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The Effect of Torsional Prestrain on the Tensile and Low-Cycle Fatigue Properties of Mild Steel*

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The effect of torsional prestrain on tensile and low-cycle fatigue properties of a medium carbon steel was studied. A series of small-sized tensile and fatigue specimens were prepared from large-sized prestrained specimens in order to ensure good homogeneity of the torsional prestrain in the cross-section of the small-sized specimens. Three modes of prestraining were selected in this study; unidirectional, twist-back, and single- or cyclic-reversed torsion. Fracture ductility decreased almost linearly with increasing unidirectional prestrain, while the decrease of fracture ductility in the other modes of prestrain was much less than that in the unidirectional one. A transitional decrease in fracture ductility, which has been reported for inhomogeneously prestrained specimens, was not observed in this study. A slight trace of recovery in fracture ductility due to twisting back the unidirectional prestrain to the macroscopically undistorted original state was observed, in contrast with the almost complete recovery for the inhomogeneously prestrained specimens. The low-cycle fatigue life of the unidirectionally prestrained specimens was reduced by an amount which would be predictable from the decrease in fracture ductility of those specimens. For other modes of prestrain, however, the influence on fatigue life was undistinguishably small in this study.

1. Introduction

It has been established⁽¹⁾ that the low-cycle fatigue life of a given material depends closely on fracture ductility of that material. It is also well known that the fracture ductility is varied with prestraining. This may give an expectation that the effect of prestraining on the low-cycle fatigue life could be predicted from the influence of prestraining on fracture ductility of that material. The authors have already made several studies⁽²⁾⁻⁽⁶⁾ in this line. This paper is on an extension of these previous studies and is concerned with the effect of torsional prestrain on fracture ductility and the low-cycle fatigue behavior of a mild steel.

Only a limited amount of publications concerned with the effect of torsional prestrain on the tensile properties can be found in the literature. Swift⁽⁷⁾ and Rockey⁽⁸⁾ examined the effects of unidirectional and twist-back torsion on the subsequent tensile properties of low carbon steels by

utilizing as-twisted cylindrical specimens. Backofen et al.⁽⁹⁾ did a similar investigation with an OFHC copper: In this case tensile specimens were prepared by removing a certain depth of the surface layer from pretwisted cylindrical specimens by machining. In these studies, a sudden transitional decrease in fracture ductility was noticed when a certain value of unidirectional torsional prestrain was exceeded. Twist-back torsion was found to recover the fracture ductility approximately to its original value determined by using unprestrained specimens, except for the results obtained by Rockey.

Nypan⁽¹⁰⁾ also did a similar experiment on 2024-T4 aluminum alloy. However, he used conventional elongation at fracture as a measure of ductility, which is less favorable as compared with fracture ductility.

In all of these investigations, the torsional prestrain in the cross-section of a specimen changed linearly in the radial direction; zero at the center and a maximum at the surface. Therefore an exact evaluation of the effect of torsional prestrain on fracture ductility was very difficult, since the observed fracture ductility represented a complex integrated effect. In order to overcome this difficulty, Theocaris⁽¹¹⁾⁽¹²⁾, and Theocaris and Samaras⁽¹³⁾ used small-sized tensile plate specimens, which were cut from several predetermined radial positions of large-sized cylindrical pretwisted bars. However, because of the rectangular cross-section of the prepared tensile specimens, only a conventional elon-

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gation was determined for each specimen as information on ductility.

Under these circumstances, attention was focused in this study on evaluation of the true effect of torsional prestrain on both tensile and low-cycle axial fatigue properties of a mild steel. Correlation between fracture ductility and the low-cycle fatigue life was also studied.

To ensure good homogeneity of torsional prestrain across the cross-section of specimens, small-sized cylindrical tensile and fatigue specimens were cut out from large-sized cylindrical bars, which in advance had been subjected to torsional prestrain.

Three kinds of prestrain modes were selected; unidirectional, twist-back and single- or cyclic-reversed torsion.

