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Two Parameters Describing Cyclic Hardening/Softening Behaviors of Metallic Materials

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In this article, cyclic hardening/softening behaviors of metallic materials are studied by using 40 alloys' test results. In the analysis, two parameters are introduced: one parameter is new fracture ductility parameter; the other is cyclic hardening/softening factor. The new fracture ductility parameter expresses cyclic hardening/softening. According to the criterion, there are three critical values—2, 20, and 65.4%. When the new fracture ductility parameter is smaller than 2%, or ranges from 20% to 65.4%, the alloy behaves in a cyclic softening manner. However, when the new fracture ductility parameter ranges from 2% to 20%, or is greater than 65.4%, the alloy behaves in a cyclic hardening manner. The cyclic hardening/softening factor describes the degree of cyclic hardening/softening. If the cyclic hardening/softening factor is greater than 1, the material behaves in a cyclic hardening manner. But if the cyclic hardening/softening factor is smaller than 1, the material behaves in a cyclic softening manner. The more the cyclic hardening/softening factor deviates from 1, the greater the degree of hardening/softening. Compared with the traditional criteria, on the one hand, the present criterion has no indeterminate range, while on the other hand, the cyclic hardening/softening factor quantitatively describes the degree of cyclic hardening/softening. Therefore,the two parameters provide a more descriptive way to describe cyclic hardening/softening behaviors for metallic materials.

Keywords cyclic hardening/softening, cyclic hardening/softening factor, new fracture ductility parameter

1. Introduction

In engineering, most mechanical structures and components experience cyclic loadings; therefore, failure due to fatigue is often encountered. Knowing fatigue lives in the design and use of the structures and components is of great importance. However, to know the fatigue lives, the cyclic hardening/softening behavior of the structures and components must be known (Ref 1-3). Without doubt, the best way to know the cyclic hardening/softening behaviors of them is to test the materials. However, fatigue testing is not only expensive but also time-consuming. Therefore, theoretically estimating the cyclic hardening/softening behavior of materials is useful.

The cyclic hardening/softening behavior is defined through the relative position between the cyclic stress-strain curve and the tensile one (Ref 1-5). When the cyclic stress-strain curve is above the tensile stress-strain curve, the material behaves in a cyclic hardening manner, but when the cyclic stress-strain curve lies below the tensile stress-strain curve, the material behaves in a cyclic softening manner. Ordinarily, the cyclic hardening/softening behavior is described by ratio of the ultimate tensile strength to the yield strength or by the strain-hardening exponent. It will be seen, hereafter, that neither the ratio of the ultimate tensile strength to the yield strength nor the strain-hardening exponent properly describes the cyclic hardening/softening behavior. Therefore, in the present article, the cyclic hardening/softening behavior of metallic materials is studied by careful analysis of 40 alloys. In the study, two parameters are introduced: one parameter is the fracture ductility parameter, while the other is defined as the cyclic hardening/softening factor. The new fracture ductility parameter outlines the cyclic hardening/softening criterion. The cyclic hardening/softening factor describes the degree of cyclic hardening/softening. Compared with the traditional methods, the two parameters provide a more descriptive way to understand cyclic hardening/softening behavior for a wide range of metallic materials.

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2. New Fracture Ductility Parameter

In the process of studying the relationships among the conventional tensile properties, a new fracture ductility parameter has been introduced (Ref 6, 7).

$$\alpha = \psi\varepsilon_f \tag{Eq 1}$$

Since,

$$\psi = \frac{A_0 - A_f}{A_0} \tag{Eq 2}$$

$$\varepsilon_f = \ln\frac{A_0}{A_f} \tag{Eq 3}$$

Equation 1 becomes

$$\alpha = \frac{A_0 - A_f}{A_0}\ln\frac{A_0}{A_f} \tag{Eq 4}$$

In Eq 1 to 2, ψ is the reduction of area from a tensile test, A_0 is the initial cross-section area, and A_f is the fracture cross-section area. Obviously, for an initial cross-section area A_0, both α and A_f reflect the plastic deformation capability of the material. The greater the value of α, the greater the plastic deformation capability of the material.

