THE INFLUENCE OF GRAIN SIZE ON CREEP RUPTURE PROPERTIES OF TYPE 316 STAINLESS STEEL

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ABSTRACT

The influence of grain size in the range 0.040-0.650 mm on creep rupture properties of type 316 stainless steel has been investigated at 873 K and 973 K over a wide range of stresses. Rupture life and rupture ductility generally decrease with increase in grain size. However, at 973 K, a peak in the variation of rupture life with grain size has been observed for 70 MPa applied stress. Further, strain at the inception of tertiary creep stage has been found to be independent of grain size. These variations are considered to arise due to the influence of grain size on the crack growth stage of creep fracture. Metallographic evidence in support is presented. The results are in general agreement with the Griffith-Orowan critical crack length criterion. The variation of rupture life with grain size is consistent with a model for intergranular creep fracture that considers growth of creep cracks to be controlled by deformation.

KEYWORDS

Creep crack growth, 316 stainless steel, rupture life, creep ductility, grain size effects

INTRODUCTION

It is generally observed that decreasing the grain size increases the creep ductility under test conditions where the mode of fracture is intergranular cavitation (Fleck and coworkers, 1970, 1975; Kutumba Rao, Taplin and Rama Rao, 1975; Lagneborg, 1969; Morris 1978; Venkiteswaran and Taplin, 1974). Rupture life, t_r, has been reported to either increase or decrease with grain size depending on test conditions (Fleck and Taplin, 1973). There have also been observations of a maximum in t_r at an intermediate grain size (Kutumba Rao and Rama Rao, 1973; Morris 1978; Venkiteswaran and Taplin 1974). Morris (1978) has examined the creep rupture behaviour in type 316 stainless steel at 898 K. The influence of grain size on creep rupture properties of 316 stainless steel at other temperatures and over a wide range of stresses has not been investigated so far. The aim of the present work, therefore, was to examine the influence of grain size on rupture life and creep ductility at 873 K and 973 K over a wide range of stresses (70-260 MPa). The influence of grain size on creep rate under these test conditions has been reported elsewhere (Mannan and Rodriguez, 1983).

EXPERIMENTAL

The type 316 steel composition, treatments to produce different grain sizes, specimen details and creep rupture testing techniques have been described previously (Mannan and Rodriguez, 1983). Constant load creep rupture tests were carried out at 873 K and 973 K on specimens in the grain size range from 0.040 mm to 0.650 mm using stresses in the range 70-260 MPa. The rupture ductilities were obtained by fitting together the two halves of the fractured specimens and measuring the longitudinal strains. Reduction in area was calculated by measuring the final minimum cross sectional area. Longitudinal sections of the fractured specimens were examined by optical metallography to study creep damage. Scanning electron microscopy was used to examine the fracture surfaces.

RESULTS AND DISCUSSION

The variation of rupture elongation (ϵ_r %), reduction in area (R.A.%) and strain at the onset of tertiary creep (ϵ_2 %) with grain size at 873 K is shown in Fig.1 for applied stresses of 200 and 260 MPa. Both the elongation and reduction in area show general decrease with increase in grain size. A tendency for a ductility minimum, however, is noted at an intermediate grain size, similar to that reported by Fleck and Taplin (1973) in an industrial copper base alloy. ϵ_2 increases with grain size but at lower stresses, this increase is very small. The variation of ductility with grain size at different stresses at 973 K is shown in Fig.2. The effect of grain size on creep ductility is more pronounced at 973 K than at 873 K, although the general grain size dependence is similar at both temperatures. An important feature to note in Fig.2 is the near constancy of strain at the onset of tertiary creep (ϵ_2) with grain size while the total elongation shows significant decrease with increase in grain size. This implies that the grain size dependence of the creep elongation is essentially due to the influence of grain size on the tertiary creep stage which involves the growth and interlinkage of cracks that lead to final failure.