2. Experimental procedure

2.1 Material

The material used was an S25C carbon steel, and was supplied in a form of a 90 mm $\times$ 10000 mm hot-rolled bar. No heat treatment was given in this study. The chemical composition and the mechanical properties of this material are shown in Tables 1 and 2, respectively. Fig.1 illustrates the microstructure observed near the center of the longitudinal section of the received bar.

Fig.2 shows the distribution of Vickers' hardness and other mechanical properties in the cross-section of the bar. The distributions are approximately flat within the radius less than 30 mm*. The values of the mechanical properties shown in Table 2 represent the average values at five points within this flat distribution area. (See Fig.2)

2.2 Torsional prestrain

Geometry of the large-sized torsional specimen for prestraining is illustrated in Fig.3. The prestraining was conducted by using a Shimadzu torsion testing machine, RET-2500, of 2500 kgm capacity.

The modes and values of prestrain given in this study are tabulated in Table 3. The rate of prestraining was 10°/min for unidirectional torsion (Series A) and twist-back (Series B), and 40°/min for cyclic-reversed torsion (Series C). The twisting angle and the shear strain were determined between the central parallel gauge section of 100 mm shown in Fig.3.

2.3 Specimens

In preparing small-sized tension and fatigue test specimens from the large-sized prestrained specimen, the gauge section of the prestrained specimen was cut into two halves 50 mm long each; one was used for tension specimens and the other for fatigue specimens. This was done in order to minimize a bias of test results either in tension or in fatigue due to scatter of properties in large-sized specimens. In cutting out small specimens from one of the foregoing halves,

* The diameter of test section of the large-sized specimen used for torsional prestraining was 60 mm, as seen in Fig.3.

Table 1 Chemical composition of the material tested (%)

C	Si	Mn	P	S	Cu	Ni	Cr
0.25	0.26	0.44	0.10	0.13	0.03	0.01	0.02

Table 2 Mechanical properties of the material tested

σ_S (kg/mm ²)	σ_B (kg/mm ²)	σ_T (kg/mm ²)	ϕ (%)	ψ (%)	ϵ_F (%)
30	51	103	47	61	95

Fig.1 Microstructure of the material tested

Fig.2 Distribution of hardness, ultimate tensile strength and fracture ductility in the cross section of the received material

Table 3 Details in torsional prestraining of a large-sized specimen

Prestrain mode	Angle of twist θ°	Shear strain γ_{sur}	Cycle history	Number of torsion cycles, n
A	A-1	288	✕	(fracture)
	A-2	214		1/4
	A-3	186		
	A-4	100		
B	B-1	170	⌢	1/2
	B-2	130		
	B-3	89.3		
C	C-1	100, -41.6	⌢	(fracture)
	C-2	±89.3		3/4
	C-3	±89.3	⊖	1
	C-4	51.1		6
	C-5	±20.7		36

θ° : angle of twist between gage length, γ_{sur} : shear strain at the surface of the large-sized specimen, A-1, -2...; numbering of the large-sized specimen

Fig.3 Geometry of large-sized torsional specimen

more than two radial positions, from which the small-sized specimens were cut out, were selected in the cross-section of the large-sized specimen, as will be indicated in Figs. 4 and 5. This enabled us to obtain more than two levels of prestrain for a small-sized specimen from a given angle of twisting (or a given shear strain at the surface of a large-sized specimen). By combining this twisting angle and the radial positioning, a wide and overlapped variety of prestrained small-sized specimens were obtained which would constitute statistically more homogeneous ensembles.

In representing the prestrain values of the small-sized tensile and fatigue specimens thus prepared, the prestrain value at the center of the small-sized specimen was utilized.

Fig.4 shows the geometry and the cutting positions of the small-sized specimen for tension test. Four radial positions, two specimens for each position except for the central position, were selected.

Hour-glass type specimens were used for fatigue tests as shown in Fig.5. Two radial positions, six specimens for each position, were selected for one piece of the large-sized specimen. Fig.5 shows an example of this positioning. For crack observation, the surfaces of specimens were finished with up to #04 emery papers.