Substituting Eq 2 and 3 into Eq 1 gives:

$$\alpha = \varepsilon_f(1 - e^{-\varepsilon_f}) = -\psi \ln(1 - \psi) \quad \text{(Eq 5)}$$

Since ε_f is the fracture ductility and α is related to ε_f, α can be viewed as a new fracture ductility parameter. This new parameter affects the relationships among the conventional tensile properties in the following way. When $\alpha < 5\%$ or $10\% \le \alpha < 20\%$ (Ref 6, 7), results are:

$$\sigma_{0.2}^{\frac{5}{3}} = \sigma_b^{\frac{2}{3}} K(0.002)^n \quad \text{(Eq 6)}$$

$$\sigma_f = K\varepsilon_f^n \quad \text{(Eq 7)}$$

While when $5\% < \alpha < 10\%$ or $\alpha > 20\%$, results are:

$$\sigma_{0.2}^{\frac{3}{2}} = \sigma_b^{\frac{1}{2}} K(0.002)^n \quad \text{(Eq 8)}$$

$$\sigma_f = \frac{\sigma_b}{\sigma_{0.2}} K\varepsilon_f^n \quad \text{(Eq 9)}$$

In Eq 6 to 9, $\sigma_{0.2}$ is the tensile yield strength, σ_b is the ultimate tensile strength, σ_f is the fracture strength, K is the strength coefficient, and n is the strain-hardening exponent. From Eq 6 to 9 the strain-hardening exponent and the strength coefficient can be expressed as (Ref 8):

$$n = \frac{\lg\left(\frac{\sigma_f^3 \sigma_b^2}{\sigma_{0.2}^5}\right)}{3\lg(500\varepsilon_f)} \quad \text{(Eq 10)}$$

$$K = \sigma_f \varepsilon_f^{-n} \quad \text{(Eq 11)}$$

for $\alpha < 5\%$ or $10\% \le \alpha < 20\%$ in the first instance, and

$$n = \frac{\lg\left(\frac{\sigma_f^2}{\sigma_{0.2}\sigma_b}\right)}{2\lg(500\varepsilon_f)} \quad \text{(Eq 12)}$$

$$K = \frac{\sigma_f \sigma_{0.2}}{\sigma_b} \varepsilon_f^{-n} \quad \text{(Eq 13)}$$

for $5\% < \alpha < 10\%$ or $\alpha > 20\%$ in the second instance.

Similarly, it will be seen hereafter that different values of the new fracture ductility parameter correspond to different cyclic hardening/softening behaviors.

3. Relationship Between New Fracture Ductility Parameter and Cyclic Hardening/Softening Behavior

3.1 Traditional Parameters Describing Cyclic Hardening/Softening Behavior

Miller uses the ratio between the ultimate tensile strength and the tensile yield strength (Ref 9, 10) $\sigma_b/\sigma_{0.2}$ to describe alloy cyclic hardening/softening behavior. If $\sigma_b/\sigma_{0.2}$ is greater than 1.4, the alloy behaves in a cyclic hardening manner. If $\sigma_b/\sigma_{0.2}$ is smaller than 1.2, the alloy behaves in a cyclic softening manner. Table 1 lists the tensile properties of 40 alloys as well as their cyclic hardening/softening behavior (Ref 4, 5, 11-29). In the table, n is the strain-hardening exponent, while H/S represents the cyclic hardening/softening behavior of the alloys.

According to the ratio criterion of $\sigma_b/\sigma_{0.2}$, the 2Cr13 should cyclically harden since $\sigma_b/\sigma_{0.2}$ is 1.44 (>1.4), but in fact, the 2Cr13 behaves in a cyclic softening manner (Fig. 1). On the contrary, LC4CS and LC9CGS3 should cyclically soften since $\sigma_b/\sigma_{0.2}$ is 1.08 (<1.2), but in fact, they behave in a cyclic hardening manner (Fig. 2 and 3).

Landgraf (Ref 5, 30) studied high-strength materials commonly used in engineering. He related the cyclic hardening/softening behavior to the strain-hardening exponent n. He also found that when the strain-hardening exponent n is greater than 0.2, the material behaves in a cyclic hardening manner and the cyclic strain-hardening exponent n' will decrease. However, when the strain-hardening exponent n is smaller than 0.1, the material behaves in a cyclic softening manner and the cyclic strain-hardening exponent n' will increase. So, only when the strain-hardening exponent n is not smaller than 0.1 can the high-strength materials have good mechanical properties. But, in fact, the strain-hardening exponents of 2024-T351 and LY12CZ (plate) are 0.032 and 0.089, respectively, and they behave virtually in a cyclic hardening manner (Fig. 4 and 5).

