CREEP CRACK GROWTH CRITERION

S.I. OLKIN

Central Aero-Hydrodynamic Institute (TsAGI), Zhukovsky, Moscow Region, Russian Federation

ABSTRACT

A crack growth criterion for the case of the long-term static loading is formulated and test proved. For a plate with a central crack, the analytical evaluation technique to compute the stress concentration factor under creep condition is proposed; it allows us to determine the local stress value after the relaxation process is over.

KEYWORDS

Creep strength limit, creep crack growth, net stress, steady local stress, stress concentration factor.

The creep crack growth study is necessary mainly in connection with the crack growth prediction at the combined fatigue/creep process. When the crack growth at a long-term static loading is either absent or very slow, the crack growth rate analysis at the combined loading becomes significantly easier because the time dependent factors (long-term static damages, high temperature corrosion) may not be considered.

Metal behaviour in the presence of a crack under creep conditions is defined, on the one hand, by the damage accumulation for both the long-term damage and corrosion and, on the other hand, by the factors caused by the local creep strain (stress relaxation and a crack tip blunting). The contribution of every of these competing processes depends on the metal creep resistance as well as on the temperature and stress level. The crack tip deformation resistance defined by the stress state has also a significant effect. Due to all these factors, there exist a variety of creep crack growth behaviours.

The studies of the stress and strain kinetics in the stress concentration zone showed that relaxation rate is the highest at the beginning of the test when the metal creep rates at the notch (crack) tip differ greatly from that in the rest of the section. Thereafter the difference in the creep rates decreases with the stress peak smoothing, with the relaxation process and the stabilization of the stress at the notch tip. The stress concentration remains, however, significant.

The test data show that the relaxation degree and rate are defined not only by metal creep resistance but also by the net section stress level at which creep tests are performed. Olkin (1974) found out that higher the stress level, lower was the creep stress concentration. Specific to creep stress redistribution at the notch (crack) tip is also the fact that a constant stress zone appears in front of the concentrator, and the creep damage is accumulated at the same rate at all the points of this zone.

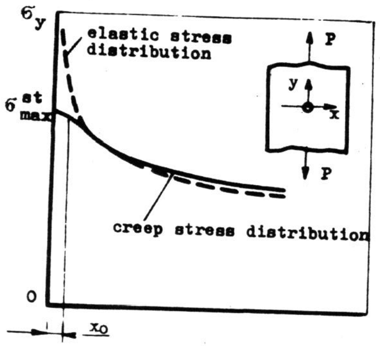

Fig.1 Stress distribution in the crack section.

The zone size x_o (Fig.1), as the test results show, depends on the static stress level, the notch sharpness and the degree of restraint to deformation. For example, in a case of a very sharp notch (crack), the constant-stress zone size for a plane stress is as low as 0.2mm, as reported by Barnby and Nicholson (1974).

When studying the creep influence on the stress state, it is necessary to account for the fact that, for all the metals, the creep strength limit exceeds the creep limit for a specified deformation at the same temperature and for the time. This is the case with all the metals. This is why a creep strain accumulation process (and, as a consequence, the relaxation process) continues when the crack tip stress is less than the creep strength limit. This means that the local stress continues to reduce after significant reduction (or even termination) of the accumulation of long-term static damages that case the crack growth.

Taking this fact into account, it can be supposed that if the

metal creep strength limit is high enough to satisfy the condition

$$\sigma^{st}_{max} < \sigma^{T}_{t}, \qquad (1)$$

(where σ^{st}_{max} is steady stress near the crack tip after the completion of relaxation, and σ^{T}_{t} is the creep strength limit at the temperature T) and if the relaxation process is slow enough, then, after the insignificant growth (usually of the order of several tenths of a millimeter) of the crack introduced before the creep test, the creep crack growth either retards abruptly or stops. In this case the crack grows for a time $t<t_1$ where t_1 is the time during which the stress at the crack tip decreases to the creep strength limit. This takes place when the metal creep strength limit is high enough and the net section stress level σ_{net} is comparatively low.

If the relaxation process ends off quickly and the following condition is satisfied in the zone of constant stress

$$\sigma^{st}_{max} > \sigma^{T}_{t}, \qquad (2)$$

the crack will continuously grow during the creep.

The steady local stress can be evaluated using the following formula proposed by Konson (1969) for the stress concentration factor at the steady creep

$$\alpha^{c}_{\sigma} = \alpha_{\sigma}^{2/(n+1)} \qquad (3)$$

where α_σ is the elastic stress concentration factor and n the power index in the power law widely used in engineering analysis. The parameter n is to be determined by using standard creep test results.

For the case of a plate with a central crack of length $2l$, the elastic stress concentration factor may be determined by modelling the crack by a very narrow ellipse. Such modelling seems possible because the radius at the actual crack tip differs from zero even without the creep, as discovered by Iino (1978).

For an elliptical hole in an axially loaded plate of infinite width along one axis, we have according to Peterson (1974)

$$\alpha^{\infty}_{\sigma} = 1+2b/a, \qquad (4)$$

where b is the ellipse axis normal to the acting stress, a the second axis. It is evident that the major ellipse axis b is equal to $2l$. The minor axis a is assumed equal to the crack opening displacement in the center, δ, that is determined by the formula

$$\delta = 4\sigma l/E$$

(see Broek (1974)). Then, the equation (4) may be written as

$$\alpha_\sigma^\infty = 1+E/\sigma. \qquad (5)$$

If the plate is of finite width, an appropriate correction may be introduced.