2.4 Testing apparatus

A Shimadzu Autograph, IS-10T, was used both for tension tests and for low-cycle fatigue tests. The low-cycle fatigue tests were conducted by automatically controlling the completely reversed radial plastic strain at the minimum cross-section

3. Representation of prestrain

Since the modes of twist-back and cyclic-reversed torsion were selected for prestraining in addition to the mode of unidirectional torsion, it was necessary to define a common parameter which could represent approximately and unifiedly the effect of prestrain in the three different modes⁽¹⁴⁾. It is clear that none of residual plastic shear strain, plastic strain amplitude (or range) and cumulative plastic strain⁽¹⁵⁾ is suitable for this purpose.

In this study, a concept of damage based on the linear cumulative low-cycle fatigue damage assumption⁽¹⁴⁾ was utilized in expressing the effect of prestrain in various torsional modes.

Assume the Manson-Coffin relation between the reversed shear strain range, $\Delta\gamma$,

Fig.4 Geometry, positions and numbering of small-sized tensile specimen in the cross section of a large-sized torsional specimen

Fig.5 Geometry and positions of fatigue specimen in the cross section of a large-sized torsional specimen

and the number of cycles to failure N , then extending this relation to the unidirectional torsion test, which could be interpreted as an extreme of the low-cycle fatigue test of $N=1/4$ at $\Delta\gamma=2\gamma_F$, the following equation is obtained,

$$\Delta\gamma^a N = (2\gamma_F)^a / 4 \quad (1)$$

where γ_F denotes fracture strain in the unidirectional torsion test and a is a material constant. Then accumulated damage due to prestraining is expressed as

$$D = n/N = 4n(\gamma^*/\gamma_F)^a \quad (2)$$

where γ^* is the value of prestrain (or prestrain amplitude) at the center of the cross-section of the small-sized specimen, and n is

Fig. 6 Effect of unidirectional torsional prestrain (A) on subsequent tensile properties

the number of cycles of prestrain tabulated in Table 3. In computing the D -value for each prestrain, the Manson-Coffin relation for crack initiation life was used, in which $a=1.77$ and $\gamma_F=1.507$.

4. Tension test results

4.1 Effect of unidirectional torsion (A)

Fig. 6 shows the effect of unidirectional torsional prestrain on fracture ductility, ϵ_F , fracture elongation, ϕ , and ultimate tensile strength, σ_B . The chained line in the figure represents a relation obtained by assuming that fracture ductility decreases linearly with prestrain and is exhausted at a prestrain of γ_F . In a range of small prestrains γ^* , fracture ductility ϵ_F approximately follows this relation. However, the fracture ductility tends to separate upward from this imaginary relation with increasing prestrain. A similar tendency is also observed more clearly for fracture elongation ϕ . This tendency is quite similar to that found in the effect of compressive prestrain on fracture ductility in the direction perpendicular to the compressive axis⁽²⁾. When the damage value D defined in the preceding section is used instead of the direct shear prestrain value, the observed values are represented by the solid curve shown in Fig. 7, which is more concaved upward.

The ultimate strength σ_B increases with prestrain in a curve convex upward. This tendency does not change when the damage D is taken on abscissa instead of shear prestrain γ^* , as indicated in Fig. 9 by a solid curve.

The appearance of the fractured surface was generally of cup-and-cone type, with only one exception of the specimen prestrained by $\gamma^*=1.2$ and fractured at $\epsilon_F=9\%$. In this specimen no local contraction was observed along the parallel test section and the fracture appearance was of a 45° shear fracture type.

Fig. 7 Change in fracture ductility with varied damage D of three kinds of torsional prestrains

Fig. 8 Change in fracture ductility when torsional prestrain cycle is varied with $n=0, 1/4, 1/2$ and 1 under a constant prestrain amplitude of $\theta=89.3^\circ$

4.2 Effect of twist-back (B) and cyclic torsional (C) prestrain

The observed values of fracture ductility are shown in Fig. 7 against the damage values due to prestraining. For comparison purpose, the result for unidirectional prestraining is shown in the figure by a solid line. Fracture ductility decreases quickly in a range of small D -values, which is similar to the tendency of the unidirectional case. However, in the present case, fracture ductility tends to be saturated much faster to a high fracture ductility level, which is about (75~85)% of the original ductility level.