In addition, both approaches have a range in which the alloy behaves in an indeterminate manner. For the criterion related to the ratio of the ultimate tensile strength to the yield strength, $\sigma_b/\sigma_{0.2}$, is in the determinant range from 1.2 to 1.4. For the criterion related to the strain-hardening exponent n, the range is from 0.1 to 0.2.

3.2 Relationship Between New Fracture Ductility Parameter and Cyclic Hardening/Softening Behavior

If the new fracture ductility parameter α is related to alloy cyclic hardening/softening behavior, then it can be seen from Table 1 that there are three critical values—2, 20, and 65.4%.

When

$$\alpha < 2\% \quad \text{(Eq 14)}$$

or when

$$20\% < \alpha < 65.4\% \quad \text{(Eq 15)}$$

the alloy behaves in a cyclic softening manner. However, when

$$2\% < \alpha < 20\% \quad \text{(Eq 16)}$$

or when

$$\alpha > 65.4\% \quad \text{(Eq 17)}$$

the alloy behaves in a cyclic hardening manner.

For $60Si2Mn_1$, 40CrMnSiMoVA, 30CrMnSiNi2A and 08_2, the cyclic stress-strain curve crosses the tensile one (Fig. 6-9). $60Si2Mn_1$ and 08_2 are considered as cyclic hardening, while 40CrMnSiMoVA and 30CrMnSiNi2A are viewed as cyclic softening. The reason for this is that in engineering materials, the cyclic strain experienced by the mechanical structures and components is usually less than 5%, and sometimes very much so.

It has been mentioned above that the cyclic hardening/softening behaviors of 2Cr13, LC4CS, LC9CGS3, 2024-T351, and LY12CZ (plate) predicted by the traditional criteria are contrary to actual test results. However, according to the

Table 1 Cyclic hardening/softening behaviors of metallic materials

Materials	ψ, %	σ_b	$\sigma_{0.2}$	$\sigma_b/\sigma_{0.2}$	*n*	α, %	H/S	Reference
$K417_1$(a)	3.4	748	628	1.19	···	0.1	S	11
$K417_2$(a)	5.4	662	546	1.21	···	0.3	S	11
60Si2CrVA	9.5	1318	1106	1.19	···	1.0	S	12
$60Si2Mn_1$(b)	14.8	924	455	2.03	0.22	2.4	H	5
LC4CS	16.5	613.9	570.8	1.08	0.063	3.0	H	4
LY12CZ (rod)	16.5	545.1	399.5	1.36	0.158	3.0	H	4
Zr	20	434	304	1.43	···	4.5	H	13
2124-T351	21	439	274	1.60	0.111	5.0	H	14
LC9CGS3	21.0	560.2	518.2	1.08	0.071	5.0	H	4
2024-T351	25	469	379	1.24	0.032	7.2	H	15
LY12CZ (plate)	26.6	475.6	331.5	1.43	0.089	8.0	H	4
GH4133	29	1202	791	1.52	···	9.9	H	4
GH2036	32	952	628	1.52	···	12.3	H	4
7075-T6	33	579	469	1.23	0.113	13.5	H	15, 16
2024-T4	35	476	303	1.57	0.200	15.1	H	15, 16
TA5	40	700	650	1.08	···	20.4	S	17
$60Si2Mn_2$(b)	40.9	2091	1869	1.12	···	21.5	S	18
Ti-6Al-4V	41	1234	1186	1.04	0.063	21.7	S	19
GH4169	44	1440	1220	1.18	···	25.5	S	20
TC4	45.4	956	896	1.07	···	27.5	S	4
40CrMnSiMoVA	43.7	1875	1513	1.24	0.1468	27.7	S	4
Ti-8M-1Mo-1V	48	1020	1007	1.01	0.078	31.7	S	16
2Cr13	50	635	440	1.44	···	34.7	S	21
30CrMnSiNi2A	52.3	1655.4	1308.3	1.27	0.091	38.7	S	4
45_1(b)	52.9	934	716	1.30	···	39.8	S	22
30CrMnSi	53.6	1177	1104.5	1.07	0.063	41.4	S	4
AISI4340	57	1241	1179	1.05	0.066	47.9	S	15, 16
08_1(b)	63.9	414	400	1.04	0.049	65.2	S	5
40	63.9	931	883	1.05	0.06	65.2	S	5
30CrNiMo8	64	930	775	1.2	···	65.4	S	23
40CrNiMoA	64.0	885	738	1.20	···	65.4	S	24
45_2(b)	64	610	370	1.65	···	65.4	H	25
16Mn	64	586	361	1.62	0.2029	65.4	H	26
316_1(a)	64	472	155	3.05	···	65.4	H	27
316_2(a)	67	471	149	3.16	···	74.3	H	27
Ti	74.9	860	463	1.86	···	103.5	H	28
Z3-CND 17-12	77	588	270	2.18	···	113.2	H	29
316_3(a)	80	590	283	2.08	···	127.7	H	27
08_2(b)	80	345	262	1.32	0.16	127.7	H	5
316_4(a)	81	539	284	1.90	···	134.5	H	27

