General paper

Remaining Life Evaluation of 316LC Steel Based on a New Creep-Fatigue Damage Rule

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Abstract: Creep-fatigue remaining life of 316LC steel subjected to PP-type testing and CP-type testing is evaluated by use of two procedures that the authors proposed in the previous work for Mod.9Cr-1Mo steel. A new creep-fatigue damage rules determined by the authors for 316LC steels are used, where crack initiation life cannot be neglected in CP-type straining or in PP type straining. The results show that both proposed procedures yield more accurate estimations of remaining life, material damage and applied inelastic strain range for 316LC steel than for Mod.9Cr-1Mo steel. Among the two procedures, procedure 1 yields superior prediction accuracy over procedure 2, where the former requires measurement of surface crack length at a given total number of cycles, whereas the latter requires measurement of surface crack growth rate. Especially satisfactory results are obtained when procedure 1 is adopted and the measured surface crack length is 300 μm or longer. That is, the ratio of the predicted value of remaining life to the actual value is below 1.1 and the corresponding ratios for material damage and applied inelastic strain range are from 0.9 to 1.3.

Key words: Creep-fatigue, Damage rule, Material damage, Small crack, Crack growth, Remaining life evaluation, Life prediction, 316LC steel

1. INTRODUCTION

In a previous paper [1], the authors presented procedures for evaluating remaining life on the basis of a new creep-fatigue damage rule [2, 3], and applied the procedures to remaining life evaluation of Mod.9Cr-1Mo round bar specimens tested at 873K in air. The proposed procedures could estimate remaining life, applied strain range and material damage from surface crack length at a certain number of cycles or from the change of surface crack length during a certain numbers of cycles, and therefore could obtain a more general solution to the remaining life evaluation problem than the conventional methods [4 - 7].

The results by the present authors show that the prediction accuracies of the procedures are very good in case of PP tests, whereas they are extremely poor when the applied strain ranges were small in PC, CP and CC tests, especially in cases where the difference between measured crack length and the hypothetical initial crack length is 30 μm or less, or where the change in crack length during a given interval of measurement is 30 μm or less. Except for these cases, remaining life evaluation is accurate to a factor of about 3~4. This suggests the need for further improvements. One of the causes of unsatisfactory prediction accuracies in the PC, CP and CC tests lies in the creep-fatigue damage rule proposed for Mod.9Cr-1Mo steel being based on the assumption that crack initiation life is negligible in comparison with total life, regardless of the level of the applied strain range in these tests.

In the present study, the proposed procedures for the remaining life evaluation are applied for 316LC steel. The creep-fatigue damage rule of this material in PP- and CP-type straining was studied previously, yielding the finding that crack initiation life should be considered in CP-type straining as well as in PP-type straining [8]. The results of such consideration show that the prediction accuracies in the remaining life evaluation of 316LC steel are much more satisfactory than in case of Mod.9Cr-1Mo steel, suggesting that the creep-fatigue damage rule of Mod.9Cr-1Mo steel in PC-, CP- and CC-type straining should be improved to the level found in the case of 316LC steel.

2. CREEP FATIGUE DAMAGE RULE AND LIFE EVALUATION

The creep-fatigue damage rule derived for 316LC steel is shown as follows:

(1) Under the PP type straining the ratio of crack initiation life to total fatigue life N_{pp} , α , is not negligible when the applied inelastic strain range, $\Delta\epsilon_{pp}$, is smaller than a critical value, $(\Delta\epsilon_{pp})_{cr}$. The crack growth curve is given by Eq. (1). In Eq.(1-a), α is the crack depth at n th cycle, $(a_o)_{pp}$ and $(a_f)_{pp}$ are the initial and final crack depth, respectively, when $\Delta\epsilon_{pp}$ is cycled. And the value of α is given by Eq. (1-b).

$$\frac{n}{N_{pp}} = \alpha + (1-\alpha) \frac{\ln(a/a_o)_{pp}}{\ln(a_f/a_o)_{pp}} \quad (1-a)$$

