NOTCH WEAKENING AND STRENGTHENING IN CREEP OF $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V STEEL

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ABSTRACT

Experimental results are reported on circumferentially notched tensile bars of a $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V steel subjected to a nominal stress across the notch throat of 300 MPa and a temperature of 565°C. The radii of the notch throat, a, and notch root, R, were varied to alter the state of stress in the notch region. Notch-strengthening was observed at low ratios of a/R with a tendency towards notch-weakening as a/R was increased.

The results are explained in terms of the strains required to redistribute the stresses from their initial elastic to final stationary state values. An increase in strain is required with increase in a/R to achieve the stationary state stress distribution. It is shown that the material exhibits insufficient creep ductility to enable a stationary state to be achieved at the high a/R values so that notch-weakening is expected with increase in a/R. The results have important practical consequences: they suggest that caution should be exercised in using reference stress methods to predict design lives in the absence of complete stress redistribution. Also, extrapolation of accelerated laboratory tests to lower practical stresses, where lower ductilities are expected, may be inadvisable.

KEYWORDS

Multi-axial stress states; stress redistribution; reference stress; creep ductility.

INTRODUCTION

There is a risk of equipment that is severely loaded at elevated temperatures failing by creep. These failures are most likely to occur from regions of stress concentration, such as holes and abrupt changes of section. The susceptibility of a material to fail at such a location will depend upon its uni-axial creep ductility and its response to triaxial states of stress.

Approximate procedures for designing against creep rupture in structures are often based on reference stress methods (Leckie, 1971; Marriott, 1970). Reference stress methodology neglects transient behaviour and assumes that the material has

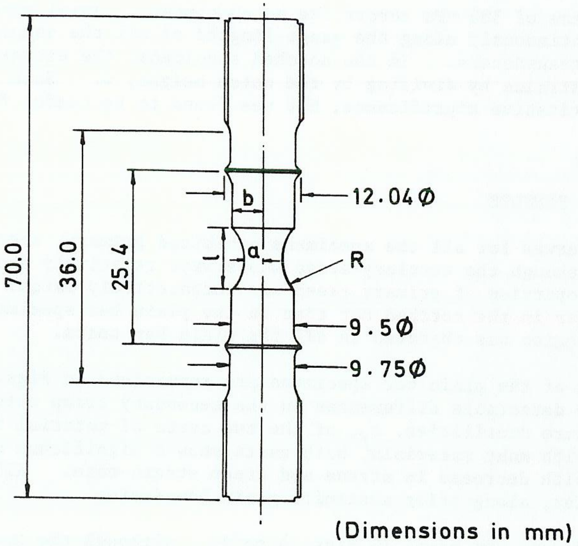

Fig. 1 A typical circumferentially notched bar tensile specimen

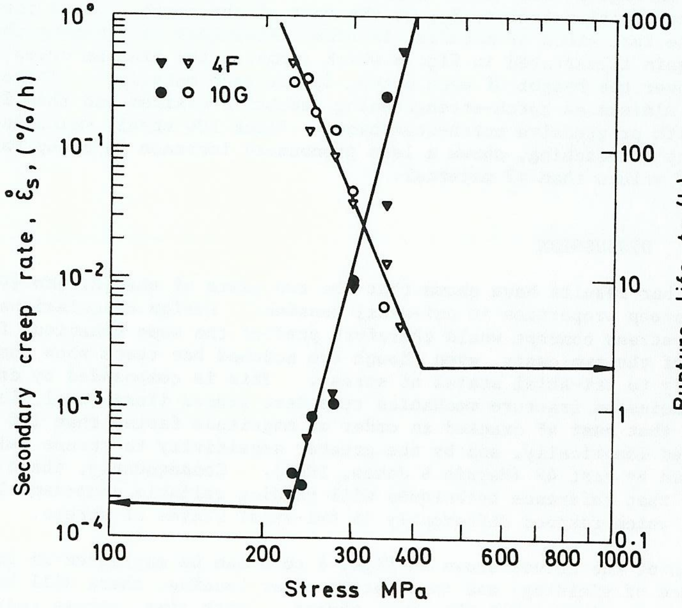

Fig. 2 Secondary creep rates and rupture lives of plain bar specimens as a function of stress

adequate ductility throughout its working life to allow complete stress redistribution and a stationary-state to be achieved. If a stationary-state stress distribution is not reached, predictions based on reference stress techniques may not be conservative.

