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Effect of grain size on creep crack formation in an austenitic steel

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Summary
The elongation to fracture in a 20Cr35Ni steel at 700°C decreases drastically as the grain size is increased over the range of 20-275 μm. The difference is accounted for mainly by a longer incubation period before the start of cracking. Once cracking has started it grows exponentially with about the same nucleation constant for all grain sizes. Final fracture occurs when the number of cracks has reached 2-10% of the total number of grain boundary facets. Two fracture models are considered.

Introduction

This paper is concerned with the nucleation and growth of sharp grain boundary cracks in an austenitic steel containing 20 per cent chromium and 35 per cent nickel. It is based on statistical measurements of the number and length of cracks for different grain sizes and is an extension of a previous study [1] which was limited to one grain size, 50 μm. The progress of creep damage and the final creep fracture are considered.

Experimental

The material was Sanicro 31 containing 0·046C, 0·53Si, 0·51Mn, 0·008P, 0·007S, 20·3Cr, 35·2Ni, and 0·01Ti in weight per cent. The original grain size was 50 μm (linear intercept). To obtain different grain sizes the material was cold-swaged and subsequently annealed for 1 h at different temperatures: 1050°C giving 20 μm, 1160°C giving 100 μm and 1320°C giving 275 μm. The 50 μm, 100 μm and 275 μm material was then given a final heat treatment at 1050°C for ½ h to equalize the state of precipitation as much as possible with that of the 20 μm material. Round tensile specimens were pulled to various strains in an Instron machine at 700°C in getting purified argon. The testing was performed with constant cross head speed giving a strain rate over the specimen of 10^{-4}/min. Certain specimens were instead strained in vacuum in a constant-load machine where the load was adjusted to give the desired strain rate (Table 1). A total of 22 specimens were tested. The cracks were then counted on polished sections of the specimens as described in the previous paper [1]. The slow tensile testing is physically identical to a creep test since the stress is constant during most of the testing. For simplicity, the high temperature deformation is therefore referred to as creep.

Crack formation

The mechanical data and the crack counting results appear in Table 1. The figures given are average values and there is considerable scattering in the primary data. The crack density is expressed in the quantity ν giving the number of cracks per unit area. A related quantity is q, the number of cracks per grain boundary facet. The relation between q and ν depends on the grain shape but is taken as

$$q = 0{\cdot}4\, d^2 \nu \tag{1}$$

where d is the linear intercept grain size. The crack number q is plotted in Fig. 1 versus strain.

It was found in the previous paper [1] for 50 μm grain size that the number of cracks increased exponentially with strain. This seems to be the case also for the other grain sizes (Fig. 1). Moreover the slopes of the log q versus ϵ lines are nearly identical for all grain sizes studied. The cracks thus form according to

$$q = q_0\, e^{\beta\epsilon} \tag{2}$$

with about the same β for all the grain sizes (Table 1). This means for instance that it takes the same amount of strain to increase the crack density by a factor of 10, say, in all specimens. The pre-exponential q_0 is more grain-size dependent, however. It represents the number of cracks or defects at $\epsilon = 0$ if the model is stretched that far back. More realistically q_0 may be associated with an incubation strain required for the exponentially increasing cracking to start. The incubation strain increases markedly as the grain size is lowered. During the deformation there is a continuous build-up of damage, creep deterioration, in the specimen. The material, however, has a certain capacity to heal the damage. This capacity is evidently much larger for fine grain sizes giving larger incubation strains than for coarser grain sizes. Once the capacity for healing is used up the cracks form in the same way for all grain sizes, since the factor β is about the same. In the later stages of straining the cracking mechanism is thus grain size independent to a good approximation.

The details of the physical process which acts to heal the creep damage are unknown. It is clear from the stress-strain curves, however, that the healing process takes place at constant stress level for a constant strain rate test. Furthermore, in spite of the large variations in incubation strain, there is hardly any grain-size dependence of this stress level (Table 1), substantiating results by Lagneborg [2] for lower strain rates. An increase in the dislocation density would normally have

raised the stress level. We therefore tentatively conclude that the healing process does not affect the dislocation density and that the process is governed by other phenomena.

Conditions for fracture

Final fracture has occurred when the number of cracks per facet reaches between about 0·5 and 2 per cent according to Fig. 1. These figures refer to the average value measured over an area between 0 and 10 mm from the fracture surface. There is usually, however, a higher concentration of cracks near the fracture surface. Furthermore, some cracks extend over several facets. It may therefore be estimated that 2-10 per cent of all grain boundary facets are cracked in the region of final fracture. There is a tendency that the crack density is somewhat higher for 20 and 50 μm than for 100 and 275 μm but there is also a considerable scatter between specimens of the same grain size.

Lindborg has suggested two models for final creep fracture. The first is applicable to materials which behave in a comparatively brittle manner at high temperature [1, 3, 4]. It is based on the rate of growth of the cracks and predicts the time or equivalently the strain required for the growth of one of these cracks to infinite length, i.e. to fracture. The influence of neighbor cracks is neglected. The necessary growth parameters can be calculated from measurements of the crack length distribution at various instants and from this the fracture strain can be estimated. It was found previously [1] and confirmed in the present work that the length distributions remain approximately the same all through the straining, evidently because the formation of new cracks compensates for the growth of existing ones. Thus average values of the fraction single cracks ν_1/ν and double cracks ν_2/ν can be used. (ν_1/ν is the ratio of the number of cracks one facet in length to the total number of cracks as observed on sections and ν_2/ν is defined in an analogous way). By an algebraic combination of equations 6-8 and 12 of the previous paper [1] one arrives at the following estimate of the fracture strain

$$\epsilon_b \approx \frac{1}{2\beta\left(\dfrac{\nu}{\nu_1} - 1\right)\ln\left(\dfrac{\nu_1(\nu - \nu_1 - \nu_2)}{\nu_2(\nu - \nu_1)}\right)} \tag{3}$$

The nucleation factor β as well as the fractions single and double cracks are inferred directly from crack counting (Table 1) and thus ϵ_b can be calculated.

