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Low Cycle Fatigue Life: Dependence on Test Mode

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Fatigue hardening and softening in materials result in different lives in low cycle fatigue, depending on the test mode. The problem is discussed based on the cyclic stress-strain relation, and a suitable testing mode is suggested for the design of structural parts, which are subjected to either constant load or constant displacement fatigue.

Keywords cyclic stress-strain, fatigue hardening, low cycle fatigue

1. Introduction

Materials when subjected to low cycle fatigue (LCF) cyclically harden or soften depending on the initial condition.[1] Cyclic hardening may be due to generation and interaction of dislocations, solute-dislocation interaction, dynamic strain ageing, martensitic transformation, etc.[2-4] whereas cyclic softening is due to over ageing, cold working, precipitate resolutionizing, precipitate disorder, etc.[5-7] The result of these mechanisms leading to fatigue hardening or fatigue softening is that during cyclic deformation the initial values of the elastic strain $\Delta\varepsilon_{Ei}$ and plastic strain $\Delta\varepsilon_{Pi}$ change until a saturated condition is reached. In some cases no saturation will be observed where the strain values corresponding to half-life are considered. Thus, the saturation or half-life elastic and plastic strain ranges, $\Delta\varepsilon_{ES}$ and $\Delta\varepsilon_{PS}$, are different from their initial values, $\Delta\varepsilon_{Ei}$ and $\Delta\varepsilon_{Pi}$.

Low cycle fatigue life can be established from the data obtained from constant total strain range $\Delta\varepsilon_t$ or plastic strain range $\Delta\varepsilon_P$ or elastic strain range $\Delta\varepsilon_E$ tests. Weisse et al.[8] have reported the fatigue behavior of a low carbon SAE 1045 steel tested at temperatures from ambient to 400 °C. They have pointed out that a material subjected to an initial elastic strain range $\Delta\varepsilon_{Ei}$ and the corresponding initial plastic strain range $\Delta\varepsilon_{Pi}$, depending on the test mode, namely, constant stress range ($\Delta\sigma = E\ \Delta\varepsilon_{Ei} =$ constant) or constant initial plastic strain range ($\Delta\varepsilon_{Pi} =$ constant), has different LCF lives. For the same initial value of $\Delta\varepsilon_{Ei}$ and the corresponding initial value of $\Delta\varepsilon_{Pi}$, the former gives a longer LCF life N_f than the latter in a certain temperature range (dynamic strain ageing regimen, where extensive hardening is noticed), as indicated in Fig. 1 for low carbon SAE 1045 steel.[8] The different LCF lives will give the designer a degree of uncertainty about which test result to use in the actual design, even when knowing the initial load or displacement conditions.

In the current study an attempt was made to clarify the reason for this anomaly and to suggest which type of testing will be better suited to predict the LCF life in such cases where strain hardening or softening takes place during fatigue cycling. The base data given in Ref 9 are reanalyzed and presented to investigate the effects of constant initial elastic strain range and constant initial plastic strain range on the fatigue life of AISI 304LN stainless steel.

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2. Experimental Details

The material investigated was AISI 304LN stainless steel with a grain size of 200 μm. The material was in the solution-annealed condition. The elastic modulus of the material was 190 GPa. The room-temperature tensile properties were 0.2% yield strength of 283 MPa, ultimate tensile strength of 602 MPa, elongation of 61%, and area reduction of 82%. Room-temperature LCF tests were carried out in a servo hydraulic machine with a 400 kN capacity. The total strain range was controlled at values of $\Delta\varepsilon_t = 2.2\%$, 2.0%, 1.7%, 1.2%, 1.0%, and 0.8%. Tests were also carried out on material given 20% cold work. The room-temperature tensile properties of the 20% cold worked steel were 0.2% yield strength of 743 MPa, ultimate tensile strength of 771 MPa, elongation of 34%, and area reduction of 76%. The details of instrumentation, specimen dimensions, etc. are given elsewhere.[9] The values of the total strain range, the initial and half life stress range, the initial and half life values of the elastic and plastic strain ranges, and the fatigue life are given in Table 1 and 2 for the solution annealed and cold worked materials. The elastic strain values were calculated by dividing the stress values by Young's modulus of the material. The plastic strain values were obtained by subtracting the elastic strain values from the total strain values.

