THE USE OF CREEP DAMAGE MEASUREMENTS IN COMBINATION WITH MATERIAL MODELS FOR RESIDUAL LIFETIME ASSESSMENT

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Creep damage in an austenitic steel due to microcrack formation on grain boundary facets is considered. The metallographic examination is compared with non-destructive ultrasonic (US) velocity measurements. It is shown that both measurements can be related to a crack density parameter which also appears in the constitutive law for the creep strain rate.

INTRODUCTION

Creep damage in metals and alloys such as nucleation and growth of voids on grain boundaries or microcracking of grain boundary facets may lead to a catastrophic failure of pressurized components operated at elevated temperatures. A reliable assessment of the residual lifetime of such structures is only possible, if the microstructural degradation is quantified by a damage variable, that can be introduced into a macroscopic constitutive law describing the inelastic material behaviour. In order to take advantage of commonly used destructive or non-destructive testing methods, on the other hand, this variable has to be related to measurable physical quantities as well. With regard to the widely used metallographic examination it is important to know how the damage parameter depends on the microscopical aspects such as the number, density and size of the defects (voids and microcracks).

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In the austenitic steel studied in this paper, creep damage is manifest in the form of microcracks on grain boundaries. Metallographic examinations (A-parameter determination) are compared with non-destructive ultrasonic (US) velocity measurements both providing a quantitative measure of damage. Following Hutchinson (1) and Riedel (2) it is shown that a damage variable based on the microstructural defect state is available which can be related to both metallographic examination and ultrasonic testing. Experimental results are compared with those of theoretical models.

MATERIAL AND CREEP EXPERIMENTS

The material investigated is a Mn-Cr austenitic steel (trade-name AMCR 0033) in the solution-annealed condition. The basic characteristics of this steel have been compiled by Piatti and Schiller (3). Creep tests up to rupture or interrupted in the tertiary creep stage have been conducted at the temperature T = 923 K. A flat specimen geometry with a gauge length of 50 mm and 6 mm thickness was used to facilitate the US measurements. The tests were performed at initial stresses of σ = 100 MPa, 120 MPa and 150 MPa leading to rupture times from about 160 h to 2700 h. The secondary creep velocities $\dot{\varepsilon}_{ss}$ could be fitted by Norton's law with

$$\dot{\varepsilon}_{ss} = B\sigma^{n} \quad \text{with } B = 3.162\text{x}10^{-25} \text{ (MPa,s)}, \quad n = 7.80 \qquad (1)$$

and the stress dependence of the rupture time was approximated by

$$t_f = \frac{C}{\sigma^{\nu}} \quad \text{with } C = 2.34\text{x}10^{15} \text{ (MPa,h)}, \quad \nu = 6.02 \qquad (2)$$

The specimens were metallographically examined showing a globular grain structure with an average grain size of about 70 µm. Crept specimens revealed intergranular microcracks, the planes of which are preferentially oriented perpendicularly to the applied stress. In specimens having reached the tertiary creep stage, grain boundary cracks comprising one or two facets (see Fig.1) are typically observed. Close to the rupture surface in the broken specimens, longer intergranular cracks are formed because of coalescence of microcracks.

MEASUREMENT OF CREEP DAMAGE

A-parameter evaluation. The determination of the A-parameter provides a method to obtain a quantitative measure for a distribution of intergranular crack-like defects in a sample of material by evaluating 2D-micrographs (Shammas (4)). Taking a micrograph that contains the axis of the maximum principle stress, a line parallel to this axis is drawn. The A-parameter is calculated according to

$$A = \frac{\text{number of cracked facets intersecting the line}}{\text{total number of grain boundaries intersecting the line}} \qquad (3)$$

The line must be sufficiently long to determine a statistically meaningful average value, i.e. more than 400 grain boundaries should be counted (4). The A-parameter has been determined at places where the ultrasonic velocity was measured. An area corresponding to the US-transducer width has been evaluated using an optical microscope. Fig.2 shows typical results, where the uncertainty of A is about ± 0.03 because it may be difficult to identify a facet as being cracked. This also explains the value $A \sim 0.05$ in the undamaged specimen heads.

Ultrasonic velocity measurements. Because of the formation of microcracks or cavities the elastic constants and, therefore, the US velocities change. In each specimen the US-velocities have been determined in the heads and along the gauge length before and after the creep test (Lakestani and Rimoldi (5); Stamm et al. (6)). Longitudinal waves and differently polarized transverse waves propagating perpendicularly to the stress axis were used. As discussed in (5) the uncertainty on the relative values of the velocities is about 0.1%.