A more detailed examination of Fig. 7 and Table 3 reveals that the decrease in fracture ductility is larger for a case where residual prestrain exists (C-2) than for cases where no residual prestrain exists (B-1, B-2, B-3, C-3, C-4, and C-5). Further when there is no residual prestrain, the decrease is smaller for smaller angle of twist. This tendency is quite similar to that of the residual fracture ductility of specimens subjected to push-pull fatigue

loading. ⁽¹⁸⁾⁽¹⁹⁾

Recovery of fracture ductility due to twist-back, which was reported by Swift⁽⁷⁾, Rockey⁽⁸⁾, and Backofen et al.⁽⁹⁾, was slightly observed in this study, as indicated in Fig.8. In Fig.8, the angle of twist was fixed at $\theta=89.3^\circ$ and number of cycles was changed as $n=0, 1/4, 1/2, 3/4$, and 1. It is found that the fracture ductility values at $n=1/2$ (twist-back) and 1 is larger than those at $n=1/4$ and $3/4$, respectively. However, the values of recovery were very small as compared with those observed by Swift⁽⁷⁾ and Backofen et al.⁽⁹⁾ and, as indicated by the chained line in Fig.7, fracture ductility was not recovered by twist-back to the original fracture ductility level in contrast with the experiment by Swift⁽⁷⁾, who reported almost full recovery of fracture ductility by twist-back.

From the foregoing results, it is understood that the decrease of fracture ductility depends at least on two variables. One is a variable of cumulative nature, such as the D -value used in this study. The other is a variable representing the final macroscopic state of prestrain, such as final residual prestrain, which may be related to the texture of a material. This means that fracture ductility depends not only on the D -value but also on amplitude of prestrain.

Fig.9 shows the effect of prestrain on the ultimate tensile strength. The solid line in the figure represents the observed values for unidirectional prestraining. In both cases of twist-back(B) and cyclic torsion(C), the observed ultimate tensile strength changes convexly upward, similarly to the unidirectional case. The hardening at a given D -value is the smallest for the cyclic torsion(fatigue) at the smallest amplitude γ_{peak}^* , the largest for the unidirectional prestrain, in which the γ_{peak}^* is the largest in all prestrain modes, and intermediate for the twist-back prestrain. However, the hardening at a given γ_{peak}^* -value was the smallest for the unidirectional torsion, although illustration is not given in this paper. This indicates that the hardening depends both on the peak value of prestrain and on a factor such as D -value, which is of cumulative nature.

Fig.10 Effect of unidirectional torsional prestrain on subsequent fatigue fracture lives

Fig.9 Change in ultimate tensile strength with varied damage D of twist-back (B) and single- or cyclic-reversed (C) torsion

Recovery of the ultimate tensile strength by twist-back (zero residual pre-strain) was not observed in this study. This is probably because the ultimate tensile strength may depend strongly on ferrite path of the steel investigated, which may not essentially be influenced by twist-back. As described in the foregoing, fracture ductility may be highly affected by the texture of a material, which can be recovered more or less by twist-back, and this would result in recovery of fracture ductility by twist-back. One of the facts which may support this reasoning would be that anisotropy in ductility of a rolled steel plate is often much more noticeable than in strength⁽³⁾.

5. Push-pull low-cycle fatigue test results

In this study both the crack initiation life, at which cracks of (0.3 to 0.5)mm length occurred in the surface of a specimen, and the fracture life, at which the specimen was separated into two halves, were investigated. However, considering the following facts, (1) that the direction and the behavior of crack initiation seemed not to be affected by the modes of prestraining selected in this study, (2) that the crack initiation life was about 75 to 90% of the fracture life for all the modes and in the range of prestrains given in this study, and (3) that determination of the crack initiation life differed to some extent depending on observers, while the fracture life was uniquely determinable, only the fracture life will be given in this paper.

