ii) PSB damage method (D_{PSB} model) and iii) method using cumulative plastic strain.

3.1.1 D_{PSB} model

D_{PSB} is defined as follows,

$$D_{PSB} = \bar{D}_{PSB}\left[\left\{1-\exp\left(-\kappa_\varepsilon \Delta\varepsilon_p\right)\right\} + \left\{1-\exp\left(-\kappa_N . \frac{N}{N_f}\right)\right\}\right] \text{..(2)}$$

where $\overline{D}_{PSB}$, κ_ε , κ_N are the empirical values under constant plastic strain range tests.

When $N_v < N^h$ D_{PSB} is calculated directly using above equation. N_f is the number of cycles to failure under constant plastic strain range of $\Delta\varepsilon^h{}_p$. Let $D^h{}_{PSB}$ be the value of D_{PSB} when $\Delta\varepsilon_p = \Delta\varepsilon^h{}_p$ and $N = N^h$. When $N_v > N^h$, $D_{PSB} = D^h{}_{PSB} + D^l{}_{PSB}$

where $D^l{}_{PSB} = D^l{}_{PSBv} - D^l{}_{PSBh}$, $D^l{}_{PSBv}$ is the value of D_{PSB} when $\Delta\varepsilon_p = \Delta\varepsilon^l{}_p$ and $N = N_v$. $D^l{}_{PSBh}$ is the value of D_{PSB} when $\Delta\varepsilon_p = \Delta\varepsilon^l{}_p$ and $N = N^h$. N_f in this case is the number of cycles to failure under constant plastic strain range of $\Delta\varepsilon^l{}_p$. The method how to estimate A_{max} / A_0 from D_{PSB} is the same as we have reported earlier [15].

3.1.2 Constant Cumulative Plastic Strain Method

The cumulative plastic strain under variable loading may be determined by the following equation,

$$\Sigma\varepsilon_p = 2\Delta\varepsilon^h{}_p N^h + 2\Delta\varepsilon^l{}_p (N_v - N^h) \qquad (3)$$

The constant cumulative plastic strain method states that the crack growth will start when the cumulative plastic strain increment from N_{SU} to N_v reaches a critical cumulative plastic strain. When $N_{SU} > N^h$,

$$2\Delta\varepsilon^l{}_p (N_v - N_{SU}) = C \qquad (4)$$

Critical cumulative plastic strain *C* is independent of plastic strain range under constant plastic strain range. Under variable load condition, N_{SU} is small that is the start of decrease of ultrasonic back reflection will be early and the start of crack growth will also be early (small N_v). *C* can be calculated using above equation. When $\Delta\varepsilon^h{}_p$ is not so large, large N_{SU} and large N_v at crack growth start will give the same constant, *C*. So the effect of cycles under the high plastic strain range could be included through dependence of N_{SU} on the high plastic strain range. The experimental and predicted value start of crack growth using linear approximation, D_{PSB} model and cumulative plastic strain method is shown in figure 6 for $\Delta\varepsilon^h{}_p$=0.0096 and $\Delta\varepsilon^l{}_p$=0.003 and found that most of the crack initiated locations predicted values of start of crack growth using D_{psb} model are very close to the experimental one. The ultrasonic method is effective for the prediction of start of crack growth (Nsc) under variable amplitude condition because, detected N_{SU} under the variable load conditions reflects the combined damage due to the high plastic strain range and the low one. The local N_{SU} which is measured at a specific location gives the prediction of the location.

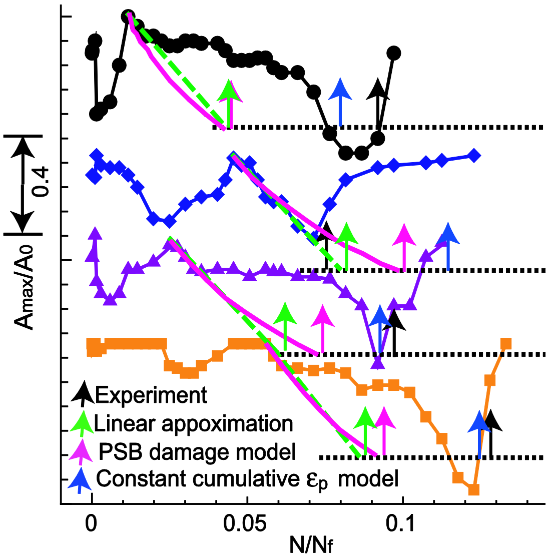

Fig 6. Comparison experimental result with simulation in crack initiated location for $\Delta\varepsilon^h_p$= 0.0096 and $\Delta\varepsilon^l_p$=0.003.

Predicted N_{SC} under variable load condition using constant cumulative plastic strain method with start of ultrasonic decrease N_{SU} seems to achieve a good correspondence with the experimental results which is shown in figure 7.

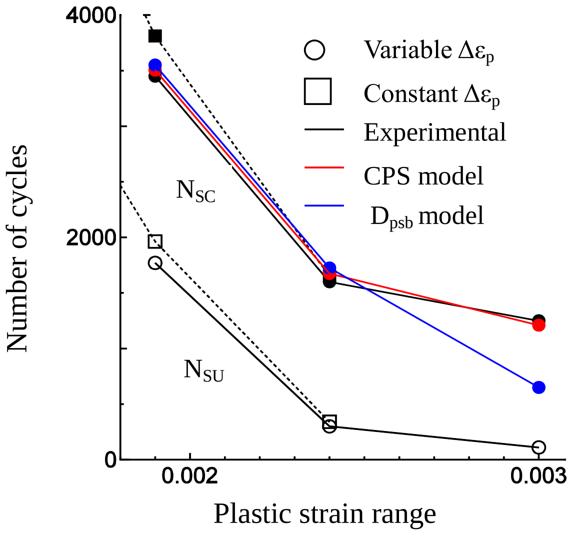

Figure 7 Predicted life to start of crack growth under variable loading of different pairs and experimental results. The plotted plastic strain range in variable loading test is the low one. CPS stands for Cumulative Plastic Strain model.

4. CONCLUSIONS

(1) The predicted value of start of crack growth, Nsc using constant cumulative plastic strain achieve a good correspondence with the experimental results.

(2) The Nsc under variable loading is shorter than corresponding one under constant low plastic strain range tests.

5. ACKNOWLEDGEMENT

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