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The effects of pre-cycle damage on subsequent material behavior and fatigue resistance of SUS 304 stainless steel

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ABSTRACT

A series of fatigue tests with type I and type II cycle damage histories were carried out to observe the effects of pre-cycle damage on the subsequent cyclic material response and fatigue resistance. It was found that the applied cycle history of damage leads to an increase in the extent of variation in cyclic hardening/softening. Furthermore, the shape of stable hysteresis loop changes with the type of cycle damage history under the same strain amplitude conditions. This is due to the occurrence of additional cyclic hardening/softening. By comparing the strain–life curves with and without a cycle damage history, it is found that the cycle damage history leads to a decrease in the number of cycles to failure. The loss in fatigue resistance is dependent on the type of pre-cycle damage history. For the fatigue test with a pre-cycle history, an equivalent cycle ration C_1^* is proposed to predict the residue cycles at the second level in this study. The validity of the modified expression is confirmed by comparing the predicted life results with the corresponding experimental data. It is apparent that the proposed method gives a better prediction than the Miner's rule for the two-step histories.

1. Introduction

In the course of manufacturing, some pre-damage is induced in the components due to plastic forming, as well as the various mechanical pre-histories on the cyclic stress–strain response lead to a problem of great importance in the fatigue life of components during their service. In several studies [1–3], it has been found that a prior mechanical pre-treatment has a strong influence on microstructure and mechanical behavior during cyclic deformation. The extent of variation in stress–strain response, due to the prior pre-deformation, depends on the magnitude of the applied loading, type of pre-deformation and the tested material [4–8]. Based on the above experimental results, it can be concluded that the pre-deformation in the fabrication process leads to the damage in the material. Generally, in the fabrication process, components may receive cyclic pre-damage and are often subject to cyclic loading during later service. Hence, it is interesting to study the stress–strain behavior and predict the residue cycles to failure after cyclic loading at high or low strain level to the specified number of cycles. Generally, the value of summing the cycle ratio at each strain level is close to Miner's proposed value of 1 [9] in most observations. Therefore, the Miner's rule [9] is usually applied to predict a fatigue life of the material subjected to a variable amplitude loading history. It should be pointed out that the rule ignores the sequence effect on damage accumulation based on the observation so that the estimation of fatigue cycles does not correspond to that with observed fatigue cycles. Consequently, in material with a variable amplitude loading history, the sequence effect on damage accumulation needs to be considered for fatigue life prediction. In the study, both cycle damage histories, which are pre-cycles corresponding to an approximate 20% of cycle ratio at strain amplitudes of 0.35% and 0.70% at $R=-1$, are investigated. The result is compared with the experimental value to assess the influence of cyclic pre-damage on the subsequent cyclic hardening/softening behavior, stable stress–strain response, and the residue cycles to failure of SUS 304 stainless steel. Moreover, for a two-step load history test, an equivalent cycle ratio C_1^* corresponding to the second strain level is proposed to estimate the residue cycles during later cyclic straining for the tested material. Simultaneously, the sequence effect on damage accumulation is taken into account on the proposed equivalent cycle ratio. The validity of the proposed method is analyzed in this study.

2. Experiment procedure

2.1. Material and specimen

In this study, the test material was SUS 304 stainless steel. The chemical compositions of the materials are given in Table 1. For the measurement on the chemical composition, the repeated times is two. The geometry of the fatigue specimen is shown in

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Table 1
Chemical compositions of SUS 304 stainless steels (weight %).

C	Si	Mn	P	S	Ni	Cr	Cu	Fe
0.04	0.32	1.79	0.027	0.001	8.15	18.18	2.11	bal.

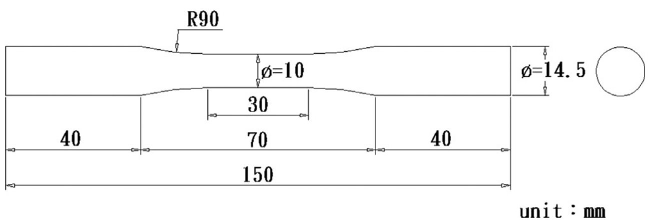

Fig. 1. Schematic illustration and dimensions of specimens.

Table 2
Mechanical properties for SUS 304 stainless steels.

E (GPa)	$S_{y,0.2\%}$ (MPa)	S_u (MPa)	$E.L.$ (%)	K (MPa)	n
187.15	490.5	537.5	50.5	895.98	0.1007

Fig. 1. By use of a CNC lathe, the as-received material was machined to form a specimen with a geometry shown in Fig. 1 and the surface was polished with a fine emery paper. Before the fatigue test, the tensile fracture test was performed under stoke controlled condition with a crosshead rate of 0.01 mm/s. The results of the tensile properties are listed in Table 2. It is noted that the values presented in Tables 1 and 2 are obtained by performing a mean value calculation on the measured results.

