The effects of pre-deformation on the subsequent fatigue behaviors of SUS 430 Stainless Steel in load-control

Yung-Chuan Chiou, Jen-Kang Yang

1. Introduction

For practical component and work-piece during the production process, engineering materials often undergo a mechanical prehistory and the pre-deformations are usually induced on materials. The behaviors of the used engineering material after pre-straining are often profoundly altered. Therefore, the respective materials in engineering applications need to be evaluated for the effect arising from pre-deformation on the subsequent cyclic deformation behavior and cyclic life. However, the degree of the variations in the subsequent material behaviors such as mechanical properties, plastic performance, creep behavior, fatigue resistance and etc. is more sensitive to the degree of the induced pre-strain and the applied type of loading which leads to the occurrence of pre-strain. Essentially, the pre-strain causes a change in micro-structural alteration and yields variations in various mechanic behaviors. Hence the variations in material response due to the pre-strain are investigated on the basis of experimental observation in several papers (Froustey and Lataillade, 2008; Giacometti et al., 2001; Kang et al., 2007; Mall et al., 2003; Ratchev et al., 1998; Robertson et al., 2008; Waterloo et al., 2001; Whittaker and Evans, 2009). For some materials in (Froustey and Lataillade, 2008; Kang et al., 2007; Robertson et al., 2008; Whittaker and Evans, 2009), it has been found that the tensile plastic pre-strain can cause a change in subsequent fatigue behavior under cyclic loading as compared to the as-received material. This can be attributed that the tensile pre-strain leads to the variation of cyclic stress–strain response for cyclic loading. For the above reason, a monotonic loading process under strain mode is employed to produce the initial pre-strain on the tested material in this paper and the effects of the various pre-strain levels on material response were observed for cyclic loading with a zero stress. The experimental results and observations here provided a basis for a fundamental discussion.
understanding of the dependence in loading history that is a monotonically strained following by a cyclic loading for the tested material. With the consideration of tensile pre-strain effect, three damage energy parameters, $\Delta W_{p}$, $W_{f}$, and $\sigma_{ep}$, are applied to perform life calculations with tensile pre-strain level effect. The tested material is the 430 Stainless Steel.

2. Experiment

The material used in this study is 430 Stainless Steel. The composition of the steel is given in Table 1. For the as-received bar of the tested material, cylindrical test specimens with a gage diameter of 9 mm and a gage length of 30 mm were machined by the CNC lathe. After machining, the gages of the surfaces of all specimens were polished by a fine emery paper to ensure a smooth surface. In the study, first, the tensile fracture tests with a crosshead rate of 0.01 mm/sec were performed under stoke control mode in order to obtain mechanical properties of the tested material. Meanwhile, in order to investigate the influences of the tensile pre-strain on the fatigue behaviors, tensile pre-strain conditions were established for cycling tests at three levels, 5%, 8%, and 12%, which were carried out under strain control mode at a strain rate of $10^{-3}$ s$^{-1}$. For all specimens in as-received condition and each given pre-strain condition, constant amplitude fatigue tests at stress ratio of $R_{p} = -1$ were performed using a triangular waveform with a frequency of 1Hz under load control mode. The applied stress amplitude, $\sigma_{p}$, for the fatigue tests was varied from 240 MPa to 380 MPa. All fatigue tests and the tensile tests were carried on the servo-hydraulic mechanical testing system (Instron 8501) at room temperature. During all mechanical tests, a clipped-on axial extensometer with a 12.5 mm gage length was used to measure the precise strain readings. In addition to the software referred to as Max integrated to the testing system was used to record the measured data throughout the fatigue tests. From this log, the cyclic hysteresis loop curve, the cumulative creep strain, and the cycles to failure for each test could be obtained. Moreover, the number of cycles to failure, $N_{f}$, is defined as the appointed cycle when the corresponding hysteresis loop begins to distort in next cycle and the Hook’s law is employed to calculate the plastic strain in this study. Moreover, based on the results of the tensile fracture tests and the definition of mechanic properties, the mechanic properties of the as-received 430 Stainless Steel were obtained and listed in Table 2.