5.1 Effect of unidirectional torsion (A)

The fatigue test results for $D=0.095$ ($\gamma_{peak}^*=0.4$) and $D=0.326$ ($\gamma_{peak}^*=0.8$) are shown in Fig.10 in comparison with the results for unprestrained specimen ($D=0$). With an increase in D -value, the fatigue life decreases. The

log-log relations between the plastic strain range $\Delta\epsilon_p$ and number of cycles to fracture N for these three conditions can approximately be represented by group of parallel straight lines; the slope of the straight lines is about 0.56. Furthermore, it is not unnatural to interpret that the plots of the fracture ductility value ϵ_F at $N=1/4$ $\Delta\epsilon_p = 2\epsilon_F$ fall on the extended portions of each of these straight lines. This means that these fatigue test results are expressed by the Manson-Coffin type relation,

$$\Delta\epsilon_p^a N = (2\epsilon_F)^a / 4 \quad (3)$$

and that the effect of prestrain can be included in this equation through the dependence of fracture ductility ϵ_F on prestrain.

5.2 Effect of twist-back (B) and cyclic torsional (C) prestrains

Some representative examples of the fatigue test results are shown in Fig.11. The result of unprestrained specimens is also illustrated by the solid line in the figure. In this figure the effect of prestraining is not noticeable within a usual band of scatter of fatigue test results: all the observed values including those for unprestrained material can be approximated by a single straight line relationship between $\Delta\epsilon_p$ and N with a slope of 0.56. This also was true for the results obtained at other prestrain values.

However, when the mode of prestrain is limited to the twist-back torsion (B), the effect of the prestrain is slightly noticed as indicated in Fig.12; the fatigue life decreases with an increase in the D -value and with the corresponding decrease in fracture ductility. This slight regularity of the effect of the twist-back torsion can not be extended to the unprestrained material as shown in Fig.12, since the life for unprestrained specimens is rather short while the fracture ductility of unprestrained material is the largest in both the prestrained and the unprestrained materials.

This little effect of the twist-back and cyclic torsional prestrain may somewhat be expected from a lesser effect of prestrain in these modes on fracture ductility as indicated in Fig.7. However, it should be noted that some distinguishable difference in fatigue life can often be observed when materials have such a difference in fracture ductility indicated in Fig.11.

6. Discussion

6.1 Tension test results

In the experiments by Swift⁽⁷⁾, Backofen et al.⁽⁹⁾ and Rockey⁽⁸⁾, torsional prestrain changed linearly from zero at the specimen

Fig.11 Effect of twist-back (B) and cyclic-torsional (C) prestrain on subsequent fatigue fracture lives

Fig.12 Effect of twist-back torsion (B) on subsequent fatigue fracture lives

center to a maximum at the specimen surface. A similar experiment was also conducted by the present authors⁽¹⁶⁾. The common summary of these experiments is as follows:

(1) For uniaxial torsional prestrain, tensile fracture ductility remained almost unchanged or decreased slightly in a range of small prestrains. However, when the prestrain exceeded a certain value, it decreased transitionally to a small value. Corresponding to this transition of fracture ductility, appearances of fracture surface changed from a cup-and-cone type to a shear type.

(2) When the unidirectional torsional prestrain, which exceeded the foregoing transitional torsional prestrain, was twisted back to zero residual strain, the fracture ductility was restored almost to the original values (fracture ductility for the unprestrained material), and the cup-and-cone type fracture reappeared.

On the other hand, when homogeneously prestrained specimens as in the present study were used,

(1) no transitional decrease in fracture ductility was observed at any prestrain, and fracture was always the cup-and-cone type except for one example, and

(2) although it was observed, the amount of restoration of fracture ductility by twist-back was very limited.

The reasons why the transition appeared for inhomogeneously prestrained specimens are considered as follows;

(1) the difference in contribution to final fracture between the hardened low-ductility surface portion and the inner soft high-ductility portion, and

(2) the texture of specimens helically distorted by torsion.

In a range of small prestrains, the reduction of ductility at the surface is very small and the texture is very little distorted. Then even if cracks are assumed to be initiated at the specimen surface they may be blunted out by rich ductility of inner material and may not extend. The final fracture may be originated at the central portion of a specimen by triaxial tension⁽¹⁷⁾ as in usual ductile fracture. Since the central portion undergoes very little prestrain, the overall fracture ductility may not be affected so much by this amount of inhomogeneous torsional prestrain, and fracture will be the cup-and-cone type.