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$$\left. \begin{aligned} \alpha &= C_1 \log \Delta \varepsilon_{pp} + C_2 \quad (\Delta \varepsilon_{pp} < (\Delta \varepsilon_{pp})_{cr}) \\ &= 0 \quad (\Delta \varepsilon_{pp} \geq (\Delta \varepsilon_{pp})_{cr}) \\ &\quad (C_1, C_2: \text{Material constants}) \end{aligned} \right\} \quad (1-b)$$

(2) Under CP type straining, where $\Delta \varepsilon_{in} \equiv \Delta \varepsilon_{pp} + \Delta \varepsilon_{cp}$, crack initiation life can be neglected in comparison with total life when $\Delta \varepsilon_{in}$ is greater than a critical value $(\Delta \varepsilon_{pp})_{cr}$, but cannot be neglected when $\Delta \varepsilon_{in}$ is smaller than $(\Delta \varepsilon_{pp})_{cr}$. The crack growth curve is given by Eqs. (2), (3) and (4);

$$\left. \begin{aligned} \frac{n}{N_f} &= \alpha + (1 - \alpha) \frac{\ln(a/a_o)_{pp+cp}}{\ln(a_c/a_o)_{pp+cp}} \\ \alpha &= C_1 \log \Delta \varepsilon_{in} + C_2 \quad (\Delta \varepsilon_{in} < (\Delta \varepsilon_{pp})_{cr}) \\ &= 0 \quad (\Delta \varepsilon_{in} \geq (\Delta \varepsilon_{pp})_{cr}) \end{aligned} \right\} \quad (2)$$

$$\begin{aligned} &\ln(a_c/a_o)_{pp+cp} \\ &= \frac{B'_{pp} F_{pp}^{1/m_{pp}} \Delta \varepsilon_{in}^{1/m_{pp}} + B'_{cp} F_{cp}^{1/m_{cp}} \Delta \varepsilon_{in}^{1/m_{cp}}}{\frac{B'_{pp} F_{pp}^{1/m_{pp}} \Delta \varepsilon_{in}^{1/m_{pp}}}{\ln(a_f/a_o)_{pp}} + \frac{B'_{cp} F_{cp}^{1/m_{cp}} \Delta \varepsilon_{in}^{1/m_{cp}}}{\ln(a_f/a_o)_{cp}}} \quad (3) \end{aligned}$$

$$\left. \begin{aligned} (a_o)_{pp+cp} &= (a_o)_{cp} \quad \text{when } \Delta \varepsilon_{cp} \geq \Delta \varepsilon_{pp} \\ (a_o)_{pp+cp} &= (a_o)_{pp} \quad \text{when } \Delta \varepsilon_{cp} < \Delta \varepsilon_{pp} \end{aligned} \right\} \quad (4)$$

where $F_{pp} = \Delta \varepsilon_{pp} / \Delta \varepsilon_{in}$, $F_{cp} = \Delta \varepsilon_{cp} / \Delta \varepsilon_{in}$, and α , a , $(a_o)_{pp+cp}$ and $(a_c)_{pp+cp}$ represent the ratio of crack initiation life to total life N_f , crack depth in number of cycles n , and initial and final crack depth, respectively, and $(a_o)_{cp}$ and $(a_f)_{cp}$ represent initial and final crack depth, respectively, when $\Delta \varepsilon_{cp}$ is cycled. The constants, m_{pp} , m_{cp} , B'_{pp} and B'_{cp} in Eq.(3), are the material constants used in Eqs. (5) and (6);

$$\Delta \varepsilon_{pp} = A_{pp} N_{pp}^{-m_{pp}}, \Delta \varepsilon_{cp} = A_{cp} N_{cp}^{-m_{cp}} \quad (5)$$

$$\left. \begin{aligned} \left(\frac{da}{dN} \right)_{pp} &= B'_{pp} \Delta \varepsilon_{pp}^{1/m_{pp}} a \\ \left(\frac{da}{dN} \right)_{cp} &= B'_{cp} \Delta \varepsilon_{cp}^{1/m_{cp}} a \end{aligned} \right\} \quad (6)$$

Equations (5) and (6) represent high temperature creep-fatigue properties of a smooth round bar specimen and crack growth properties of a semicircular crack in the specimen, respectively.