The variation of rupture life with grain size at 873 K and 973 K is shown in Figs.3 and 4 respectively. The rupture life is observed to decrease with increase in grain size. A peak in the variation of t_r with grain size is, however, observed at 973 K and 70 MPa, experimental conditions at which a minimum in the creep rate variation with grain size has been observed (Mannan, 1981; Mannan and Rodriguez, 1983).

Optical micrographs shown in Fig.5 a,b and c for three different grain sizes illustrate the occurrence of intergranular cracking and the influence of grain size on the density and morphology of grain boundary cracks. In the finer grained specimens (Fig.5a), there is a large number of small cracks with low aspect ratio (length/width). With increasing grain size (Fig.5b and c), there is a decrease in the crack density but the cracks are larger and have greater aspect ratio. Fracture surface appearance of creep tested specimens as a function of grain size is shown in Fig.6 a,b and c which show that the intergranular fracture is more pronounced at coarser grain sizes.

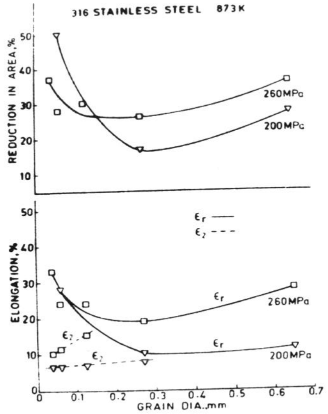


Fig.1 Elongation (ϵ_r%), reduction in area (R.A.%) at rupture and strain at the onset of tertiary creep (ϵ_2 %) as function of grain size at 873 K for applied stresses 200 and 260 MPa.

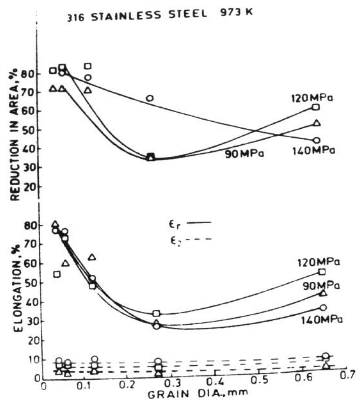


Fig.2 Elongation (ϵ_r%), reduction in area (R.A.%) at rupture and strain at the onset of tertiary creep (ϵ_2 %) as function of grain size at 973 K for applied stresses 90, 120 and 140 MPa.

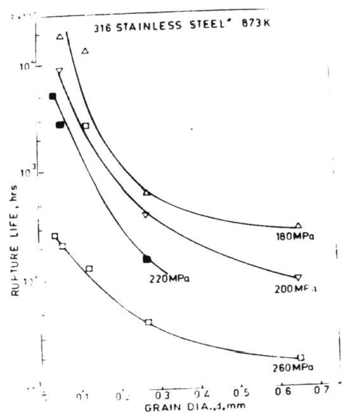


Fig.3 Variation of rupture life with grain size at 873 K for different applied stresses.

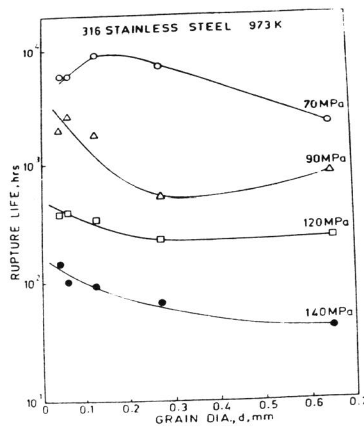
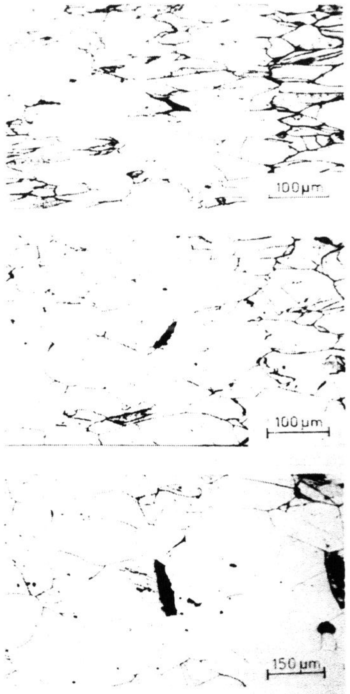


Fig.4 Variation of rupture life with grain size at 973 K for different applied stresses.