Since the planes of the microcracks are preferentially oriented perpendicularly to the direction of the uniaxial stress, the damaged material exhibits transverse isotropy with the preferential direction parallel to the stress. This damage-induced anisotropy can be characterized by the relative velocity difference

$$q = \frac{v_{\parallel}-v_{\perp}}{v_{\parallel}} - \left(\frac{v_{\parallel}-v_{\perp}}{v_{\parallel}}\right)_{virgin} \qquad (4)$$

where $v_{\parallel}$ and $v_{\perp}$ are the velocities of the shear wave with polarisation parallel to the stress axis and perpendicular to it, respectively. Fig.3 shows typical q-values in dependence of their position within the gauge length. As in the case of A an inhomogeneity is observed. This is probably due to slight geometrical inhomogeneities in the virgin specimens.

MODELLING

In this section the influence of creep damage by microcracking on the elastic-viscoplastic behaviour is modelled. For this purpose the broken grain boundary facets are idealized by randomly distributed circular cracks with radius a, the crack-planes being aligned perpendicularly to the axis of applied stress σ. Theoretical expressions relating the A-parameter and the anisotropy parameter q to the number of cracks per unit volume N with radius a will be given.

Elastic constants and US wave propagation. An arrangement of microcracks as described above in an isotropic matrix leads to a statistically homogeneous, transversely isotropic material, the symmetry axis of which is parallel to the applied stress. Such a material is characterized by 5 independent elastic constants. For elastic waves propagating in a plane normal to the symmetry axis the wave velocity is independent of the propagation direction. One pure shear mode polarized normal to the axis of symmetry and another one polarized parallel to it as well as a pure longitudinal mode exist. The relative velocity difference of the pure shear modes owing to creep damage

$$q = \frac{v_{\parallel} - v_{\perp}}{v_{\parallel}} = \frac{\sqrt{\mu_{\parallel}} - \sqrt{\mu_{\perp}}}{\sqrt{\mu_{\perp}}} \qquad (5)$$

is given by the in-plane (along the axis of symmetry) shear modulus $\mu_{\parallel}$ and the out-of-plane shear modulus $\mu_{\perp}$. The latter one is identical to the shear modulus μ_o in the undamaged, isotropic material, since the shear amplitude parallel to the crack-planes does not "see" the cracks.

Using a self-consistent method, Zhao et al. (7) determined the effective moduli for unidirectionally aligned circular cracks with a given radius a in dependence of the crack-density parameter $\eta = Na^3$ introduced by Budiansky and O'Connell (8). The result of (7) for $\mu_{\parallel}/\mu_o$ has been used and with the ratio $r = v_{OT}/v_{OL}$ of shear velocity v_{OT} and longitudinal velocity v_{OL} in the undamaged material

$$q = 1 - \left(1 + \frac{16\,\eta}{3(3-2r^2)}\right)^{\frac{1}{2}} \qquad (6)$$

is obtained. Linearizing (6) which gives an error of less than 10% up to $\eta \sim 0.1$ and with $r = 0.5659$ for the steel considered here, $q \sim -1.13\,\eta$ follows. The same relationship can be obtained from Piau (9) based on the scattering theory of waves. For cracks of different sizes the measured value of q is proportional to $\langle\eta\rangle = N\langle a^3\rangle$ where $\langle\ldots\rangle$ denotes the volume average.

Constitutive equation for creep. A solution for a dilute concentration of aligned circular cracks with radius a in a matrix obeying Norton's creep law, eq.(1), has been given by Hutchinson (1). For the uniaxial case with stress perpendicular to the crack plane

$$\dot{\varepsilon}_{cr} = (1+\rho)\dot{\varepsilon}_{ss} \quad \text{with} \quad \rho = \frac{4(n+1)}{(1+3/n)^{\frac{1}{2}}}\,\eta \qquad (7)$$

results for the creep strain rate $\dot{\varepsilon}_{cr}$ and the damage parameter ρ. Also here the crack-density parameter appears which has to be substituted by $\langle\eta\rangle$ for crack size distributions. A simple self-consistent generalization of eq.(7) for higher crack concentrations was given by Riedel (2). The constitutive equations for $\dot{\varepsilon}_{cr}$ have to be supplemented by an evolutionary law for the damage parameter ρ as e.g. given in (2). With this a set of non-linear differential equations is available enabling lifetime prediction if a critical value ρ_c has been established as a failure criterion.