The calculation formula for life N_f is expressed by Eq. (7), in which the value of α is considered.

$$\frac{1}{(1 - \alpha)N_f} = \frac{B'_{pp} F_{pp}^{1/m_{pp}} \Delta \varepsilon_{in}^{1/m_{pp}}}{\ln(a_f/a_o)_{pp}} + \frac{B'_{cp} F_{cp}^{1/m_{cp}} \Delta \varepsilon_{in}^{1/m_{cp}}}{\ln(a_f/a_o)_{cp}} \quad (7)$$

The material parameters needed in the life evaluation for 316LC steel based on the damage rule described above are listed in Table 1.

The damage rule for 316LC steel greatly differs from that for Mod.9Cr-1Mo steel, in point that α appears in Eq. (2), which coincides with Eq. (1) when the $\Delta \varepsilon_{cp}$ component is zero. Therefore, Eq. (2) is the general form of the damage rule and incorporates Eq. (1).

Table 1. Material parameters for 316LC steel.

ij	pp	cp
A_{ij}	0.376	0.565
$1/m_{ij}$	1.57	1.28
B'_{ij}	22.0	10.4
$\ln(a_f/a_o)_{ij}$	4.74	5.01
$2(a_o)_{ij} \text{ (mm)}$	8.7×10^{-2}	8.7×10^{-2}
$2(a_f)_{ij} \text{ (mm)}$	10.0	13.0

$(\Delta \varepsilon_{pp})_{cr} = 0.0023, C_1 = -1.80, C_2 = -4.75$

3. PROCEDURES FOR REMAINING LIFE EVALUATION

The two procedures for remaining life evaluation that the authors proposed in a previous paper [1] are based on measurement of the small surface crack length $2a$ of the structural components. Considering that many small distributed cracks usually grow during the creep-fatigue damage process, in remaining life evaluation the maximum observed crack length or the maximum value estimated from the measured distributed cracks is used as the value of $2a$. The two proposed procedures can be described below in the case of CP-type straining. Both procedures require acquisition of the values of F_{pp} and F_{cp} by detailed inelastic analysis that considers the operating conditions of the components.

3.1. Procedure 1

Procedure 1 requires knowledge of both the number of operation cycles after start up n and the maximum surface crack length $2a$ at the point of the remaining life evaluation. Assuming that the cracks have a semicircular geometry, the crack depth is equal to a . Equation (2) gives the relationship between a and n . Since the value of $(a_o)_{pp+cp}$ is 0.087mm from Eq. (4) and Table 1, and the values of F_{pp} and F_{cp} are also known, three equations in Eqs. (2) and (7) include three unknowns: total life N_f , α and $\Delta \varepsilon_{in}$. When these equations are solved, the remaining life N_r can be evaluated as $(N_f - n)$.

3.2. Procedure 2

In procedure 2, remaining life can be determined when the maximum surface crack length $2a_1$ and $2a_2$ before and after a given interval of operation cycles, $\Delta n (\equiv n_2 - n_1)$, are known even if the numbers of opera-

tion cycles after start-up, n_1 and n_2 , are unknown.

From the first relationship in Eq. (2), the following relationship can be obtained.

$$\frac{\Delta n}{N_f} = (1 - \alpha) \frac{\ln(a_2/a_1)_{pp+cp}}{\ln(a_c/a_o)_{pp+cp}} \quad (8)$$

Three unknown parameters N_f , α and $\Delta \varepsilon_{in}$ are determined by solving the second relationship in Eq. (2), Eqs. (7) and (8). Subsequently, the value of n_2 can be determined by use of the first relationship in Eq. (2) and Eq. (3), the determined value of N_f , α , $\Delta \varepsilon_{in}$, and the measured value a_2 . Consequently, the remaining life N_r can be evaluated as $(N_f - n_2)$.