(a)

(b)

(c)

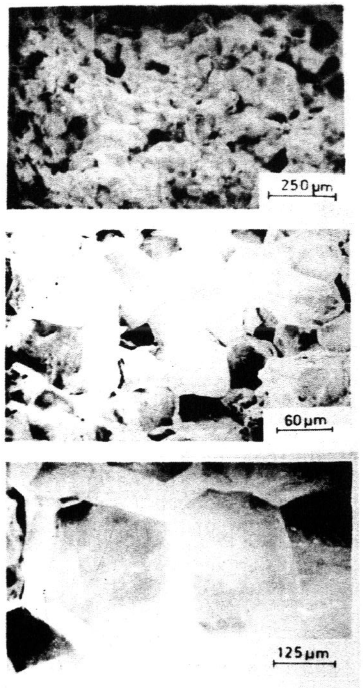


Fig.5 Optical micrographs showing the variation in the number, shape and size of the grain boundary cracks with grain size. Tested at 873 K, 260 MPa.

Fig.6 Scanning Electron Micrographs of fracture surfaces of specimens creep tested at 873 K, 260 MPa.

(Grain sizes: (a) 0.06 mm (b) 0.125 mm (c) 0.270 mm)

The above results are in agreement with the critical crack length criterion for intergranular creep fracture (Soderberg, 1969, 1975; Taplin, 1965) found to be applicable in a variety of materials (Fleck and coworkers, 1970, 1975; Kutumba Rao and coworkers, 1975; Venkiteswaran and Taplin, 1974) including type 316 stainless steel (Morris, 1978). Since the aspect ratio for the cracks increases with increasing grain size, the stress concentration at the crack tip is higher for coarser grain sizes. The cracks can therefore readily grow through triple points and a critical crack length is attained faster, resulting in lower ductilities and rupture lives with increasing grain size.

The variation of rupture life t_r with applied stress σ could be represented by the relationship $t_r = A' \sigma^{-n}$ analogous to the power

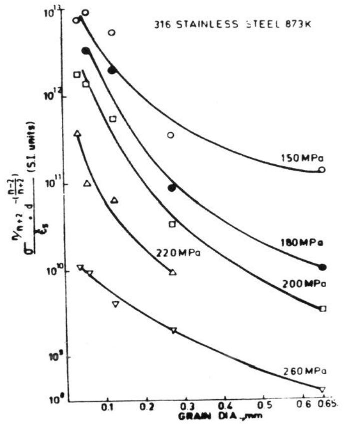


Fig.7 Variation of the parameter

$$\sigma^{n/n+2}\, d^{-\frac{(n-2)}{n+2}} / \dot{\epsilon}_s$$

(Eq.1) with grain size at different stresses for 873 K.

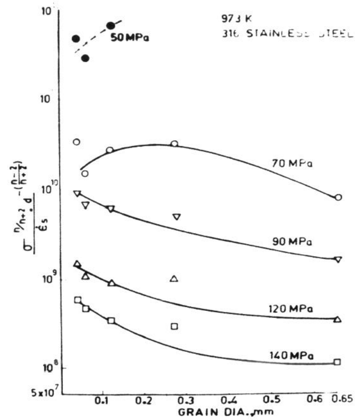


Fig.8 Variation of the parameter

$$\sigma^{n/n+2}\, d^{-\frac{(n-2)}{n+2}} / \dot{\epsilon}_s$$

(Eq.1) with grain size at different stresses for 973 K.