3. Results and Discussion

3.1 Strain Range-LCF Life Relation

It has been reported for AISI 304LN stainless steel in the annealed condition that at higher strains cyclic strain hardening occurs. At lower strain ranges, slight softening was observed.[10] In the case of cold worked material there was continuous cyclic softening at all strain ranges.[11] Thus, the introduction of cold work has resulted in large cyclic strain softening.[9] The relationships between half-life plastic and elastic strain ranges and the LCF life are shown in Fig. 2(a) and 2(b) for the solution annealed and cold worked materials. The relations between the elastic strain range and the plastic strain

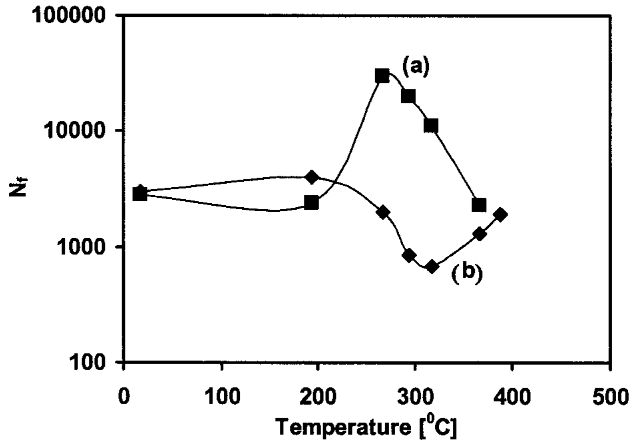

Fig. 1 Effect of test mode on low cycle fatigue life of low carbon SAE 1045 steel tested in two different control modes at a frequency of 0.25 Hz[8]: curve **(a)** constant stress range of 800 MPa, curve **(b)** constant plastic strain range of 1.0%

Table 1 Values of Stress and Strain Ranges and LCF Life SS 304LN, Solution Annealed; *d* = 200 μm, *E* = 190 GPa

$\Delta\varepsilon_t$, %	$\Delta\sigma_i$, MPa	$\Delta\varepsilon_{Ei}$, %	$\Delta\varepsilon_{Pi}$, %	$\Delta\sigma_s$, MPa	$\Delta\varepsilon_{ES}$, %	$\Delta\varepsilon_{PS}$, %	N_f cycles
2.2	690	0.363	1.837	840	0.442	1.758	610
2.0	640	0.337	1.663	760	0.400	1.600	1 020
1.7	630	0.331	1.369	688	0.362	1.338	1 250
1.2	610	0.321	0.879	600	0.316	0.884	3 500
1.0	600	0.316	0.684	540	0.284	0.716	7 000
0.8	560	0.294	0.506	498	0.262	0.538	11 200

($\Delta\varepsilon_E = \Delta\sigma/E$; $\Delta\varepsilon_P = \Delta\varepsilon_t - \Delta\varepsilon_E$; Subscript i – initial; S – half life)

range for the two conditions are shown in Fig. 3(a) and 3(b). In the case of solution annealed material, due to cyclic hardening, the half life $\Delta\varepsilon_{ES}$-$\Delta\varepsilon_{PS}$ relation lies above that of the initial $\Delta\varepsilon_{Ei}$-$\Delta\varepsilon_{Pi}$ relation at higher strain ranges and reverses itself in the case of the cold worked material due to cyclic softening at all strain ranges.

3.2 Effect of Test Mode on LCF Life

The material tested in the two conditions is a typical example for different LCF lives depending on the test mode, namely, $\Delta\varepsilon_{Ei} = \Delta\varepsilon_{Es}$ = constant or $\Delta\varepsilon_{Pi} = \Delta\varepsilon_{PS}$ = constant test methods. In the relation

$$\Delta\varepsilon_t = \Delta\varepsilon_E + \Delta\varepsilon_P \quad \text{(Eq 1)}$$

if one of the strain ranges is kept constant, the other two will readjust and have different half-life values as the cyclic hardening or cyclic softening takes place.