When the value of prestrain exceeds a transitional value, the reduction of ductility in an outer portion of a specimen is considerable and the helical angle of the distorted texture may be close to or smaller than 45° . Then cracks initiated at the specimen surface may grow inward along the distorted texture by inducing coalescence of microcracks and flaws which would often be distributed along the texture. The inner portion of rich ductility may not affect this mode of fracture because of a triaxial tension plane strain condition at the tip of growing cracks. This results in a small value of fracture ductility and slant fracture surface without local contraction. The transition in the overall fracture ductility value, therefore, would correspond to the transition in the mechanisms of fracture.

In the case of the homogeneously prestrained specimens used in this study, ductility is uniform at any point in the cross-section. Then the most favorable site of initiation of crack nuclei would be at the center of the cross-section due to the triaxial tension after the occurrence of necking. The cup-and-cone type fracture will prevail and fracture ductility may decrease gradually with no transitional phenomenon. However, when an extremely high value of prestrain is given, ductility of the material becomes very low and the material is very sensitive to preexisting flaws or cracks, as observed in the case of engineering brittle fracture of high strength materials. The transition of the fracture mode from the cup-and-cone type to the shear or opening type would occur and a transitional drop in fracture ductility will follow, as observed in Fig. 6 at a prestrain of $\gamma^*=1.2$ described as an exceptional case.

According to this reasoning, the restoration of fracture ductility by twist-back would be attributed to the highly distorted helical texture. By twisting-back, the distorted texture also recovers approximately to an original state, in which the fibrous texture runs parallel to the specimen axis. In this state, cracks, flaws or weak sites, which had been introduced by high prestrain

Material S10C, cyclic reversed shear strain range of 0.116, damage at surface of specimen $D=0.729$

Fig.13 Appearance of a fractured specimen prestrained inhomogeneously by cyclic-reversed torsion

along the fibrous direction of the texture, would also line up in the direction of the specimen axis. Then these defects would not work as a nucleus of unstable fracture under the uniaxial tension, and surface cracks would be blunted out. This, combined with rich ductility around the specimen center, results in the almost full recovery of fracture ductility by twist-back.

Fig.13 illustrates an appearance of a fractured specimen prestrained inhomogeneously by cyclic-reversed torsion⁽¹⁶⁾. The blunting-out of surface cracks and the resulting cup-and-cone type fracture are observed.

According to Rockey⁽⁸⁾, a transition was observed in restoration of fracture ductility by twist-back. This may be due to incomplete recovery of the fibrous texture by twist-back, as indicated by photographs in his paper.

It was found that the D -value was not a good index representing the effect of prestrain, particularly in the case of cyclic-reversed torsion(C). The D -value is primarily an index of fatigue damage, which is accumulated concentratedly in the thin surface layer of a specimen⁽¹⁸⁾. In this study, no such a surface layer remained in the surface of the small-sized specimens. Furthermore ductile fracture is originated in the central portion of a specimen, while fatigue damage is accumulated in the surface layer of that specimen. This may be the reason why the D -value was not a good index.

6.2 Fatigue test results

There are several investigations on cumulative fatigue damage in the high cycle fatigue region produced by reversed torsion followed by rotary bending or vice versa^{(20)~(22)}. It is reported that Miner's linear cumulative hypothesis approximately applies in this case.

In order to compare the fatigue test results in this study with this Miner's hypothesis, accumulation of the D -value due to prestrain and the damage value D' due to the low-cycle fatigue was examined as shown in Fig. 14. The chained line in the figure represents

Miner's hypothesis. A clear difference is observed between the unidirectional torsion(A) and the twist-back(B) or the cyclic-reversed torsion (C); the accumulated damage values were less than unity for A, but more than unity for B, and C. The D' -value seems to decrease with an increase in the D -value for unidirectional torsion and twist-back, while the D' -value in the case of the cyclic-reversed torsion remained about unity.