3. Results and discussion

3.1. Cyclic response

The cyclic strain range responses of 430 Stainless Steel in as-received condition cycled at the stress ratio of $R_{p} = -1$ and at different stress ranges $\Delta \sigma$ are presented in Fig. 1. As shown in Fig. 1, the cyclic strain range always decreases slightly at beginning of the cycles. After the first few cycles, a quasi-steady strain range is gradually reached except when the applied stress range is 760 MPa. In the case of the 760 MPa stress range, the cyclic response of strain range exhibits an immediate increase in the strain range after the first few cycles. It is inferred that the occurrence of fatigue crack initiation is induced in the early cycles and results in the crack propagation for the rest of the fatigue life of the material tested at the stress range of 760 MPa. Moreover, it is found that the higher stress level leads to greater cyclic strain range response. Based on the above observation, the cyclic hysteresis loop was approximately stabilized after the first few cycles. Hence, the hysteresis loop from near half the cycles to failure is used to represent the stable behavior in this study. Furthermore, using Hook’s law, the stable plastic strain range $\Delta \varepsilon_p$ can be determined by examining the defined stable hysteresis loop. Moreover, a power law relation could be used to express the relationship between the applied stress amplitude and stable plastic strain amplitude response. The correlation is referred to as the cyclic stress–strain curve. The relationship is expressed as follows:

$$\Delta \sigma / 2 = K(\Delta \varepsilon_p / 2)^n$$  \hfill (1)

The constant, $K$, is the cyclic strength coefficient and exponent, $n$, is the cyclic hardening exponent. Similarly, the tensile stress–strain curve can be simulated by the power law expression. But the constant, $K$, represents the strength coefficient and exponent, $n$, represents the strain hardening exponent. For comparison, the experimental and simulated tensile stress–strain curves; and the fitted cyclic stress–strain curves with no prior pre-strain, 5%, 8%, and 12% level pre-strain were presented in Fig. 2. As shown in Fig. 2, it is found that a good agreement exists between the simulated and experimental tensile stress–strain curves. Furthermore, it is observed that the experimental curve in tension is always higher than all cyclic stress–strain curves. The comparison indicated that cyclic softening occurred during the cyclic deformation for the as-received material and the extent of cyclic softening increased with increasing of cyclic strain amplitude. Moreover, a very clear and concise trend is also found that the magnitude in strain amplitude increases slightly with increasing pre-strain level under the same stress amplitude condition. The observation revealed that the softening response increased with increasing pre-strain level as compared to the softening response in as-received

![Fig. 1. Cyclic strain range responses of 430 Stainless Steel subjected to a symmetric cyclic loading.](image)
condition. Fig. 3 showed the cyclic hysteresis loops at the first and second cycles from the specimen with prior pre-strain cycled at the stress range of 760 MPa. As shown in Fig. 3, it is clearly that the hysteresis loops at the first and second cycles are open; and the gap in hysteresis loop from the first cycle to the second cycle is decreased. Meanwhile, the point C₂ was located on the left side of the point C₁ in this diagram. It represents that cyclic hysteresis loop moves towards the left-hand side of the diagram. From the view of engineering, the segment OC₂ shown in Fig. 4 represents the shortened amount in strain for the specimen after 2 cycles as compared to the original specimen. The observation implied that the specimen from the as-received material would be shortened in length with cycles during completely reversed cyclic loading. The cyclic behavior is termed compressive cyclic creep behavior. Here, the segment OCₐ on strain axis is referred to as the total creep strain at the N cycle during the whole fatigue life of the material. Essentially, in observing cyclic creep behavior, the cyclic total creep strain is an important index since it can be used to trace the eventual direction of cyclic creep and estimate the amount of the residual deformation on material at any moment throughout the whole fatigue life. Fig. 4 shows a plot of the total creep strain versus the number of cycles at six different stress ranges for the as-received material. As shown in Fig. 4, the tested material displayed cyclic creep from the beginning of cycling at stress ranges from 640 to 760 MPa. The amount of the cyclic total creep strain increased with increasing numbers of cycles in the first approximately 30 cycles and then remained almost constant. Moreover, it was observed that higher stress range caused greater compressive total creep strain response at the thousand cycles. Consequently, a conclusion can be made that there exists an anisotropy between tension and compression on the as-received tested material and a compressive cyclic creep could be induced in all applied cyclic loading. Generally speaking, the cyclic creep results from a difference in the form of the stress–strain curves for successive half cycle, and the difference between the strain hardening curves in tension and compression determines the direction of cyclic creep in next cycle. Experimental data of stress–strain hysteresis loops which were recorded at the first, 40th, and half-life cycles, respectively, for specimens with the pre-strain levels of zero, 5%, and 8% cycled at Δσ = 720 MPa were plotted in Fig. 5(a)–(c); and cycled at Δσ = 6320 MPa for specimens with 12% pre-strain effect was shown in Fig. 5(d). As plotted in Fig. 5(a)–(d), a very clear trend was found that hysteresis loop moved towards the left-hand side of the diagram as compared to the hysteresis loop at the first cycle. The observation revealed that a pronounced compressive creep existed in the tested steel with and without different pre-strain levels in all applied loading cases. In order to realize the pre-strain effects on the stable total creep strain, four kinds of stable total creep strain were also plotted as a function of stress amplitude in Fig. 6. A discernible trend could be observed in Fig. 6 that stable total compressive cyclic creep is found in all applied loading cases and the magnitude in the stable compressive total creep strain increased as the stress amplitude increased for the various values of pre-strain. Moreover, the stable total compressive creep strain scaled with increasing tensile pre-strains for same cyclic loading. This was attributed to the fact that the larger the pre-strain, the larger the an-isotropic behavior effect; and thus, the greater the offset of the hysteresis loops from the origin.