The second model is applicable to more ductile materials [5]. It is based on the linking of creep cracks. It is assumed as a simplification that the cracks form in the grain boundaries in a random fashion. The tendency for cracks to grow spontaneously is neglected but from the laws of statistics some cracks happen to form adjacent to existing ones. The theory considers two such cracks as combining and forming a larger crack. When a sufficiently large number of cracks have formed there will be a continuous channel established through the whole specimen. This was shown to occur for a fraction of 10 per cent cracked boundaries [5]. Here then the crack density q is the essential parameter for fracture. To be more exact it is the fraction cracked boundaries in the cross-section with the highest crack concentration which is decisive. Let us, however, neglect the tendency for the cracking to be inhomogeneously distributed along the specimen and estimate the elongation to fracture ϵ_d assuming homogenous cracking and a q value of 10 per cent over the whole specimen. This is an overestimation. From equation (2) we obtain

$$\epsilon_d = \frac{1}{\beta} \ln \frac{10}{q_0} \tag{4}$$

Again Table 1 gives the relevant data.

The results from the brittle growth theory ϵ_b and the ductile linking theory ϵ_d are plotted in Fig. 2 and compared with the observed elongation to fracture. The growth theory gives values which are lower than the experimental results. This is partly at least accounted for by the incubation strain necessary for cracking to start because only the growth of existing cracks is considered for the elongation estimate. At 275 μm the value is quite good, however, suggesting that the growth model is a good representation of the rupture process at this large grain size. The linking theory gives excellent agreement at small grain sizes. Thus at 20 μm 21 per cent elongation is calculated and 18 per cent observed. Taking into consideration that cracking in practice would be somewhat inhomogenous will bring down the theoretical values to an even better agreement. At the largest grain sizes, however, the discrepancies are larger and it may be that a growth mechanism leads to fracture before the linking is completed. We thus conclude that the linking model applies best at small grain sizes and the growth model at large grain sizes.

Practical implications

A material with a large creep ductility should fulfil two physically different requirements.

1. Crack formation should be slow.
2. The material should be able to stand a large crack density before final fracture.

The first condition means primarily for the present steel that a low value is desired for q_0 in equation (2), and evidently the finer grained materials are superior in this respect. For the second condition the crack

linking model suggests an upper limit for very ductile materials, 10 per cent cracks per grain boundary facet. In our case this figure is well approached particularly for the finer grain sizes. If the cracks have a large tendency to grow spontaneously, however, fracture occurs much before these 10 per cent are reached. This may limit the elongation and may have a particularly large effect in many precipitation hardened creep resistant materials where one of the first cracks formed rapidly propagates in a final fracture.

References

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Table 1.
Mechanical data and crack counting results (700 °C)

grain size d μm	*steady stress* σ kg/mm²	*fracture elongation* ϵ %	*number of cracks counted*	*nucleation parameters* β 1/%	q_0 %	*fraction single cracks* ν_1/ν	*fraction double cracks* ν_2/ν
20	16·4	18·0	10 700	0·8	10^{-6}	0·91	0·06
50	15·4	11·0	11 500	0·6	0·005	0·66	0·23
100	15·3	6·2	4 400	0·9	0·005	0·82	0·12
275	15·0	2·5	150	1·2	0·02	0·76	0·15

The strain rate was $1{\cdot}0 \cdot 10^{-4}$ 1/min. The fractions single and double cracks refer to average values for all specimens of each grain size.

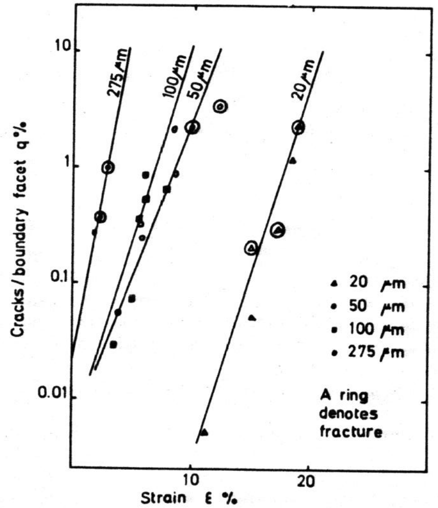

Fig. 1. Crack density versus strain at 700°C for 20Cr35Ni of different grain sizes.

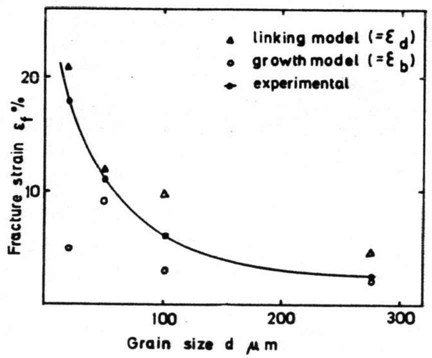

Fig. 2. Fracture strain versus grain size estimated from the crack linking model and the crack growth model.