Effect of Compressive Stress Field During Dwell Time in Creep Fatigue Evaluation

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ABSTRACT

In this survey, we present a comparison of multiaxial stress effects in creep fatigue damage. The open literature proposes ten equivalent stress criteria which can be tested with experimental creep and creep-fatigue results.

INTRODUCTION

From a long time, it is well known that creep depends on multiaxial stress state. (ASME Code Case N 47) and the previous version of the (RCC-MR, 1985) are based on the maximum shear criterion for the first one and the octahedral shear criterion for the second one to calculate the equivalent stress in creep fatigue analysis. Some authors as (Huddleston, 1985), (Hayhurst, 1972), (Contesti-Pineau, 1985), (Browne) have demonstrated that creep damage depends on Von Mises criterion and also the maximum principal stress, the hydrostatic pressure. The creep multiaxial criteria are a combination of these parameters.

DAMAGE CRITERIA

The criteria could be classify in three categories

$$\left.\begin{array}{ll}
\sigma^* = \sup|\sigma_i| & \text{maximum principal stress} \\[2ex]
\sigma^* = \sqrt{\frac{2}{3} S_{ij} S_{ij}} = \sigma_{eq} & \text{Von Mises} \\[2ex]
\sigma^* = \sup\limits_{i \neq j} |\sigma_i - \sigma_j| & \text{Tresca} \\[2ex]
\sigma^* = \sqrt{\frac{3}{2} S_{ij} S_{ij}} \left[\frac{2}{3}(1-\nu) + \frac{1-2\nu}{3} \left(\frac{\sigma_{kk}}{\sqrt{\frac{3}{2} S_{ij} S_{ij}}} \right)^2 \right]^{\frac{1}{2}} & \text{Elastic Energy}
\end{array}\right\} \text{Mechanical criteria}$$

$\sigma^* = \alpha \, \mathrm{Sup}|\sigma_i| + \beta \, \sigma_{eq} + \gamma \, \sigma_{kk}$
with σ_{kk} 3 of the hydrostatic pressure in uniaxial torsion
the coefficients must satisfy the following equations

$$\alpha + \beta + \gamma = 1.$$

The different parameters are:
(Hayhurst, 1972), (Contesti-Pineau,1985) $\alpha = 0$; $\gamma = 0.25$
(Roche, 1986) $\alpha = 0$; $\gamma = 0.1$
RCC-MR New Version, (Cabrillat, 1989) $\alpha = 0$; $\gamma = 0.133$
(Sdobyrev, 1958) $\alpha = 0.5$; $\gamma = 0$

Phenomenological criteria

(Cane, 1979) $\sigma^* = \sup|\sigma_1|^{\frac{\nu}{m}} \sigma_{eq}^{m-\frac{\nu}{m}}$

m is a slope of the uniaxial stress creep rupture and ν a mechanical characteristic.

(Huddleston, 1985) $\sigma^* = \sigma_{eq} \exp\left(0.24 \left(\frac{\sigma_{kk}}{S_s} - 1 \right)\right)$

$S_s = \sqrt{(\sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2)}$

Metallurgical criteria

The conservatism of these criteria is evaluated by comparison with experimental results taken from (Huddleston, 1985) and (Chubb and Bolton, 1980).

Some tubes in 304 and 316 stainless steel are submitted to different kinds of static load controlled internal pressure, tension, torsion, axial tension or compression at temperature around 600°C. The figure 1 presents the results obtained with the better criterion. On the abscissa, we have plotted the ratio of stress σ_{eq}, the 3 times hydrostatic pressure σ_{kk}, by the Von Mises equivalent and on the ordinate the ratio of the equivalent stress σ^* calculated with a criterion by the Von Mises equivalent stress. For the experimental results σ^* corresponds to a stress obtained from the uniaxial creep rupture curve of the material for a time equal to the experimental time to rupture.

We can noticed that no experimental results are available in compressive region. The Von Mises criterion is not conservative in biaxial tension. The equivalent stress reduction coefficient proposed varies from 0.6 to 0.25 in the biaxial compressive stress state.