In order to investigate the reliability of these techniques further, creep experiments have been carried out in tension on circumferentially notched bars of a $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V steel. The dimensions of the notch throat have been systematically varied to change the state of stress in the notch region and the elastic stress concentration factor at the notch root (Hayhurst et al, 1977a,b; Peterson, 1974).

EXPERIMENTAL TECHNIQUES

Material and Specimens

The $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V steel investigated is used extensively for high temperature applications in steam power generation equipment. The material was received as two cast blocks approximately 300 mm square and 75 mm thick, designated 4F and 10G. They were part of a wider investigation (Harris & Jones, 1972) of the effects of slight compositional changes and de-oxidation practice on the reheat cracking tendencies of the steel. The chemical composition of each block is listed in Table 1. A 25 mm thick slice was removed from the side of each block and subsequently austenitised for $\frac{1}{2}$ h at 1250°C, quenched in oil, tempered for 24 h at 680°C, and finally air-cooled. This heat-treatment was chosen to simulate stress-relieved, heat-affected zone material in practical components. It resulted in a tempered bainitic structure with a prior austenite grain size of 200 - 300 μm.

TABLE 1 Chemical Composition of $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V steel

Cast	Weight %									
	C	Mn	Mo	V	Cu	Sn	Al	Ce	Ti	Zr
4F	0.11	0.36	0.42	0.22	0.07	0.005	0.019	0.002	0.005	0.001
10G	0.08	0.37	0.69	0.33	0.06	0.005	0.005	0.025	0.005	0.002
	Cr	S	P	Si	Ni	Nb	B	Co	As	Sb
4F	0.37	0.012	0.012	0.29	0.05	0.005	-	0.01	0.011	0.0015
10G	0.42	0.013	0.012	0.48	0.05	0.008	-	0.012	0.011	0.0025

Both plain and notched test pieces were machined from each slice. The unnotched specimens had a gauge diameter of 6.35 mm. The dimensions of the notched samples are shown in Fig. 1. The notch throat radius, a, and the notch root radius, R, were varied to cover a range of a/R ratios from 0 to 18.

Test Procedure

All the specimens were tested in dead-load creep machines, each having a lever ratio of 10:1 and at a temperature of 565°C ± 1°C, which is a temperature of practical relevance for the $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V steel. Loads for the plain bar specimens were chosen to give stresses in the range 220 to 400 MPa and rupture lives between about 5 and 500 h. The loads on the notched test pieces were selected to give a

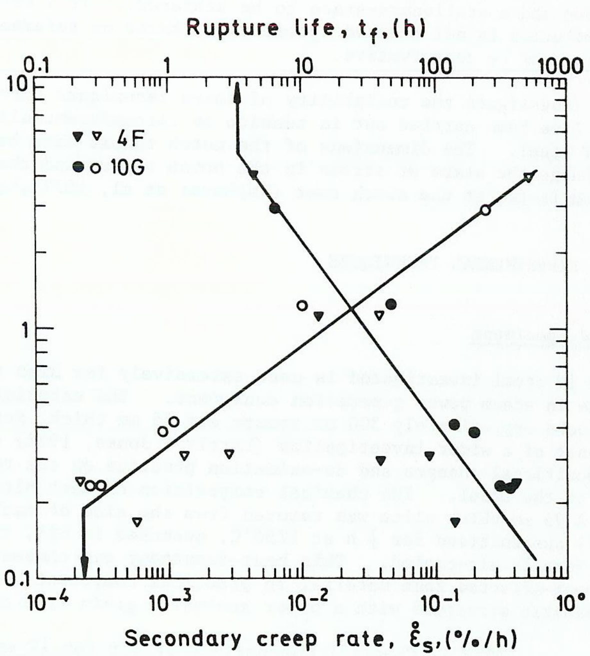

Fig. 3 Rupture ductility of plain bar specimens as a function of life and secondary creep rate