These difference may be caused by the following two facts:

(1) A physical entity of fatigue damage at room temperature may be interpreted to be in reduction in fracture ductility for fatigue in a very high plastic strain range, the life of which is less than several cycles, and to be in surface damage with a life longer than several cycles. In preparation of the small-sized specimens used in this study, this surface damaged layer was removed. Therefore, in the case of cyclic-reversed torsional prestrain, in which a relatively small plastic strain range was repeatedly applied, the D -value(prestrain) is considered to have little affected the subsequent fatigue life. In the case of unidirectional or twist-back torsion, in which the amplitude of prestrain was high, the D -value contributes to a decrease in fracture ductility as illustrated in Figs.10 and 12. This may cause some decrease in the subsequent fatigue life as shown in Fig.14.

(2) The difference in helical angle of the prestrained texture, which exists between the unidirectional torsion(A) and the twist-back(B) or the cyclic-reversed torsion(C), could be a cause of the foregoing difference in the accumulated value of fatigue damage.

In the high-cycle fatigue damage study⁽²⁰⁾⁻⁽²²⁾ quoted in the earlier part of this section, no fatigue-damaged surface layer was removed. Also there may be no difference in the physical entity of fatigue damage between cyclic-reversed torsion and rotary bending from a view point of surface damage. Under these circumstances, the linear cumulative damage hypothesis would apply.

In general it has been considered that there is a good correlation between fracture ductility and the low-cycle fatigue life, as seen in Fig.10. However, in the results shown in Fig.11, no significant difference in fatigue lives was observed in spite of a considerable difference in fracture ductility. This may be attributable to the following three reasons:

(1) There are two material constants n and C in the Manson-Coffin equation, $\Delta\epsilon_p N = C$. Both would take different values for different materials, different strain histories and so on.

(2) The relation between the fatigue life and fracture ductility is an empirical formula which, in general, is not so accurate as to be able to discriminate the difference in fracture ductility observed in this study.

(3) In this study, work softening for the prestrained materials and work hardening for the unprestrained material were observed during fatigue tests.

Fig.14 Cumulation of damage D due to torsional prestrain and D' due to low-cycle fatigue

Since this behavior of work softening and work hardening was different for different modes of prestrain, magnitude of prestrain, fatigue lives and so on, it may be questionable to think that the fatigue life was destined only by the fracture ductility before the start of fatigue tests.

If the fact that the 95% confidence limit of fatigue life ratios ranges from 0.7 to 1.4 in elaborated fatigue experiments is considered, the results in this study could rather be evaluated to be in fairly good agreement with the accepted experiences.

7. Conclusions

The effect of torsional prestrain on tensile mechanical and low-cycle fatigue properties was studied with 0.25% carbon steel(S25C), with special reference to homogeneous prestrain in the cross-section of tensile and fatigue specimens. The following are the conclusions derived from this investigation.

(1) Fracture ductility ϵ_f decreased by unidirectional torsion in a curve slightly concave upward. All the specimens were fractured with cup-and-cone surfaces with one exception. No transition in fracture ductility nor in mode of fracture was observed in this study.

(2) Decrease in fracture ductility in the case of twist-back and cyclic-reversed torsion was considerably smaller as compared with that observed in the unidirectional torsion, when the prestrain was evaluated on the basis of Miner's linear cumulative damage hypothesis. The decrease was influenced by the amplitude(or the maximum value) of prestrain. The amount of restoration of fracture ductility by twist-back was very limited; this was quite different from previous results which had been determined by inhomogeneously prestrained specimens.

(3) The foregoing two conclusions can be reasonably explained both by the reduction in ductility due to prestrain and helical distortion of fibrous texture of the test material by torsion.

(4) The unidirectional torsion decreased the fatigue life. This decrease in fatigue life was predictable from the decrease of fracture ductility using the Manson-Coffin type relation.

(5) The effect of twist-back and cyclic-reversed torsion on fatigue test results was negligibly small in considering the usual scatter of the experimental values. From the engineering point of view, it could be concluded that the effect of prestrain on fatigue life can be predicted from the change of fracture ductility by using the Manson-Coffin relation.

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