UNIAXIAL CREEP FATIGUE TESTS (Autrusson, 1987)

A group of continuous fatigue and relaxation fatigue tests were conducted on EDF-SPH 316L steel SQ plate. The variations in total strain were 0.7 or 1.2%, and the holding times were 10, 30, 90 and 300 minutes in tension and compression. These time intervals are short in comparison with those encountered in service.

This programme has a twofold objective:

- accurate determination of the continuous fatigue service life, to be used as a reference;
- evaluation of the reduction of this service life caused by the superposition of a relaxation at the extremities of the cycle, either in tension or in compression, in order to quantify the differences in damage.

  Figure 3 presents the test results. The service life reduction coefficient $F_{R_{25}}$ is defined as follows:

  $$F_{R_{25}} = \frac{N_{25}\ (t_m)}{N_{25}\ (t_m=0)}$$

  $N_{25}(t_m)$ is the service life corresponding to a drop of 25% in the stress σ_t in comparison with the maximum measured during the test, corresponding to already widely propagated cracks.

  $N_{25}(t_m=0)$ is the reference service life in continuous fatigue.

(Cabrillat, 1989) made an interpretation of the results shown in figure 2. The criteria employed for the interpretation are the Von Mises, Huddleston and Hayhurst-Pineau criteria, and the RCC-MR new version.

For uniaxial tensile hold-times all the criteria are equivalent and conservative. For compressive hold-times, the Von Mises criterion is very conservative, and its predictions are identical to those obtained for tensile hold-times.

The Huddleston criterion and the RCC-MR Addenda are conservative, the former providing a better fit of experimental results. The Hayhurst-Pineau criterion predicts slightly longer service lives than the average of the test results for compressive holding time, but remains within the scatter of the experimental results.

CRACK INITIATION IN CREEP FATIGUE WITH IMPOSED STRAINS (Autrusson, 1987)

The CEA-DEMT conducted relaxation fatigue tests on specimens stressed in cyclic bending at 600°C. The specimen material was EDF-SPH 316L stainless steel. The specimens were tested at imposed strains with a variation in total strain $\Delta\varepsilon = 0.8\%$. Two tests were performed without holdtime and another two with a hold-time of 15 minutes at a cycle extremum. Hence one side of the specimen was also relaxed in compression and the other in tension.

For each test, crack initiation was detected by the potential drop method. Figure 3 shows the main test results. The hold-time of 15 minutes reduces the number of cycles to crack initiation by a factor of 2 in comparison with fatigue stressed specimens.

The number of cycles to initiation is virtually identical whether the hold-time is in tension or compression. No difference was therefore recorded in initiation time. In this analysis, the criteria accounting for triaxiality (sign of the stresses) do not sheld light on the initiation phase.

After examining the facies of specimen n°4 subjected to a relaxation fatigue test, the following was noted:

- On the side relaxed in tension, the cracks propagated considerably with an intergranular facies. This is therefore a case of creep fracture during which fatigue has accelerated the detachment of the grains.
- On the side relaxed in compression, the fracture facies is transgranular. This is therefore a case of fatigue fracture during which creep has only limited or negligible effect on crack propagation. On the two sides the cracks were initiated after the same number of cycles, but propagation is not of the same type,
  - . creep on the side of tensile hold-time,
  - . fatigue on the side of compressive hold-time.

To estimate the creep fatigue damage, it is necessary to have curves of materials. Our specimens were of EDF-SPH 316L steel, and the documents of the materials Working Group and the technical notes of SRMA give the average properties, the cyclic consolidation curve, the oligocyclic fatigue curve and the creep fracture curve.

The fatigue damage estimated ranged between 0.25 and 0.3 and the creep damage between 0.4 and 0.5 without considering relaxation. Figure 3 shows the results of creep fatigue damage in specimens 3 and 4.

USE OF MULTIAXIAL CRITERIA IN CREEP

The criteria taking account of the sign of the stresses at the start of the hold-time can only be used after elastic-plastic or inelastic analysis. This is because elastic analysis generally gives a false evaluation of the tensor at the start of the hold-time if the latter does not correspond to the maximum loading.