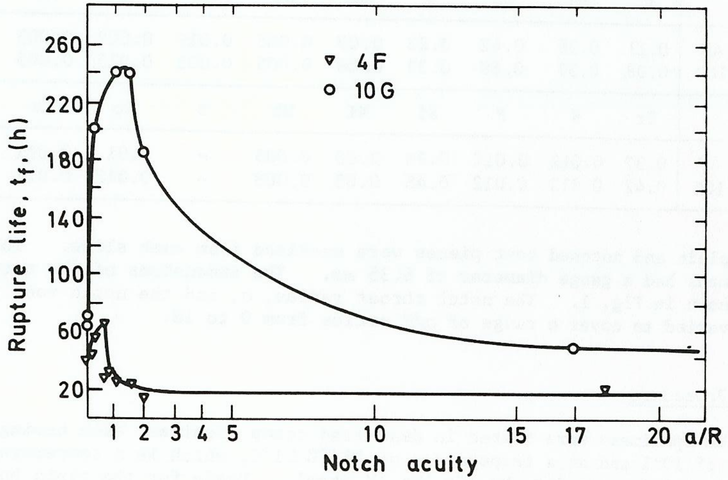

Fig. 4 Rupture life versus notch acuity ratio

nominal stress of 300 MPa across the notch throat. Axial elongations were measured continuously along the gauge lengths of all the samples with the aid of electrical transducers. In the notched specimens, the elongations were converted to nominal strains by dividing by the notch height, l. Such a procedure has little quantitative significance, but was found to be useful for ranking the results.

RESULTS

The creep curves for all the specimens exhibited primary, secondary and tertiary regions, although the tertiary stage was always relatively short. It was noted that the proportion of primary creep was comparatively larger and the secondary stage shorter in the notched bar than in the plain bar specimens. A pronounced secondary region was observed in all the plain bar tests.

The results of the plain bar specimens are summarised in Figs. 2 and 3. These indicate no detectable differences in the secondary creep rates, $\dot{\varepsilon}_s$, rupture lives, t_f, or rupture ductilities, ε_f, of the two casts of material in uni-axial tension. In common with many materials, both casts show a significant decrease in creep ductility with decrease in stress and creep strain-rate. All the fractures were intergranular, along prior austenite grain boundaries.

The notched data are given in Figs. 4 to 6. Although the trends for the two casts are similar, there are quantitative differences. Figure 4 shows that rupture life first increases with notch acuity (a/R) and then decreases, thus demonstrating first notch-strengthening and then notch-weakening. The same features are indicated in Fig. 5 which shows rupture life plotted as a function of elastic stress concentration factor, K_t, at the root of the notch. Both these figures demonstrate that block 4F material is more susceptible to notching than block 10G. This is again illustrated in Fig. 6 which compares the minimum creep rates, averaged over the height of each notch, l, for each material. These creep rates fall to a minimum as notch-strengthening reaches a maximum and then increases rapidly with progressive notch-weakening. Block 10G steel, which indicates less sensitivity to notching, shows a less pronounced increase in creep rate at the larger a/R values than 4F material.

DISCUSSION

The plain bar results have shown that the two casts of the ½Cr ½Mo ¼V steel have the same creep properties in uni-axial tension. Design calculations based on the reference stress concept would therefore predict the same behaviour for components made out of the two casts, even though the notched bar tests show that they respond differently to tri-axial states of stress. This is compounded by creep crack growth studies on fracture mechanics type test pieces (Todd et al, 1980) which indicated that cast 4F cracked an order of magnitude faster than 10G material, when loaded identically, and by the greater sensitivity to stress relief cracking experienced by cast 4F (Harris & Jones, 1972). Consequently, there is no certainty that reference techniques will predict reliable component lives in materials which respond differently to tri-axial states of stress.