Consider the solution annealed material tested at $\Delta\varepsilon_t$ = 2.2%. When the initial $\Delta\varepsilon_{Ei}$ = 0.363% is applied, the corresponding initial $\Delta\varepsilon_{Pi}$ = 1.837%. Now if a LCF test is carried out keeping the elastic strain range constant throughout the test,

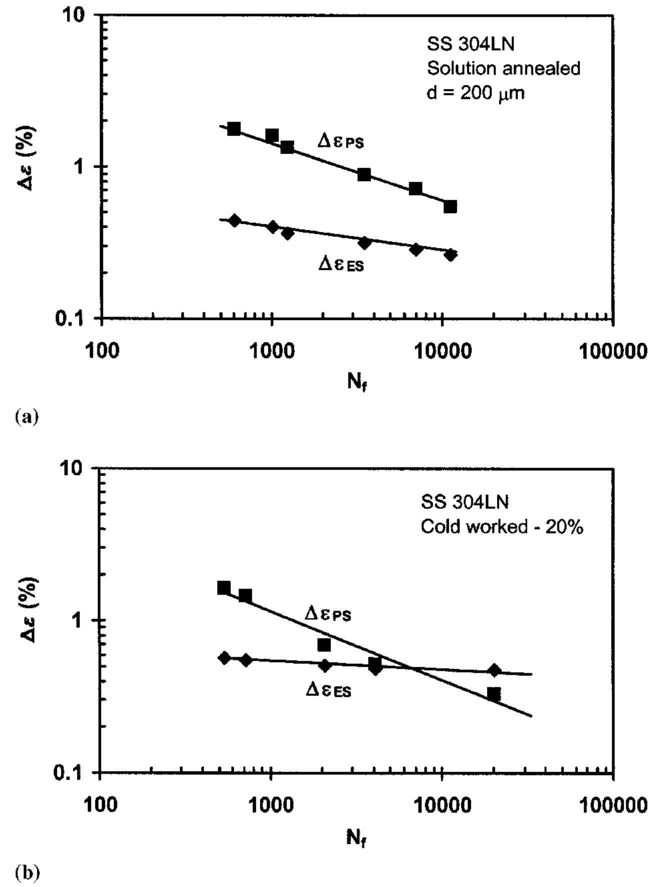

Fig. 2 Relation between plastic strain range and life and elastic strain range and life: **(a)** solution annealed SS 304LN and **(b)** cold worked SS 304LN

Table 2 Values of Stress and Strain Ranges and LCF Life SS 304LN, 20% Cold Worked; E = 190 GPa

$\Delta\varepsilon_t$, %	$\Delta\sigma_i$, MPa	$\Delta\varepsilon_{Ei}$, %	$\Delta\varepsilon_{Pi}$, %	$\Delta\sigma_s$, MPa	$\Delta\varepsilon_{ES}$, %	$\Delta\varepsilon_{PS}$, %	N_f cycles
2.2	1 400	0.737	1.463	1 079	0.568	1.632	540
2.0	1 360	0.716	1.284	1 041	0.548	1.452	720
1.2	1 240	0.653	0.547	961	0.506	0.694	2 100
1.0	1 200	0.632	0.368	912	0.480	0.520	4 150
0.8	1 080	0.568	0.232	900	0.474	0.326	20 200

($\Delta\varepsilon_E = \Delta\sigma/E$; $\Delta\varepsilon_P = \Delta\varepsilon_t - \Delta\varepsilon_E$; Subscript i, initial; S, half life)

i.e., $\Delta\varepsilon_{Ei}$ = 0.363% = $\Delta\varepsilon_{ES}$, then the life will be around N_f = 1250 cycles, as indicated in Fig. 4(a).

On the other hand, if the initial $\Delta\varepsilon_{Pi}$ = 1.837% (= $\Delta\varepsilon_{PS}$) is maintained constant, the total strain range $\Delta\varepsilon_t$ and the elastic strain range $\Delta\varepsilon_E$ will readjust and the LCF life will be around 500 cycles as shown in Fig. 4(a). Thus, if the initial elastic strain range is kept constant a longer LCF life is obtained than when the initial plastic strain range is kept constant in the solution-annealed condition of the material, which exhibits cyclic hardening. Now consider the cold worked material which shows large cyclic softening tested at $\Delta\varepsilon_t$ = 0.8%. When the initial elastic strain range $\Delta\varepsilon_{Ei}$ = 0.568%, the corresponding