(a) 1-4 represent the different test temperatures. (b) 1-2 represent the different heat treatments

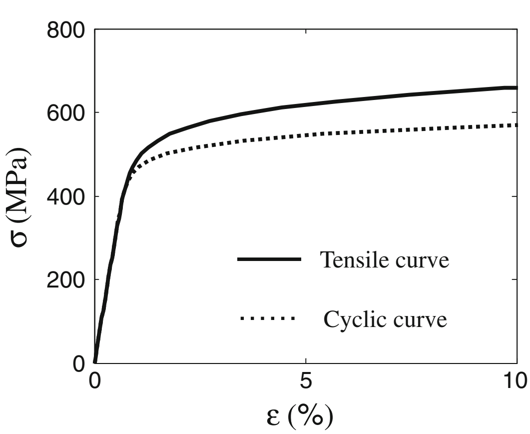

Fig. 1 Stress-strain curves of 2Cr13

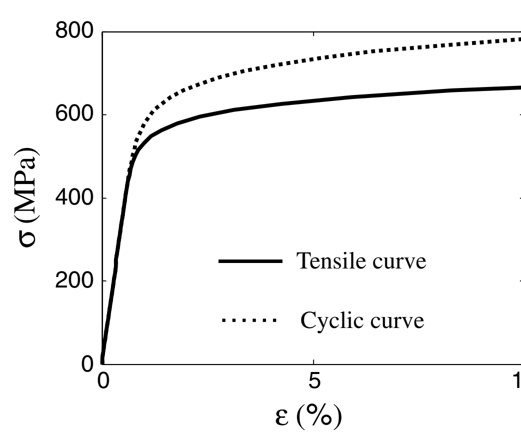

Fig. 2 Stress-strain curves of LC4CS

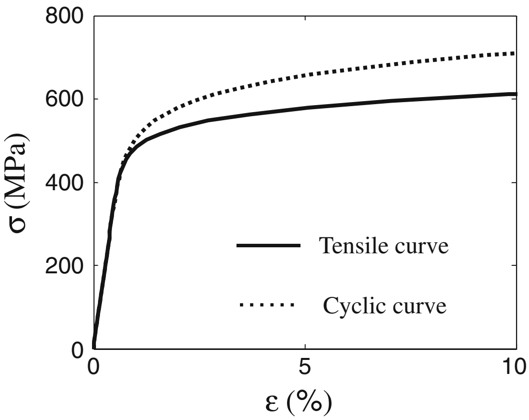

Fig. 3 Stress-strain curves of LC9CGS3

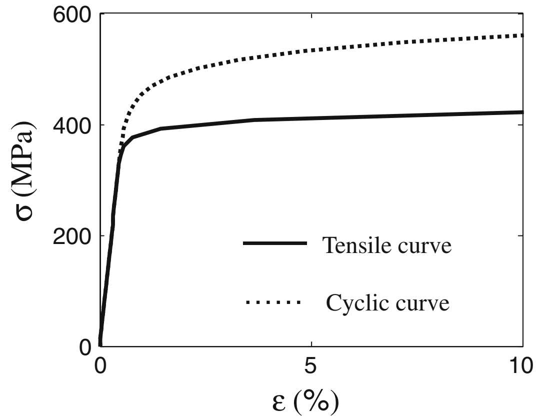

Fig. 4 Stress-strain curves of 2024-T351

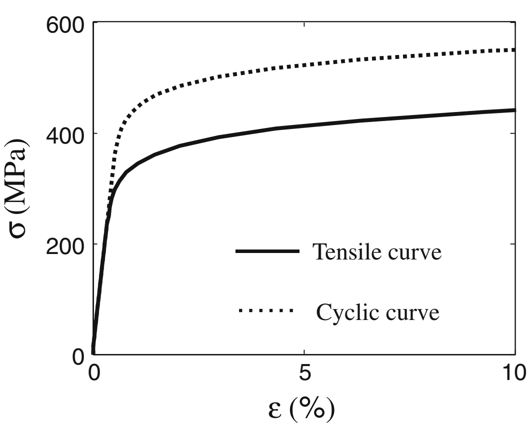

Fig. 5 Stress-strain curves of LY12CZ (plate)

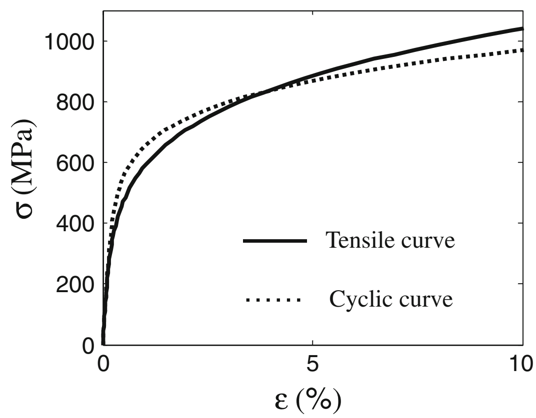