4. REMAINING LIFE EVALUATION OF 316LC STEEL DURING PP AND CP TESTS

In the previous report [8], the authors measured the maximum crack length on the surface of 316LC smooth round bar specimens at the various life stages during PP and CP tests. The results are shown in Figs.1 and 2. The measurement was conducted by stopping the test intermittently at a given cycle ratio n/N_f and calculating the remaining life. In the present paper, the remaining lives are evaluated from these data by both procedures at various cycle ratios of the tests. Table 2 shows the interval Δn of surface crack length measurement corresponding to each of the tests.

In procedures 2, remaining life was evaluated at every measurement interval, Δn , in the tests. As shown in Fig.1, the observed surface crack length was smaller than the hypothetical initial crack length $(a_o)_{cp}$. In such case, the remaining life was calculated under the assumption that the measured value is equal to the hypothetical initial crack length. In cases where the change in surface crack length was 30 μm or less, remaining life was not evaluated by procedure 2.

Table 2. PP and CP test results on 316LC steels analyzed by the proposed remaining life evaluation procedures (N_f , Δn : Cycles).

Test	$\Delta \varepsilon_t$	$\Delta \varepsilon_{in}$	F_{pp}	F_{cp}	N_f	Δn
PP	0.010	0.0069	1	0	616	≈ 55
	0.003	0.0012	1	0	10659	1268
CP	0.010	0.0074	0.108	0.892	300	75
	0.005	0.0030	0.168	0.832	1024	≈ 100
	0.003	0.0013	0.538	0.462	4599	≈ 500

4.1. Results of Remaining Life Estimation

In Figs.3 and 4, estimated remaining life is plotted against corresponding evaluation points (cycle ratios). The broken lines represent actual remaining lives. Figure 5 shows the relationship between estimated remaining life and actual remaining life.

Fig.1. Maximum surface crack length $2a$ measured during PP straining tests.

Fig.2. Maximum surface crack length $2a$ measured during CP straining tests.

In the case of procedure 1, as observed in Fig.3, estimated remaining life shows very close agreement with actual remaining life at almost all evaluation points. Procedure 1 tends to predict a life that is shorter than the actual remaining life. When applied inelastic strain range is small, the difference between estimated life and actual life is large at the initial evaluation points, whereas when applied inelastic strain range is large, the difference increases with the cycle ratio. Therefore, procedure 1 can be expected to yield conservative estimation. These results indicate that the prediction accuracy being very poor near 200 cycles, by a factor greater than 2, does not present a significant problem for the reliability of the procedure 1.

In the case of procedure 2, the difference between estimated life and the actual remaining life is larger than in the case of procedure 1. The estimation is conservative when applied strain range is large, whereas it is not always conservative when applied inelastic strain range is small. The estimation accuracy of procedure 2 is poorer than that of procedure 1 for 316LC steel, but is better than that of procedure 2 for Mod.9Cr-1Mo steel (by a factor of 3~4).

Fig.3. Results of remaining life estimation by procedure 1.

Fig.4. Results of remaining life estimation by procedure 2.

Table 3 summarizes the values of cycle ratio at which the remaining life of each specimen tested is estimated as zero by both procedures. Actual remaining lives are also listed for comparison with the estimated values. The procedures have approximately equal ability to precisely determine the zero-remaining-life point.

4.2. Results of Material Damage Estimation

Material damage at the evaluation point can be calculated as n/N_f in procedure 1 and as n_2/N_f in procedure 2. Figure 6 compares the estimated values of material damage, $(n/N_f)_{pre}$, with actual material damage $(n/N_f)_{exp}$, and shows that both procedures yielded conservative estimation at almost all evaluation points. Estimation accuracy is good, except for a few points in procedure 2 where accuracy is poor by a factor of 2 or more. Accuracy is especially good in procedure

Fig.5. Comparison of remaining lives estimated by the proposed procedures and actual values.