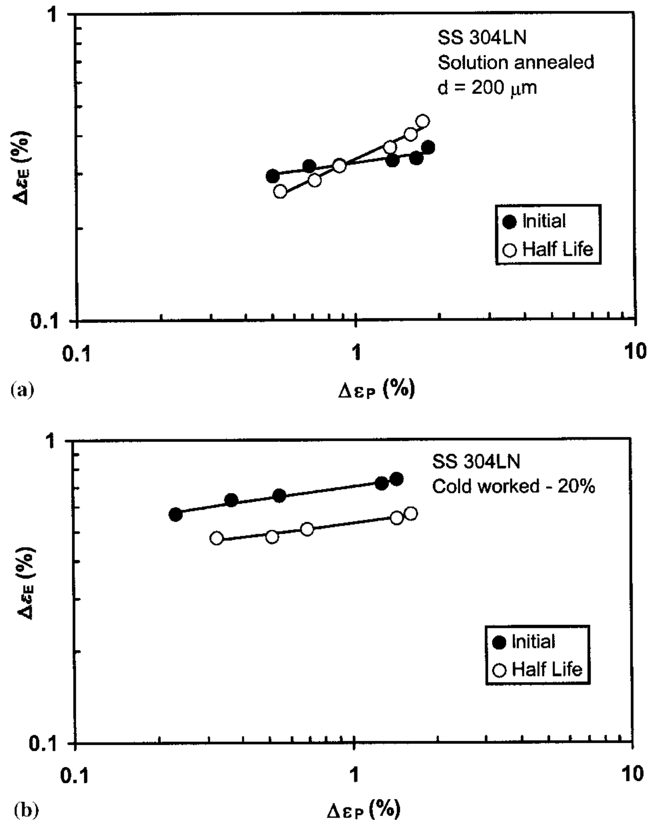

Fig. 3 Cyclic elastic strain range versus plastic strain range relation: **(a)** solution annealed material and **(b)** cold worked material

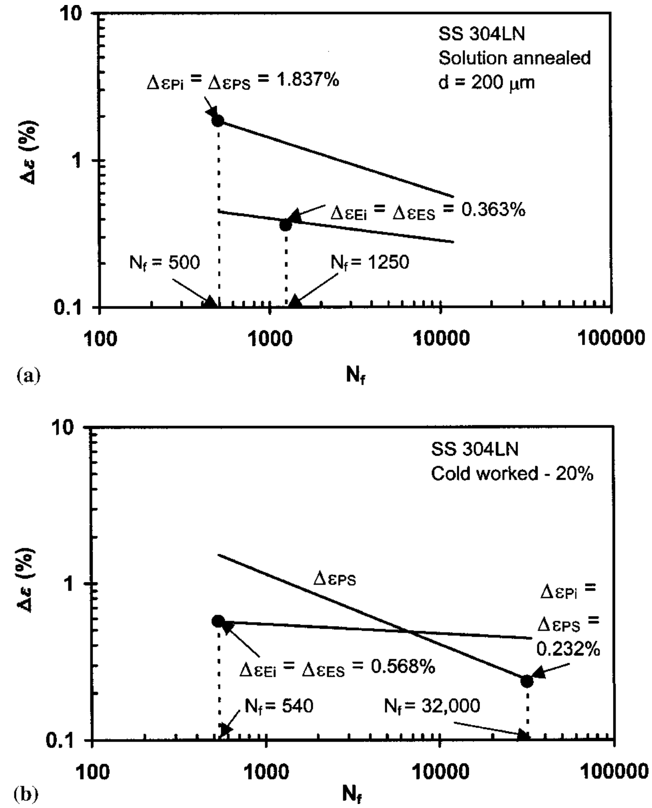

Fig. 4 Test mode dependency of LCF life: **(a)** solution annealed material and **(b)** cold worked material

initial plastic strain range $\Delta\varepsilon_{Pi} = 0.232\%$. Now, if the elastic strain range is kept constant throughout the fatigue testing, so that $\Delta\varepsilon_{Ei} = \Delta\varepsilon_{ES} = 0.568\%$, the LCF life corresponding to this condition is around 540 cycles as shown in Fig. 4(b). On the other hand, if the initial plastic strain range is kept constant, i.e., $\Delta\varepsilon_{Pi} = \Delta\varepsilon_{PS} = 0.232\%$, the life corresponding to this condition will be around 32 000 cycles. Thus, we find that when the material cyclically softens, the life under constant elastic strain range is less than that under constant plastic strain range.