Fig. 6 Stress-strain curves of $60Si2Mn_1$

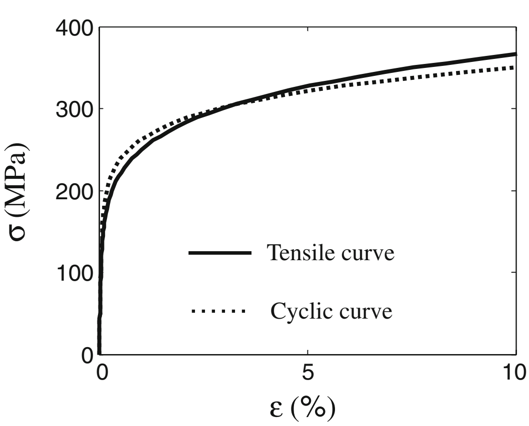

Fig. 7 Stress-strain curves of 08_2

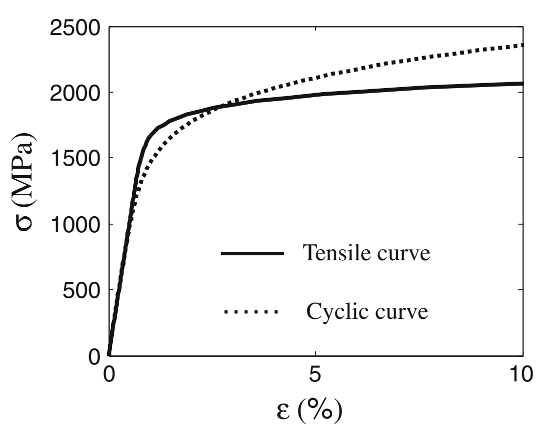

Fig. 8 Stress-strain curves of 40CrMnSiMoVA

criterion expressed by Eq 14 to 17, the 2Cr13 alloy cyclically softens while LC4CS, LC9CGS3, 2024-T351, and LY12CZ (plate) cyclically hardens since the magnitude of the new fracture ductility parameter α for them are 34.7, 3.0, 6.0, 6.8, and 8.0, respectively. These predicted results are in agreement with the test results (Fig. 1-5).