The trends of the curves shown in Figs. 4 to 6 can be explained as follows. In the absence of yielding, and immediately after loading, there will be an elastic stress distribution across the notch throat. With time, stress redistribution towards a stationary-state stress distribution characteristic of creep will occur. From Fig. 2, it can be shown that the secondary creep law of the steel can be expressed as:

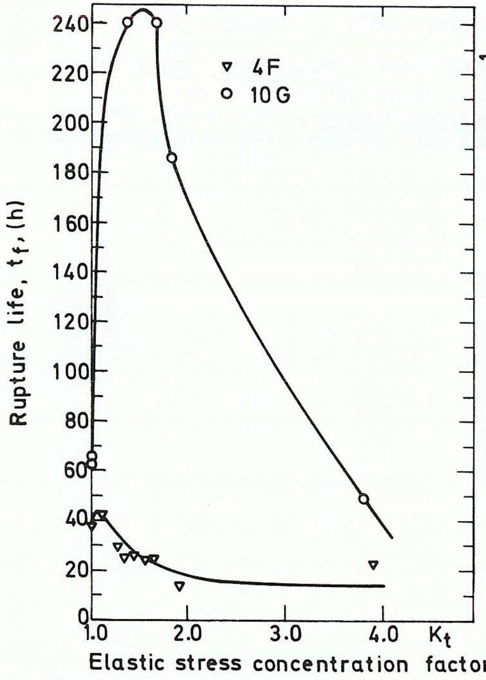

Fig. 5 Rupture life versus elastic stress concentration factor, K_t

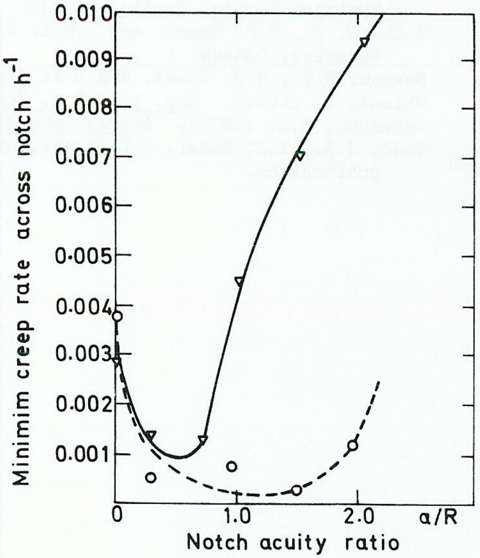

Fig. 6 Minimum creep rate across notch versus the notch acuity ratio (a/R)

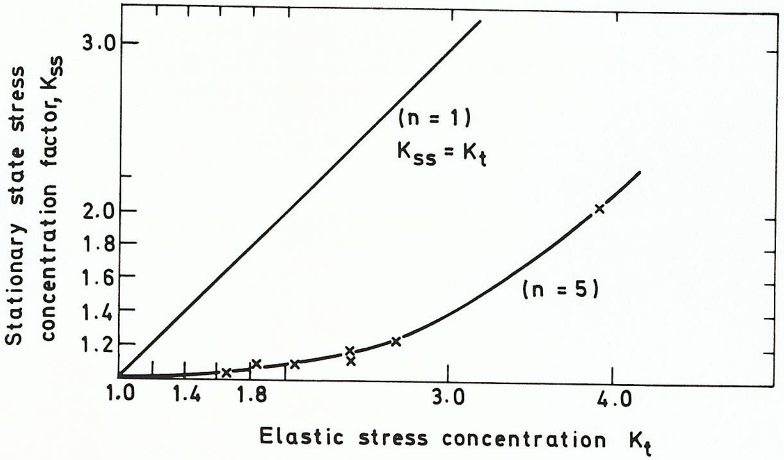

Fig. 7 Stationary state axial stress concentration factor versus corresponding elastic value

$$\dot{\varepsilon}_s = A\,\sigma^n$$

where σ is stress, A is a constant at constant temperature, and n is the stress sensitivity of creep. For this ½Cr ½Mo ¼V steel over this stress range, $n = 15$. An estimate of the maximum stationary-state axial stress concentration factor, K_{ss}, can be obtained from finite element calculations (Ohtani, 1976; Hayhurst et al, 1977a,b). It is dependent on notch geometry and the value of n and is shown in Fig. 7 for values of K_t relevant to this work. It can be seen that K_{ss} is always less than K_t and that the difference progressively increases with increase in K_t. The greater the difference, the more the stress relaxation required at the notch root for stress redistribution to be complete. Although the calculations have been presented for $n = 5$, the curve shown on Fig. 7 is representative of higher values of n.