3.2. Effect of pre-strain on stress-life curve

A variation of the stress-life curve plot can be used to compare the effect of pre-strain on the cycles to failure in this study. For the stress-life curve, generally, the relationship between the applied strain amplitude, $\sigma_{am}$, and the cycles to failure, $N_f$, under uni-axial...
loading can be expressed in the form of a power function relationship. The values of coefficient and exponent needed in the power function relationship can be obtained from a least squares fit of the data in log–log scale. For all applied tensile pre-strain levels, both values of coefficient and exponent used in the stress-life curve were determined and summarized in Table 3. By utilizing the values of the parameters in Table 3, these semi-log stress-life curves and data for the tested material with different pre-strain effects are plotted together and shown in Fig. 7. As shown in Fig. 7, it is found that the solid lines have good correlations with the corresponding fatigue data. Furthermore, it is observed that the tensile pre-strain causes a decrease in the number of cycles to failure under the same loading amplitude condition as compared to the as-received material. The extent of the decrease in fatigue life cycles also increased with increasing tensile pre-strain level. This could be attributed to the early occurrence of the fatigue crack initiation and propagation due to the applied tensile pre-strain effect, resulting in decreased cycles to failure.

### Table 3

Summary of the experimental data at $R_\sigma = -1$ with no prior pre-strain and three pre-strain levels for 430 Stainless Steel.

<table>
<thead>
<tr>
<th>Pre-strain (%)</th>
<th>Coefficient</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>470.279</td>
<td>-0.0268</td>
</tr>
<tr>
<td>5</td>
<td>749.5853</td>
<td>-0.0741</td>
</tr>
<tr>
<td>8</td>
<td>646.6243</td>
<td>-0.0636</td>
</tr>
<tr>
<td>12</td>
<td>880.8944</td>
<td>-0.0901</td>
</tr>
</tbody>
</table>

**3.3. Fatigue life prediction**

It should be noted that the previously applied tensile pre-strain to the tested material would lead to a change in the number of cycles to failure, $N_f$, as compared to the as-received tested material. Simultaneously, it is found that the number of cycles to failure decreased with an increase in the tensile pre-strain level under the same cyclic loading condition. Consequently, in fatigue life predic-

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**Fig. 5.** The variations of cyclic hysteresis loops for the first, 40th and half-life cycles for the tested material with (a) zero, (b) 5%, (c) 8% pre-strain level at stress strange of 760 MPa, and (d) 12% pre-strain level at stress strange of 630 MPa.

**Fig. 6.** Dependence of the applied stress amplitude on total creep strain at half-life-cycle. Four pre-strain levels are shown.
tion, it is unsuitable to adapt the controlled stress amplitude as a fatigue damage parameter, which takes account of the pre-strain effect on fatigue life. In addition, it is observed that the fatigue damage is governed by the history of the cyclic hysteresis loop. Therefore, damage parameter based on the energy could be appropriate to predict the fatigue life with different levels of pre-strain under fully reversed cyclic loading. In this paper, three types of the energy based damage parameters are introduced to perform fatigue life prediction with tensile pre-strain effect. They are the stable plastic strain energy, $W_p$; the total plastic strain energy, $W_t$; and the S.W.T. damage parameter, $\sigma_{f\alpha}$; respectively. For the $W_p$ damage parameter approach, essentially, it utilizes the plastic strain energy from the enclosed area within the stable hysteresis loop curve as a damage parameter.