Furthermore, both the traditional criteria have a range in which alloy behaves in an indeterminate manner. For the criterion related to ratio of the ultimate tensile strength to the yield strength $\sigma_b/\sigma_{0.2}$, the range is:

$$1.2 < \sigma_b/\sigma_{0.2} < 1.4 \quad \text{(Eq 18)}$$

While for the criterion related to the strain-hardening exponent n, the range is:

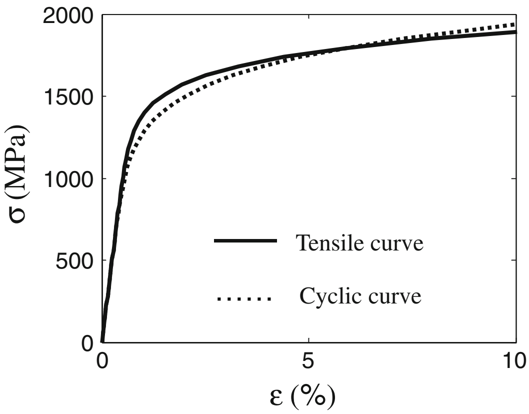

Fig. 9 Stress-strain curves of 30CrMnSiNi2A

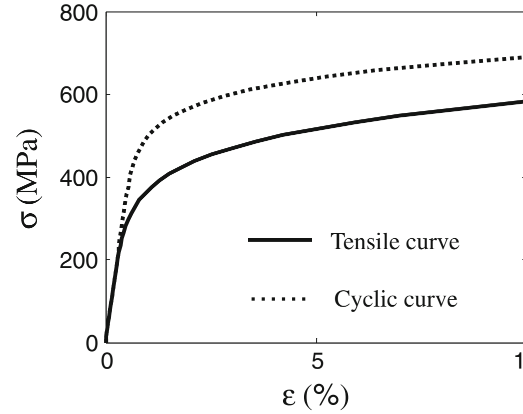

Fig. 10 Stress-strain curves of LY12CZ (rod)

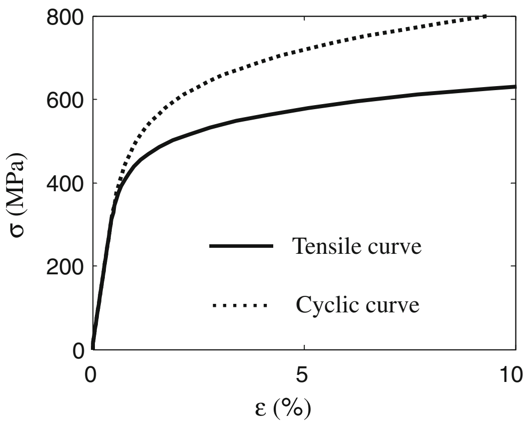

Fig. 11 Stress-strain curves of 7075-T6

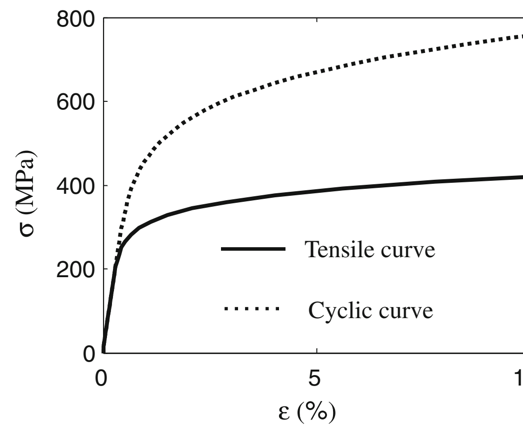

Fig. 12 Stress-strain curves of 2124-T351

$$0.1 < n < 0.2 \qquad \text{(Eq 19)}$$

According to Eq 18, the cyclic hardening/softening behaviors of LY12CZ (rod), 2024-T351, 7075-T6, 40CrMnSiMoVA, 30CrMnSiNi2A, 45_1, and 08_2 cannot be determined. Similarly, in light of Eq 19, the cyclic hardening/softening behavior of LY12CZ (rod), 2124-T351, 7075-T6, 40CrMnSiMoVA, and 08_2 cannot be determined either. In accordance with the criterion expressed by Eq 14 to 17, LY12CZ (rod), 2124-T351, 2024-T351, 7075-T6, and 08_2 are cyclic hardening (Fig. 4, 7, 10-12), while 40CrMnSiMoVA, 30CrMnSiNi2A, and 45_1 are cyclic softening (Fig. 8, 9, 13). Therefore, the method of using the new fracture ductility parameter to describe the cyclic hardening/softening behavior has no indeterminate range. In other words, compared with ratio of the ultimate tensile strength to the yield strength $\sigma_b/\sigma_{0.2}$ and with the strain-hardening exponent n, the new fracture ductility parameter α provides a better way for describing the cyclic hardening/softening behavior of a wide range of engineering alloys.