2.2. Test programs and procedures

In this paper, a series of fully reversed fatigue tests, two-stage test with a low-high strain level sequence and two-stage test with a high-low strain level sequence were performed in order to investigate the effects of cyclic pre-damage on the subsequent cyclic deformation behavior. In this fatigue test, the applied strain was maintained at a constant level until failure occurred on the testing specimen, and is referred to as the typical fatigue test. Test data generated from the typical fatigue test is essential in observing the pre-cycle damage effects on the subsequent fatigue behavior. It is worth mentioning that the strain–life curve can provide the estimation of the number of cycles to failure at a given strain amplitude. Hence, the number of cycles at an initial strain level can be calculated on the basis of the typical strain–life curve in the design of cycle pre-damage history. Consequently, the typical fatigue tests had to be carried out first in this study. For the low-high test, the specimen was tested at initial strain amplitude of 0.35% for 8000 cycles ($n_1 = 8000$). Subsequently, the strain level was changed to a second level until failure occurred. This type of cyclic straining history is defined as type I cycle damage history. With the assistance of the typical strain–life curve, corresponding to type I damage history, the cycle ratio, $C_1 = \frac{n_1}{N_{f,\text{at } \varepsilon_a = 0.35\%}}$, is calculated to be equal to 21.29%. In this procedure of determining the cycle ratios, $N_{f,\text{ at } \varepsilon_a = 0.35\%}$ is the original cycle to failure life at initial strain amplitude of 0.35%. For the high-low test, the applied initial cyclic straining was at strain amplitude of 0.70% for 500 cycles. The loading history is named as type II cycle damage history. Similarly, the value of the corresponding cycle ratio is 20.64%. All fatigue tests were conducted on a servo-hydraulic Instron 8501 materials testing system with a constant strain rate of 0.01/s and a triangular waveform. A tension–compression extensometer with a 25 mm edge separation was used to control the strain applied in each fatigue test. The cycles to failure, N_f, was defined as the number of cycles performed corresponding to a drop of 10% in load in the fatigue test. The stable stress–strain response was obtained from the hysteresis loop at approximately half-life, where the stress–strain response was stable. In this study, the performed tensile fracture tests and fatigue tests are repeated two or three times under the same experimental condition.

3. Experimental results and discussion

3.1. Effect of cycle damage history on cyclic deformation behavior

In the strain-controlled model, the variation of peak stress response with the applied cycle is usually observed for the tested material subjected to the repeating loading. As shown in Fig. 2, it has been observed that the typical cyclic-stress response curves at the different strain amplitudes also display significant decreases in the stress response for the first fifteen cycles and then the measured peak stress with cycle number decreases prior to failure. Furthermore, it can be seen from Fig. 2 that the plateau of stress in the cyclic-stress response curve increases as the cyclic strain amplitudes increase from 0.35% to 0.70%. This indicates that cyclic softening occurred during the cyclic deformation for SUS 304 stainless steel. Moreover, midlife hysteresis loop data from the fatigue tests were conventionally used to present the stable stress–strain response for the tested material subjected to the repeating loading. Hence, the scale of stable stress amplitude can be directly measured from the midlife hysteresis loop and the stable plastic strain amplitude can be estimated from $\frac{\Delta\varepsilon_P}{2} = \frac{\Delta\varepsilon}{2} - \frac{\Delta\sigma}{2E}$. In the calculation, the elastic modulus, E, measured from tension tests was used. For the correlation between the stable stress amplitude and stable plastic strain amplitude, it is usually fitted in the form of a power-law type equation and is represented as

$$\frac{\Delta\sigma}{2} = K^* \times \left(\frac{\Delta\varepsilon_P}{2}\right)^{n^*} \tag{1}$$

where K^* is the cyclic strength coefficient and the exponent n^* is the cyclic strain hardening exponent. The two parameters K^* and n^* represent the stable response of a material to cyclic straining. In Eq. (1), K^* and n^* are obtained from a least squares fit of stress data

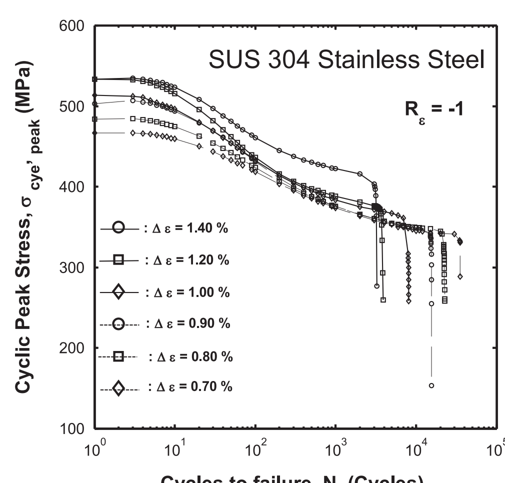

Fig. 2. Superimposed plot of cyclic peak stress with number of cycles that data obtained from typical fatigue test at the strain amplitude ranging from 0.35% to 0.70%.