To validate the relations (1) and (2) the creep tests were carried out on central crack specimens manufactured of different materials such as the AK4-1T1 aluminium alloy and the 16Cr-46Ni nickel-based alloy. The specimens of the AK4-1T1 alloy were 2mm thick by 100mm wide in the working part. Each had a concentrator in the form of three holes: one in the center, of 4mm diameter, and two near-by holes 1mm dia. each. The specimens of the Ni-based alloy were 1mm thick by 100mm wide in the working part. They had concentrators in the form of the central 2mm dia. hole with two side notches 0.3mm wide by 0.5mm long each. Before the creep test the specimens were precracked by loading them cyclically at room temperature. The crack length was measured by the 24X microscope.

Two specimens of each alloy were tested. The specimens of the AK4-1T1 alloy had the same initial crack length $2l_o$=10mm. They were creep tested at 150°C under the initial stress σ_{net} of 110 and 220 MPa. The specimens of the Ni-based alloy were tested at 650°C under the applied (external) stress of 400 MPa but the initial crack lengths were different: 1.9 and 5.8mm so initial net stresses were equal to 416 and 434 MPa, respectively.

The value of α_σ^c for these tests was determined by eq. (3).

Stress concentration factors at the steady creep appeared to be equal to 1.96 and 1.82 at σ_{net} of 110 and 220 MPa, respectively, for the AK4-1T1 alloy, and for the Ni-based alloy it was equal to 1.66. However, the values of α_σ^∞ calculated using the formula (5) were extremely large, i.e. 572 and 286, respectively, at σ_{net} of 110 and 220 MPa for the AK4-1T1 alloy.

The comparison of α_σ^∞ and α_σ^c shows that for the actual values of parameter n (in particular, n=20) the stress concentration factor α_σ^c depends on α_σ^∞ to a small extent.

Creep stresses at the crack tip, σ_{max}^{st} were determined by above-

mentioned values of α_σ^c. They are:

- for the AK4-1T1 alloy: 216 MPa (at σ_{net}=110 MPa) and 403 MPa (at σ_{net}= 220 MPa);
- for the Ni-based alloy: 690 MPa (at $2l_o$=1.9mm) and 720 MPa (at $2l_o$=5.8mm).

Creep crack growth curves for these alloys are shown in Figs.2 and 3.

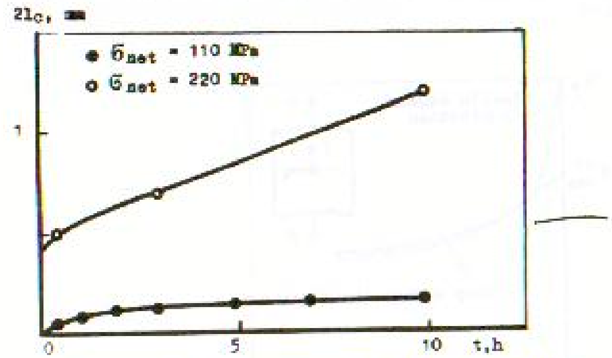

Fig 2 Crack growth curves for the AK4-1T1 alloy specimens.

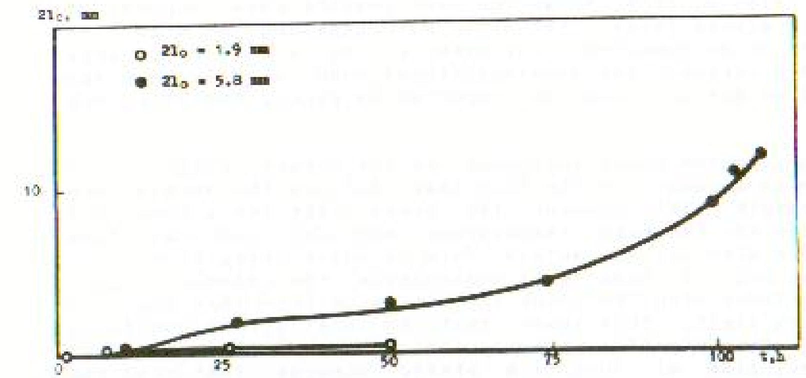

Fig.3 Crack growth curves for the Ni-based alloy specimens.

For the AK4-1T1 alloy the creep strength limit on the basis the criterion (1) is satisfied. In this case the crack stops growing after the first 2-3 hours of test and remains short.

as shown in Fig.2. At the higher stress value (σ_{net}=220 MPa) the crack tip stress exceeds significantly the creep strength limit. Therefore, the fast crack growth is observed. The crack growth rate is the highest in the first half an hour of the test, as long as the local stress remains high enough.
The similar relationship holds for the Ni-based alloy having the creep strength limit of 700 MPa at 650^{o}C. The curves shown in Fig.3 demonstrate the absence of crack growth in the case of the relatively short initial crack ($2l_o$=1.9mm), when the relation (1) is evident and, in opposition, when the relation (2) is satisfied, the crack grows rather intensively.

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