The yield strength $\sigma_{0.2}$ reflects a material's resistance to plastic deformation. The ultimate tensile strength σ_b is the maximum resistance a material can sustain before necking. The strain-hardening exponent n represents a material's response to plastic deformation (Ref 5). The value of the strain-hardening exponent n equals to the maximum strain before necking, so, the strain-hardening exponent n signifies the magnitude of the ultimate tensile strength σ_b (Ref 5). In other words, the criterion related to the ratio between the ultimate tensile strength and the yield strength $\sigma_b/\sigma_{0.2}$ is virtually the same as that related to the strain-hardening exponent n. Therefore, it is not strange that both criteria have an indeterminate range.

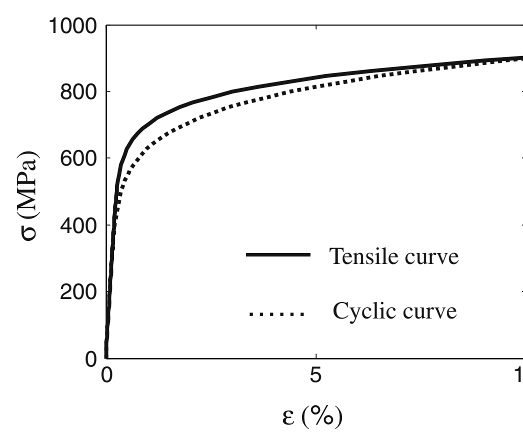

Fig. 13 Stress-strain curves of 45_1

4. Cyclic Hardening/Softening Factor

To further describe the cyclic hardening/softening, a cyclic hardening/softening factor is introduced. This cyclic hardening/softening factor is denoted by β and is defined as:

$$\beta = \frac{K' \varepsilon_{pa}^{n'}}{K \varepsilon_p^n} \quad \text{(Eq 20)}$$

In Eq 20, K' is the cyclic strength coefficient, n' is the cyclic strain-hardening exponent, K is the monotonic strength coefficient, n is the monotonic the strain-hardening exponent, ε_{pa} is the cyclic plastic strain amplitude, and ε_p is the plastic strain. Obviously, the cyclic hardening/softening factor β quantitatively describes the relative position between the cyclic stress-strain curve and the tensile one. If $\beta > 1$, the cyclic stress-strain curve lies above the tensile stress-strain curve, and the material behaves in a cyclic hardening manner. However, if $\beta < 1$, the cyclic stress-strain curve lies below the tensile stress-strain curve and the material behaves in a cyclic softening manner. The more β deviates from 1, the more alloy cyclic hardening/softening there is. When

$$\varepsilon_{pa} = \varepsilon_p = 1\% \quad \text{(Eq 21)}$$

Equation 20 changes to:

$$\beta = \frac{K' \varepsilon_{pa}^{n'}}{K \varepsilon_p^n} = \frac{K'(0.01)^{n'}}{K(0.01)^n} \quad \text{(Eq 22)}$$

If β_1 represents the calculated values from Eq 22 for different materials, and if

$$\delta = \frac{|\beta - \sigma_b/\sigma_{0.2}|}{\sigma_b/\sigma_{0.2}} \quad \text{(Eq 23)}$$

describes cyclic hardening materials, while

$$\delta = \frac{|\beta - \sigma_{0.2}/\sigma_b|}{\sigma_{0.2}/\sigma_b} \quad \text{(Eq 24)}$$

describes cyclic softening materials, a comparison between β_1 and $\sigma_b/\sigma_{0.2}$ can be made. For the cyclic hardening materials listed in Table 2,

$$\beta_1 \approx \frac{\sigma_b}{\sigma_{0.2}} \quad \text{(Eq 25)}$$

while for cyclic softening materials listed in Table 3,

$$\beta_1 \approx \frac{\sigma_{0.2}}{\sigma_b} \quad \text{(Eq 26)}$$

β_1 represents cyclic hardening/softening factor β for cyclic plastic strain amplitude ε_{pa} and plastic strain ε_p equal to 1%. In fact, when cyclic plastic strain amplitude ε_{pa} and plastic strain ε_p change from 0.2% to 5%, the cyclic hardening/softening factor β is always approximately equal to the ratio between the ultimate tensile strength and the yield strength, $\sigma_b/\sigma_{0.2}$. Thus, in the same manner as β, $\sigma_b/\sigma_{0.2}$ also describes the cyclic hardening/softening degree. The more $\sigma_b/\sigma_{0.2}$ deviates from 1, the greater the extent alloy hardening/softening.