Table 3. Cycle ratios at which each of the proposed procedures estimated remaining life is zero or less at each test (Proc.1 and 2 denote the estimated lives by procedure 1 and 2, respectively).

Test	$\Delta \epsilon_t$	$\frac{n}{N_f}$	Remaining life (Cycles)		
			Actual	Proc.1	Proc.2
PP	0.01	0.815	114	-4	-29
	0.003	0.952	512	-216	-163
CP	0.01	1	0	2	3
	0.005	0.879	124	-27	-24
	0.003	0.917	382	-28	-18

Fig.6. Comparison of material damage estimated by the proposed procedures and actual values.

1; within a factor of 1.3. In procedure 2, poor estimation accuracy is obtained in a PP test where $\Delta \epsilon_t = 0.003$ when $\Delta(2a)$ is equal to $51 \mu\text{m}$, suggesting that use of the procedure should be limited to large values of $\Delta(2a)$.

4.3. Results of Applied Inelastic Strain Range Estimation

Figure 7 compares the applied inelastic strain ranges estimated by the proposed procedures $(\Delta \varepsilon_{in})_{pre}$ and actual values $(\Delta \varepsilon_{in})_{exp}$, and Fig.8 shows the difference in $(\Delta \varepsilon_{in})_{pre}$ between two procedures at each evaluation point. Estimation accuracy is found to be better in procedure 1 than in procedure 2. In the case of procedure 1, the smaller the value of applied inelastic strain range, the more conservative the estimation, except for the initial life stages of the PP test at $(\Delta \varepsilon_{in})_{exp} = 0.0069$, where the estimated values are much smaller than the actual values. A notable finding is that approximately constant estimated values were obtained in the middle of the tests.

(a) Procedure 1

(b) Procedure 2

Fig.7. Comparison of applied inelastic strain ranges estimated by the proposed procedures and actual values.

In contrast, in the case of procedure 2, the estimation was conservative at some points and not conservative at other points, independent of the evaluation life stage, the strain waveform and the applied inelastic strain range of the tests. The estimation accuracy generally falls within a factor of 2.

5. DISCUSSION

The results of the present study show that proposed procedure 1 can estimate remaining life with good accuracy and some conservatism. However, the results also show that estimation accuracy varies from cycle ratio to cycle ratio, and that further improvement in accuracy is

(a) PP test

(b) CP test

Fig.8. Results of applied inelastic strain range estimation by the proposed procedures.

required, especially at the initial life stage when the measured surface crack length is small. Meanwhile, proposed procedure 2 is found to be inferior to procedure 1 in estimation accuracy and conservatism, and sufficient surface crack length change should be measured for accurate prediction. From these findings, the effect of measured surface crack length on the estimation accuracy of procedure 1 and the effect of the amount of measured surface crack length change on the estimation accuracy of procedure 2 are discussed below.

5.1 Effect of The Value of Measured Crack Length $2a$ on Estimation Accuracy of Procedure 1

Figures 9, 10 and 11 show the effect of measured surface crack length $2a$ on the estimation accuracy of procedure 1 for remaining life, material damage and applied inelastic range, respectively. Estimation accuracy is expressed as the ratio of the estimated value to the actual value, and therefore conservative estimation is indicated by a ratio smaller than 1.0 for remaining life and ratios

Fig.9. Effect of crack length on the prediction accuracy of procedure 1 for remaining life.

Fig.10. Effect of crack length on the prediction accuracy of procedure 1 for material damage.

larger than 1.0 for both material damage and applied inelastic strain range.

These figures show that estimation accuracy is generally very good; the ratio is 1.1 at the highest for remaining life, and 0.9 at the lowest for both material damage and applied inelastic strain range. However, poor estimation accuracies with nonconservatism are observed when $2a$ is smaller than $200 \mu\text{m}$ in PP test when $\Delta\epsilon_t = 0.01$. Therefore, completely conservative estimation with high estimation accuracy is yielded when $2a$ is larger than $300 \mu\text{m}$. Procedure 1 can estimate remaining life with an accuracy below a factor of 1.1 and both material damage and applied inelastic strain range within a factor of 0.9 to 1.3.