3.3 Theoretical Explanation

Figure 5(a) shows schematically the cyclic $\Delta\varepsilon_E$ and $\Delta\varepsilon_P$ relations for both initial and saturated (or half-life as the case may be) conditions of a material that exhibits cyclic hardening. Let point A be the initial condition of loading for the first cycle. Now depending on the three types of testing modes—namely, $\Delta\varepsilon_E$ = constant, $\Delta\varepsilon_P$ = constant, or $\Delta\varepsilon_t$ = constant—we get the three lines AB, AC and AD, respectively. When $\Delta\varepsilon_E$ = constant, the plastic strain range $\Delta\varepsilon_P$ is reduced, and so also is the total strain range. So under constant elastic strain range, the life N_f is higher due to the reduced value of the plastic strain range. On the other hand, if $\Delta\varepsilon_P$ is kept constant (line AC), the saturated $\Delta\varepsilon_{ES}$ is high, which reduces the fatigue life leading to a relatively lower N_f. When the total strain range $\Delta\varepsilon_t$ is kept constant (line AD), we get N_f in-between the above two values. So the test mode, $\Delta\varepsilon_E$ = constant gives a higher LCF life and $\Delta\varepsilon_P$ = constant gives a lower LCF life, as controlled by the saturated values of the plastic and elastic strain ranges, respectively. The solution annealed material AISI 304LN is a typical example of the category explained as above.

In the case of a cyclically softening material, as the cold worked SS 304LN, the saturated (or half-life) $\Delta\varepsilon_{ES}$-$\Delta\varepsilon_{PS}$ relation lies below the initial $\Delta\varepsilon_{Ei}$-$\Delta\varepsilon_{Pi}$ relation as shown in Fig. 5(b). In such materials, a reverse trend in LCF life will be obtained with $\Delta\varepsilon_{Ei}$ = constant or $\Delta\varepsilon_{Pi}$ = constant condition of fatigue testing due to readjustment in the other strain range as indicated in the figure.

If the initial and saturated $\Delta\varepsilon_E$-$\Delta\varepsilon_P$ curves lie very close to each other, as shown in Fig. 5(c), indicating negligible cyclic hardening or softening (generally observed at low values of total strain range, $\Delta\varepsilon_t$), the test mode will not have much influence on the fatigue life.

4. Role of Hardening and Softening Mechanisms

As mentioned in the introduction, several mechanisms either singly, or in combination, contribute to the cyclic hardening or softening. In the present investigation, solution annealed and cold worked SS 304LN show cyclic hardening and cyclic softening, respectively. Consequently, they exhibit test mode dependency with respect to the LCF life. Thus, the solution-annealed material can be cold worked and its effect on LCF life can be easily analyzed. In a similar manner, the effect of precipitation on the cyclic hardening or softening can also be