Table 2 Cyclic hardening factor for cyclic hardening materials (Ref 4, 5, 12, 13)

	LY12CZ								
Materials	Rod	Plate	LC4CS	LC9CGS3	2024-T4	7075-T6	2024-T351	2124-T351	08_2
ε_f (%)	18	30.2	18	28.3	43	41	28	24	160
α (%)	3.0	8.0	3.0	6.0	15.1	13.5	7.2	5.0	127.7
σ_b	545.1	475.6	613.9	560.2	476	579	469	439	345
$\sigma_{0.2}$	399.5	331.5	570.8	518.2	303	469	379	274	262
K	849.8	545.2	775.1	724.6	807	827	455	545	531
n	0.158	0.0889	0.063	0.071	0.2	0.113	0.032	0.111	0.16
K'	870.5	645.8	949.6	905.9	764	1151	655	1100	462
n'	0.097	0.0669	0.08	0.101	0.08	0.146	0.065	0.155	0.12
$\sigma_b/\sigma_{0.2}$	1.36	1.43	1.08	1.08	1.57	1.23	1.24	1.60	1.32
β_1	1.36	1.31	1.13	1.09	1.65	1.20	1.24	1.65	1.05
δ (%)	0.0	8.4	4.6	0.9	5.1	2.4	0.0	3.1	20.5

Table 3 Cyclic softening factor for cyclic softening materials (Ref 4, 5, 12, 13)

Materials	30CrMnSiNi2A	30CrMnSiA	AISI4340	45_1	40	Ti-8Mo-1Mo-1
ε_f (%)	74	77.27	84	75.3	102	66
α (%)	39	41	47.9	39.8	65	31.7
σ_b	1655.3	1177.0	1241	934	931	1020
$\sigma_{0.2}$	1308.3	1104.5	1179	716	883	1007
K	2355.4	1475.8	1579	1124	1172	1596
n	0.091	0.063	0.066	0.094	0.06	0.078
K'	2647.7	1771.9	1889	1237	1434	1764
n'	0.13	0.13	0.14	0.136	0.14	0.14
$\sigma_b/\sigma_{0.2}$	0.79	0.93	0.95	0.77	0.95	0.99
β_1	0.94	0.88	0.85	0.92	0.85	0.83
δ (%)	19.0	5.4	10.5	19.5	10.5	16.2

5. Conclusions

(1) The new fracture ductility parameter α expresses cyclic hardening/softening. There are three critical values—2, 20, and 65.4%. If

$$\alpha < 2\%$$

or if

$$20\% < \alpha < 65.4\%$$

the alloy behaves in a cyclic softening manner. However, if

$$2\% < \alpha < 20\%$$

or if

$$\alpha > 65.4\%$$

the alloy behaves in a cyclic hardening manner.

(2) The cyclic hardening/softening factor describes the degree of cyclic hardening/softening. By definition:

$$\beta = \frac{K' \varepsilon_{pa}^{n'}}{K \varepsilon_{p}^{n}}$$

If $\beta > 1$, the material behaves in a cyclic hardening manner, but if $\beta < 1$, the material behaves in a cyclic softening manner. The more β deviates from 1, the more alloy hardening/softening there is.

For cyclic hardening materials:

$$\beta \approx \frac{\sigma_b}{\sigma_{0.2}}$$

For cyclic softening materials:

$$\beta \approx \frac{\sigma_{0.2}}{\sigma_b}$$

Therefore, in the same manner as β, $\sigma_b/\sigma_{0.2}$ describes the cyclic hardening/softening response. The more $\sigma_b/\sigma_{0.2}$ deviates from 1, the greater degree of alloy hardening/softening.

(3) Compared with the traditional criteria, on the one hand, the present criterion has no indeterminate range, while on the other hand, the cyclic hardening/softening factor quantitatively describes the extent of cyclic hardening/softening. Therefore,these two parameters provide a more descriptive way to understand cyclic hardening/softening behavior for metallic materials.

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