In this paper, using the experimental results from fatigue tests on the as-received tested material, the $W_p-N_f$ relationship can be fitted by the least square technique and computed to be

$$W_p (\text{MJ/m}^3) = 126.1484 (N_f)^{0.5024}$$  \hspace{1cm} (2)

Eq. (2) is employed to predict the number of cycles to failure with different pre-strain effects. The predicted results using the $\Delta W_p - N_f$ relationship are compared with experimental data in Fig. 8. It should be pointed out that the diagonal line in Fig. 8 indicates a perfect agreement. The interval in both dashed lines represents a scatter of the bound of factor 2 in cycles to failure. The points above the diagonal line are conservative prediction, whereas those lying below the diagonal line are non-conservative prediction. As shown in Fig. 8, it can be seen that most of points are located within the bound of factor 2, only two points are out of the bound. Based on the comparison between the predicted and experimental results, the conclusion is made that fatigue damage parameter, $\Delta W_p$, is capable of yielding reasonable life predictions for 430 Stainless Steel with a tensile pre-strain effect. As is well known, the total plastic strain energy, $W_t$, is the sum of the areas of these loops. Generally, the magnitude in $W_t$ is equal to the product of $\Delta W_p$ and $N_f$ based on the assumption that the shape of hysteresis loop remains invariable throughout the fatigue life. The approximately value of $W_t$ would be used to establish the $W_t-N_f$ relationship to perform the prediction of fatigue life with different pre-strain effects in this paper. Similarly, a power function is used to develop the relationship between $W_t$ and $N_f$. The fitted results is expressed as

$$W_t (\text{MJ/m}^3) = 126.1484 (N_f)^{0.5024}$$  \hspace{1cm} (3)

Fig. 8 compares the predicted life results with the corresponding experimental results. It can be seen that most of the data points fall within the bound of factor 2. Based on the compassion shown

Using Eq. (3), the fatigue life predicted by the $W_t$ damage parameter can be calculated and plotted against the corresponding experimental life in Fig. 9. As shown in Fig. 9, a reasonably good agreement is found between the predicted and experimental cycles to failure. Consequently, it can be inferred that the damage parameter, $W_t$, is a suitable parameter in fatigue life prediction with tensile pre-strain effect. Considering the S.W.T. damage parameter, a log–log plot of the value of $\sigma_{f\alpha}$ versus the corresponding cycles for $N_f$ can be approximated by a straight line and the $\sigma_{f\alpha} - N_f$ relationship is found to be:

$$\sigma_{f\alpha} (\text{MJ/m}^3) = 3.5817 (N_f)^{-0.1240}$$  \hspace{1cm} (4)
in Figs. 8–10, generally speaking, the above three damage parameters can provide a satisfactory prediction accounting for the tested material with tensile pre-strain effects under stress controlled.

4. Conclusion

The tensile pre-strain effects on the fatigue behavior and resistance of the 430 Stainless Steel were investigated in this paper. Based on the discussion in the preceding section, some conclusions can be drawn as follows:

1. The cyclic softening behavior occurred during the cyclic deformation in all cases and the softening response increased with increasing pre-strain level as compared to the softening response in as-received condition.
2. The as-received 430 Stainless Steel existed an evident anisotropy between tension and compression, and a compressive cyclic creep could be induced in all applied cyclic loading.
3. The stable total compressive creep strain scaled with increasing tensile pre-strains under the same stress amplitude condition.
4. The tensile pre-strain effect caused a decrease in number of cycles to failure under the same stress amplitude condition and the extent of the decrease in fatigue life cycles also increased with increasing tensile pre-strain level.
5. Based on the compassion shown in Figs. 8–10, the three damage parameters that are $\Delta W_p$, $W_f$, and $\sigma_a \epsilon_a$ can provide a satisfactory prediction accounting for the tested material with a tensile pre-strain effect.

References