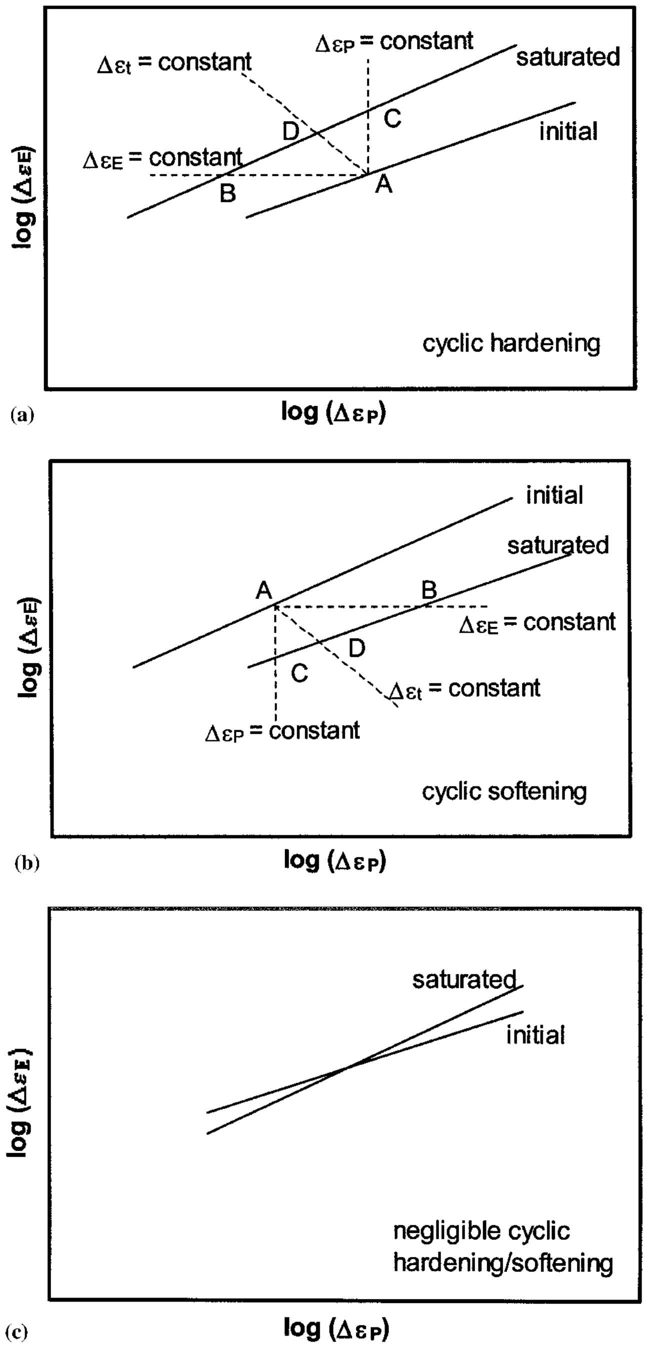

Fig. 5 Readjustment of elastic and plastic strain ranges under cyclic hardening and cyclic softening conditions during different types of loading

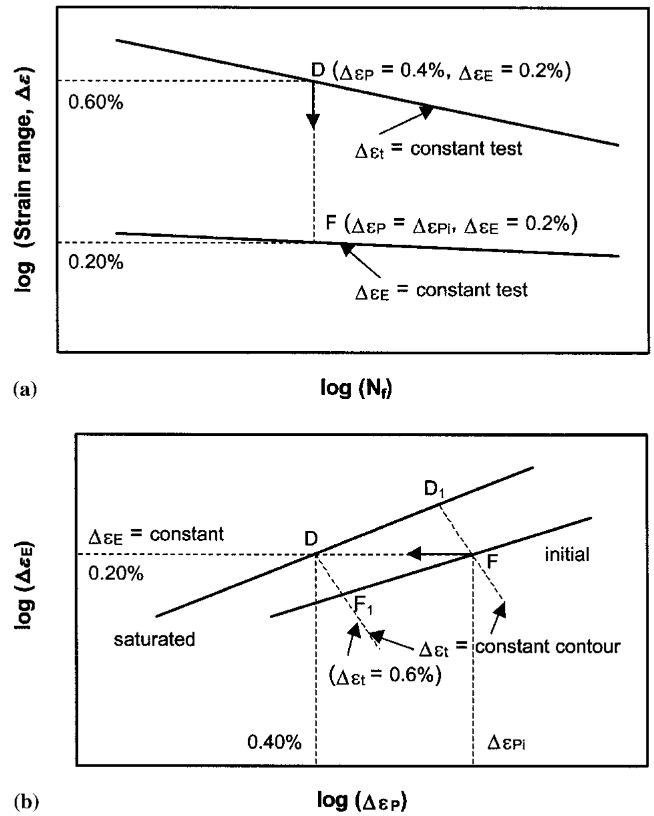

Fig. 6 Extension of total strain range versus life relation to constant elastic strain range condition

studied and test mode dependency of LCF life can be investigated.

In some cases, the effect of the controlling mechanisms cannot be so easily introduced so as to keep all the other LCF test parameters the same. For example, dynamic strain ageing is reported to occur at low frequencies and in certain high temperature ranges. For Type 304 SS, a frequency of 0.01 Hz at the temperature 650 °C is found to induce dynamic strain ageing which gives rise to cyclic hardening.[12] This may result in test mode dependency of LCF life. But at this high temperature of 650 °C and low frequency of 0.01 Hz (consequently the exposure time to high temperature is large), creep and oxidation may also contribute to the damage experienced by the material. So the role of dynamic strain ageing cannot be isolated to study its effect on LCF life, if it occurs at high temperature and low frequencies. However, whatever mechanism operates during LCF, it is the cyclic hardening or softening that will decide the test mode dependency of the life N_f.

5. Advantage of Total Strain Range Controlled Tests

Normally machine elements and other structures are subjected to fatigue under load or total displacement control conditions. Seldom does a situation arise where a constant plastic strain range is imposed on the material. To obtain base data to design structural parts in such situations, it is better to carry out total strain range controlled LCF tests with derived data of saturation (or half life) elastic strain range. Thus, the $\Delta\varepsilon_t$-N_f and $\Delta\varepsilon_{ES}$-N_f relations can be established as shown schematically in Fig. 6(a). Now the $\Delta\varepsilon_{ES}$-N_f relation can also be used for constant stress amplitude or constant $\Delta\varepsilon_{Ei}$ condition as explained below.