5.2 Effect of The Value of Measured Crack Length Change $\Delta(2a)$ on Estimation Accuracy of Procedure 2

Figures 12 and 13 show the effect on estimation accuracy of procedure 2 exerted by surface crack length change $\Delta(2a)$ measured during Δn and average surface crack growth rate $\Delta(2a)/\Delta n$, respectively. These results suggest that the estimation by procedure 2 involves a much greater deviation from nonconservatism than does procedure 1 even when $\Delta(2a)$ is larger than $200 \mu\text{m}$ or $\Delta(2a)/\Delta n$ is larger than $2 \times 10^{-4} \text{ mm/cycle}$, and that completely conservative estimation can be expected when $\Delta(2a)/\Delta n$ is larger than 10^{-2} mm/cycle .

5.3 Modification of Creep-Fatigue Damage Rule to a More General Form

The proposed procedures' greater accuracy in estimating remaining creep-fatigue lives for 316LC steel than for Mod.9Cr-1Mo steel strongly suggests that the necessity to improve the damage rule proposed for Mod.9Cr-1Mo steel; at least, to modify the rule as that proposed for 316LC steel. Another, more general modification of Eq. (1) worthy of examining in further study is the creep-fatigue damage rule based on the extension

Fig.11. Effect of crack length on the prediction accuracy of procedure 1 for inelastic strain range.

to the following form for $\Delta\epsilon_{ij}$ ($ij=pp,pc,cp,cc$) .

$$\left. \begin{aligned} \frac{n}{N_{ij}} &= \alpha_{ij} + (1 - \alpha_{ij}) \frac{\ln(a/a_o)_{ij}}{\ln(a_f/a_o)_{ij}} \\ \alpha_{ij} &= C_{1ij} \log \Delta\epsilon_{ij} + C_{2ij} \quad \text{when } \Delta\epsilon_{ij} < (\Delta\epsilon_{ij})_{cr} \\ &= 0 \quad \text{when } \Delta\epsilon_{ij} \geq (\Delta\epsilon_{ij})_{cr} \end{aligned} \right\} \quad (9)$$

Fig.12. Effect of measured change in surface crack length on the prediction accuracy of procedure 2 for evaluating remaining life.

Fig.13. Effect of measured surface crack growth rate $\Delta(2a)/\Delta n$ on the prediction accuracy of procedure 2 for remaining life.

6. CONCLUSION

Remaining creep-fatigue life evaluation was conducted on PP-tested ($\Delta\epsilon_t = 0.01$ and 0.003) and CP-tested ($\Delta\epsilon_t = 0.01$, 0.005 and 0.003) 316LC steel by using the two procedures that the authors had previously proposed for Mod.9Cr-1Mo steel. One, called procedure 1, is based on the measurement of the surface crack length $2a$ at a given number of operation cycles following start up, and the other, called procedure 2, is based on the measurement of surface crack length change during a given interval; i.e., a given number of cycles. The results show the followings:

(1) The two proposed procedures yield much greater estimation accuracies when applied to 316LC steel rather than to Mod.9Cr-1Mo steel.

(2) Among the two procedures, procedure 1 is superior to procedure 2 in the estimation accuracy. Especially satisfactory results are obtained when procedure 1 is adopted and the measured surface crack length is $300 \mu\text{m}$ or longer. The ratio of the predicted value to the actual value ranges below 1.1 for remaining life and from 0.9 to 1.3 for both material damage and applied inelastic strain range.

(3) The two procedures yield satisfactory prediction accuracy of zero-remaining-life operation cycles, and little difference is found between the two.

These results strongly suggest that the creep-fatigue damage rules determined by the authors for 316LC steel should be applied to remaining life evaluation of Mod.9Cr-1Mo steel; specifically, crack initiation life can be neglected in neither CP-type straining nor PP-type straining.

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