In selecting the design cycles, special attention will be paid to the position of the hold-time in the strain cycles.

CONCLUSIONS

This work has been done in the status of European Fast Breeder R.&D. Cooperation agreement Structural Integrity Group AGT9b, and a milestone report has been made on this task (Autrusson, 1987). From these results, we can conclude that:

- The classic model used to evaluate pure creep damage by design codes and based on the Von Mises criterion is overconservative in pure shear, non-conservative in biaxial tension.

- To predict creep fatigue fracture, these two models help to describe the effect of the sign of the stress correctly by taking account of relaxation. The Hayhurst-Pineau model $\gamma = 0.25$ could become slightly non-conservative for long hold-times, and the modification of the coefficient assigned to the hydrostatic pressure by RCC-MR new version ($\gamma = 0.133$) makes this criterion definitely conservative.

But the design rules as RCC-MR intend to predict crack initiation relaxation fatigue. The experimental results (Autrusson, 1987) on creep fatigue tests reveal that the number of cycles to initiation is identical whether the holdtime is in tension or in compression, and complementary test results are necessary to confirm these points. The materials properties in design rules have been established for the rupture of the specimen, and the design margins could cover the propagation of cracks or the coalescence of cavities.

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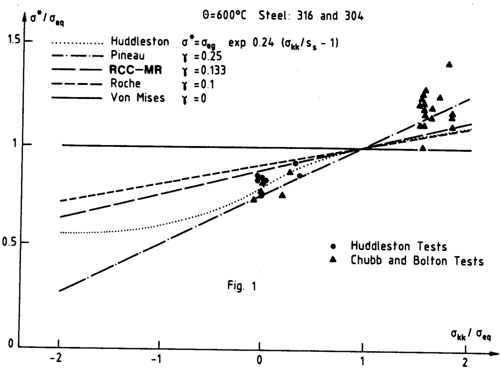


Fig. 1

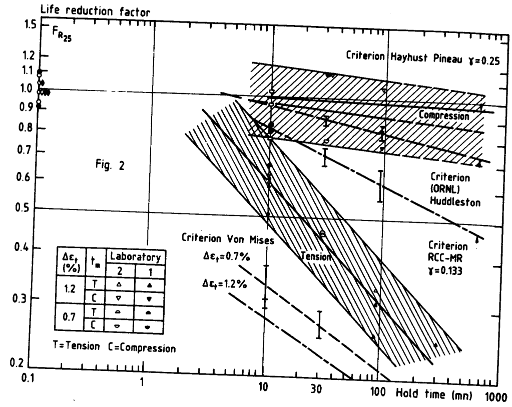
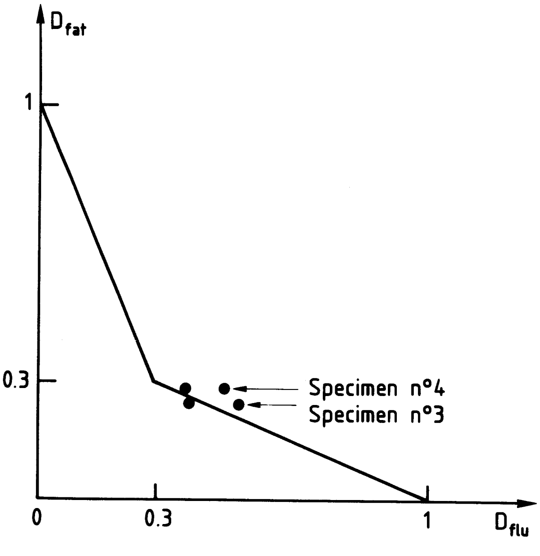


Fig. 2



$\theta = 600°C$
$\Delta\varepsilon = 0.8\%$
t_m = 15 minutes
Material = 316L SPH

	Δε%	N_c	
Specimen 3	0.79	1140	Hold time in tension
	0.81	1120	Hold time in compression
Specimen 4	0.81	1100	Hold time in tension
	0.75	1100	Hold time in compression
Specimen 1	0.70	2500	Without hold time
Specimen 2	0.85	2540	Without hold time

Fig. 3