Consider point D ($\Delta\varepsilon_{PS} = 0.4\%$ and $\Delta\varepsilon_{ES} = 0.2\%$) on the $\Delta\varepsilon_t$ constant line. This point can be located on the $\Delta\varepsilon_{ES}$-$\Delta\varepsilon_{PS}$

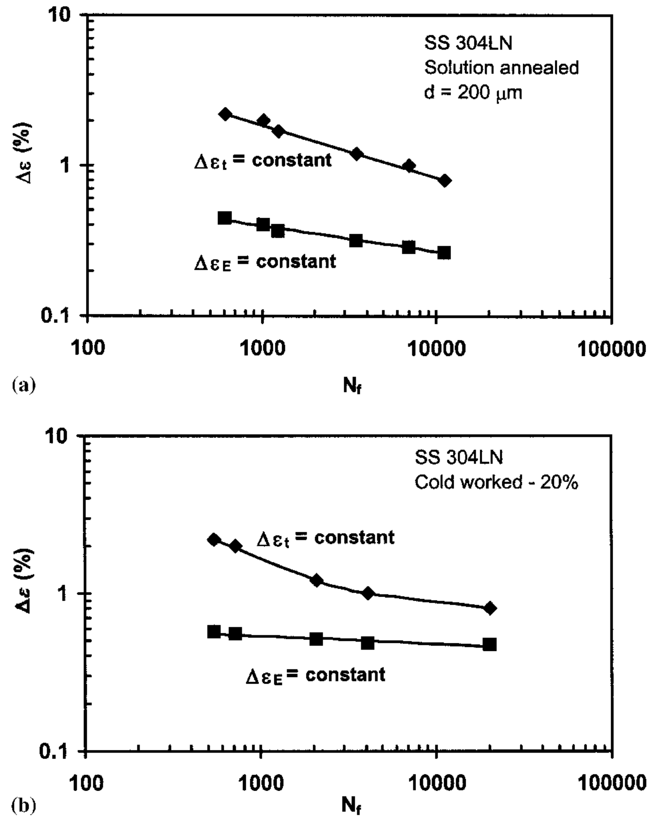

Fig. 7 Relation between total strain range and life and elastic strain range and life: **(a)** solution annealed condition and **(b)** cold worked condition

line as shown schematically in Fig. 6(b), which also shows the $\Delta\varepsilon_{Ei}$-$\Delta\varepsilon_{Pi}$ relation. The line DF_1 shows the constant $\Delta\varepsilon_t$ contour. Now the horizontal line DF indicates constant $\Delta\varepsilon_E$ condition. So, if the constant $\Delta\varepsilon_{Ei}$ test is carried out with F as the starting point ($\Delta\varepsilon_E = 0.2\%$), it will end up at point D (0.4%, 0.2%). Then point F on the $\Delta\varepsilon_{ES}$-N_f relation in Fig. 6(a) also indicates the failure condition with $\Delta\varepsilon_E$ constant test, and the LCF life under constant elastic strain range can be obtained. Thus, carrying out the constant total strain range tests and obtaining the elastic strain range at the saturation condition, the relations $\Delta\varepsilon_{ES}$-N_f and $\Delta\varepsilon_t$-N_f can be established which will be sufficient to get the LCF life under the two important loading conditions in actual practice, namely, constant stress amplitude or constant total displacement amplitude. Figure 7(a) and 7(b) show above basic relations for design purposes in the case of SS 304LN austenitic stainless steel.

6. Conclusions

From the experimental investigations carried out on SS 304LN stainless steel to study LCF life under different loading conditions the following were concluded:

1. The material in the solution-annealed condition exhibits cyclic hardening especially at high strain ranges. The material in the cold worked condition exhibits large cyclic softening over the entire range.
2. The material in both conditions exhibits test-mode dependency of the LCF life. In the solution-annealed condition with cyclic hardening, constant elastic strain range tests show a longer LCF life than the constant plastic strain range tests. In the cold worked condition with large cyclic softening, constant elastic strain range tests show lower LCF life than the constant plastic strain range tests.
3. The above observations are based on the cyclic elastic strain range and cyclic plastic strain range relation at the initial and the saturation stages.
4. Test data are based on total strain range and the derived elastic strain range versus LCF life appear to give the required base criteria for the structural engineers and the designers.

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