A-parameter. Following the prescription (3) for the determination of the parameter A, the cracks that intersect a line $\mathscr{L}$ of length L parallel to the stress axis must be counted. Considering cracks with radius a, all the $n_{\mathscr{L}}$ cracks the centres of which are contained in a circular cylinder with radius a around $\mathscr{L}$ and height L intersect this line, i.e. $n = N\pi a^2 L$. If the shape of the grains is statistically isotropic, the number of grain boundaries m intersected by $\mathscr{L}$ is given by $m = L/l$ where l is a length characterizing the dimensions of the grain. Because of the statistical isotropy of the grain shape, the crack radius a which is a multiple of the facet dimension must linearly depend on l. With this $L \propto ma$ and according to eq.(3)

$$A = \frac{n_L}{m} \propto Na^3, \quad \text{i.e. } A \propto \eta \tag{8}$$

holds. Based on a similar consideration, Riedel (2) obtained $A = 6.8\eta$ for equiaxed grains. A more detailed study including a size distribution of the cracks correspondingly yields $A = P \langle\eta\rangle$ with a proportionality factor P depending on the variance of the crack size and grain size distribution, the average number of facets per grain and the average number of connected broken facets forming a crack (Stamm (10)).

DISCUSSION

The compilation of theoretical results demonstrates that creep damage owing to microcrack formation on grain boundaries allows a macroscopic description of the elastic and inelastic properties, which is related to the microstructural defect state by the crack-density parameter $\langle\eta\rangle$. Also measurable quantities such as the anisotropy parameter q obtained from ultrasonic velocity measurements and the A-parameter from metallographic evaluation depend on $\langle\eta\rangle$. Therefore, combining $A = P \langle\eta\rangle$ with $q \sim -1{,}13 \langle\eta\rangle$ a linear relationship

$$A = 6 \, |q| \tag{9}$$

is obtained assuming $P = 6.8$ as in Riedel (2). Values for A obtained from metallographic examination plotted versus q from US-measurements at the same places are shown in Fig.4. Taking into account the uncertainties in determining A, the agreement with (14) is quite satisfactory. A more detailed calculation of the factor P is given in (10) and yields values which are closer to the slope obtained from the least-square fit (dashed line in Fig.4). The 0.05 offset of this fit corresponds to the A-value counted in the undamaged specimen head. From the results in Fig.4 it can be concluded that the damage determination by measuring the anisotropy parameter q should be competitive with the metallographic methods for this type of damage, since the uncertainty in q is only about 0.001. In particular, it must be emphasized that US-measurements are non-destructive.

Determining $\langle\eta\rangle$ from experimental results for A or q, the actual value for the damage variable ρ appearing in the constitutive equation for the creep strain rate can be determined. With an appropriate evolutionary law, residual lifetimes can be assessed by integrating a system of differential equations.

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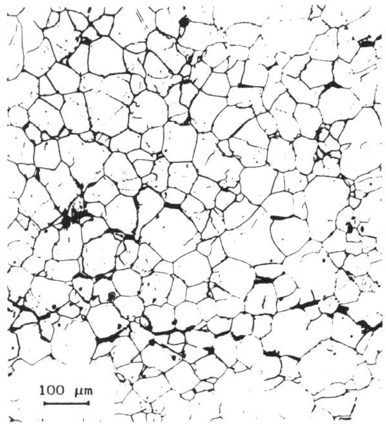

Fig. 1: Optical micrographs showing creep damage. σ = 120 MPa; t_f = 569 h; distance from rupture: 3.5 mm

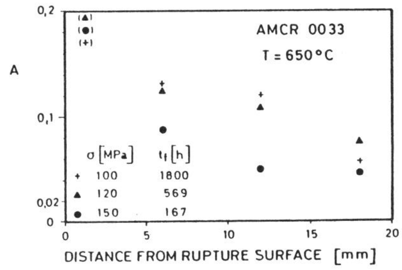

Fig. 2: A-Parameter in ruptured creep specimens. For the values in brackets only ca. 200 facets were counted.

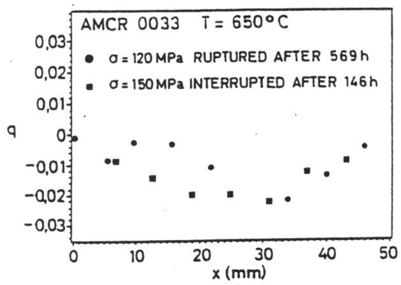

Fig. 3: Dependence of the anisotropy-parameter q on the position within the gauge length (x: coordinate parallel to the stress)

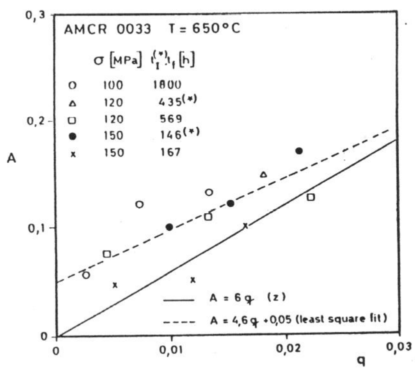

Fig. 4: A-parameter in dependence of the anisotropy parameter q