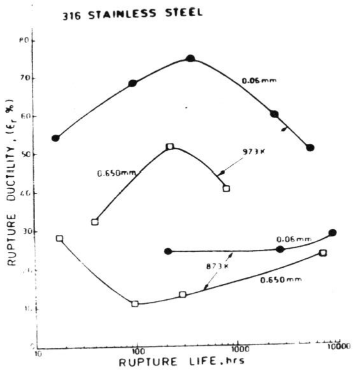


Fig.9 Variation of rupture ductility with rupture life at 873 K and 973 K for different grain sizes.

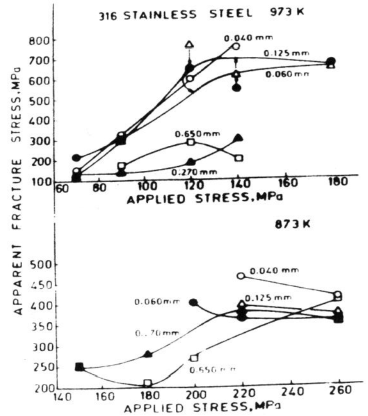


Fig.10 Apparent fracture stress as function of applied stress for various grain sizes at 873 K and 973 K.

law for creep rate $\dot{\epsilon}_s = A\,\sigma^{n}$. The values of n' at 873 and 973 K for different grain sizes are shown in Table 1 along with the n values from the work of Mannan and Rodriguez (1983).

TABLE 1 Values of Stress Indices n and n′

Grain size (mm)	873 K		973 K	
	n	n'	n	n'
0.04	13.1	11.2	7.0	6.0
0.06	13.6	12.5	7.3	6.4
0.125	14.3	12.4	8.5	6.5
0.27	10.3	9.1	8.1	6.2
0.65	11.4	10.2	6.6	5.5

The similarity in the values of n and n′ indicates that matrix plasticity is the dominant cavity growth mechanism.

The variation of t_r with grain size is further examined in terms of the model due to Nix and coworkers (1977). The model assumes that intergranular fracture occurs by the propagation of mode I wedge cracks along grain boundaries and that the propagation of these cracks is controlled by the creep growth of cavities which reside on the grain boundaries ahead of the cracks. The creep rupture life in this model has been shown to depend on applied stress σ, grain size 'd' and creep rate $\dot{\epsilon}_s$, as follows:

$$t_r = \sigma^{n/n+2}\, d^{-(n-2)/n+2} \,/\, \dot{\epsilon}_s \qquad (1)$$

where n is the power law exponent. This equation is consistent with the relationship of Grant and Monkman (1956). The right hand side of equation (1) has been plotted against grain size for various values of applied stress in Figs.7 and 8. All the terms in the ordinates of these figures are expressed in S.I. units. It can be seen that the variation of the right hand side term in equation (1) is similar to the variation in experimental rupture life with grain size (Figs. 3 and 4).

The variation of rupture ductility with rupture life is shown in Fig.9 and is similar to that reported earlier for 316 steel (Morris, 1978; Harries and Morris, 1978) and has been shown to depend on the state of intergranular and intragranular precipitation. An apparent fracture stress calculated taking into (the decrease in load-bearing area due to internal cracking has been neglected) account the decrease in load-bearing area by necking has been found to depend on both grain size and initial applied stress (Fig.10) indicating that failure under these creep conditions is not controlled by net stress. Similar results have been reported earlier by Morris (1978).

In summary, the metallographic evidences on the variation of crack size and aspect ratio with grain size and the general decrease in rupture life and rupture ductility with increase in grain size support the Griffith-Orowan critical crack length criterion; the variation of rupture life with grain size and particularly the peak in the variation at 973 K and 70 MPa is however more consistent with the model of Nix and coworkers (1977) of intergranular creep crack growth controlled by matrix plasticity.

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