The greater proportion of primary creep observed in the notched tests is indicative of stress redistribution occurring in the notch throat. Whilst the stresses are redistributing towards their stationary-state values, a constant secondary creep rate would not be expected. In the short life-time tests, a point of inflection only was seen in the creep curves, suggesting that failure occurred before stress redistribution was complete. In contrast, the longer-life tests exhibited a pronounced secondary region.

An estimate of the amount of strain required to allow the stationary-state stress distribution to be achieved can be obtained from the finite element calculations. The maximum axial elastic stress concentration factor, K_t, always occurs at the notch root, whereas the corresponding maximum value of K_{ss} can occur just below the notch surface or near the notch axis, depending upon the notch geometry and value of n. Low values of K_t and high values of n favour the maximum occurring on the axis and vice-versa. In either case, the stress at the notch root relaxes to close to the nominal stress, σ_{nom} (load/area of notch throat), or less. Consequently, local strains of at least $K_t(\sigma_{nom}/E)$ (where E is Young's modulus), on top of the mean elongation experienced within the notch throat, are needed to redistribute the stress at the notch root, since calculations (Hayhurst et al, 1977a,b) and measurements (Loveday & Dyson, 1979) have shown that these strains can be elevated significantly by a tri-axial state of stress. For the notch geometries investigated, this results in minimum local strains of between 0.3% and 0.8% for values of K_t between 1.5 and 4, respectively. These strains are in excess of many of the uni-axial creep ductilities measured in the present tests, suggesting that notch-weakening at the high values of K_t occurred because the steel had inadequate creep ductility to enable relaxation of the high elastic stresses at the notch root to take place before the onset of cracking from the notch root. This view is supported by the evidence that little secondary creep was observed in the notched bar tests which exhibited notch-weakening, whereas those which showed strengthening exhibited pronounced secondary creep, indicative of stress redistribution having been completed before failure occurred. In this case, the strengthening occurs because of a reduction of the effective stress caused by the state of tri-axial tension developed in the notch throat (McLean et al, 1977; Hayhurst et al, 1978).

Notch-strengthening and notch-weakening have been observed in a number of previous investigations (e.g. Davis & Manjoine, 1953; Newman et al, 1953) on circumferentially notched test pieces. The results have generally shown that the most pronounced strengthening is exhibited by materials with the greatest uni-axial creep ductilities and for relatively shallow notches. In contrast, sharp notches (leading to high values of K_t) and low uni-axial ductilities have tended to promote notch-weakening. These observations are in agreement with the above interpretation of the present data. Since most laboratory results are obtained at stresses higher than are experienced in practice, and because creep ductility in most materials decreases with strain rate (and stress), laboratory test data may indicate more strengthening (or less weakening) than may be obtained in practice. The results of such tests may therefore not be conservative if they do not reflect accurately the amount of stress redistribution that is possible in practical situations before the onset of fracture.

The results on the two casts of $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V steel have shown that slight alloying changes which do not necessarily affect uni-axial creep properties can give different responses to tri-axial states of stress. Harris & Jones (1972) attributed the greater sensitivity to stress relief cracking of cast 4F to the greater aluminium content introduced by the de-oxidation practice. Since stress relief cracking is most pronounced in regions of high states of tri-axial tension, the present work suggests that excess aluminium somehow makes the cavitation response more sensitive to stress state. It has been shown experimentally that cavity nucleation is stress-state sensitive (Dyson & McLean, 1977; Cane, 1979) and leads to lower ductilities as the ratio, maximum principal stress to effective stress, increases. Similarly, there is every reason to believe that the sensitivity to cavity nucleation of material within a notch throat is dependent on detailed composition.

CONCLUSIONS

Notch-strengthening and notch-weakening have been observed in tensile creep tests on two casts of a $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V steel. Shallow notches resulted in strengthening and there was a progressive trend towards weakening with increase in notch acuity. These results have been explained in terms of the strain required to redistribute the stresses from their initial elastic to final stationary-state values. It is shown that the material exhibits insufficient creep ductility to enable complete redistribution to take place for sharp notches. The effects of stress state on cavity nucleation are invoked to explain cast to cast differences.

The results suggest that caution should be exercised in using reference stress concepts in component design for materials which exhibit only limited uni-axial creep ductility.

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