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CREEP-FATIGUE INTERACTIONS IN A LOW ALLOY STEEL

D. Sidey*

INTRODUCTION

The analysis of high temperature low cycle fatigue data (with and without hold times) has proceeded along many lines with the object of predicting material behaviour at lower strain ranges and longer times than can be simulated in the laboratory [1]. Such analyses require certain assumptions to be made about interactions between creep and fatigue. For example, in the American Code 1592 no interaction is assumed and failure is designated to occur when the sum of the independent damage processes reaches unity i.e.

$$\frac{t}{t_f} + \frac{N}{N_f} = 1 \qquad (1)$$

where the two terms represent the fractions of lifetime of pure creep and pure fatigue failures used up. Under cyclic deformation conditions, it is very difficult to separate the fatigue and creep processes at high temperatures since time-dependent mechanisms still operate and, in fact, become more important as frequency is lowered. One method of looking at interaction processes is to use sequential testing in which the effects of prior static creep on the high temperature low cycle fatigue behaviour and the effects of prior fatigue on the subsequent creep behaviour are studied [2,3,4].

This paper describes some preliminary results obtained from sequential testing of a 1% Cr.Mo.V. rotor steel.

Deformation and fracture processes are two important damage mechanisms which operate during both fatigue and creep. In the case of the creep behaviour of this alloy, fracture is normally associated with the growth and interlinkage of intergranular cavities at long times to failure whilst transgranular fracture without any extensive cracking is found at short failure times. This allows a comparison to be made of the effect of prior creep damage with and without cracks on the low cycle fatigue behaviour. Similarly, the importance of cyclic softening or hardening and of the presence of cracks produced by fatigue on the subsequent creep behaviour at various stress levels can be determined.

EXPERIMENTAL PROCEDURE

The material was a forged low alloy steel containing 0.20% C, 0.88% Cr, 0.64% Mo, 0.32% V. Heat treatment procedure: 1223/1233 K, 15 h., Oil Quench + 973/978 K, 48 h., Furnace Cool + 893/903 K, 30 h., Air Cool. This gave a microstructure consisting of 90% upper bainite and 10% ferrite. Specimens with a parallel gauge length of 12.7mm and diameter of 6.3mm

*Christ's College, Cambridge, UK.

were employed. The gauge length terminated in ridges suitable for the attachment of extensometers.

All the fatigue testing was carried-out in a servo-hydraulic machine with induction heating of the specimen. This gave a temperature distribution of $\pm$ 1 1/2 K on the specimen gauge length. Creep tests were done in constant load single lever machines with specimen extension being transmitted to a capacitance transducer by means of extensometers from the gauge length. A temperature of 838 K was used in all tests. In the fatigue + creep type of tests, specimens were fatigued under triangular strain control at a strain rate of $8 \times 10^{-5}s^{-1}$ for various fractions of their fatigue life. The specimens were then set-up in the creep machines and loaded as soon as the testing temperatures had been reached. A similar procedure, but in reverse, was used for the creep + fatigue tests.

RESULTS

Prior fatigue + creep

Most specimens were fatigued at a strain range of 1.0% for up to 50% of their lifetime before being creep tested to failure at stresses between 220 and 285MPa. It was found that prior fatigue increased the steady state creep rate and reduced the fracture life except in one instance where 10% prior fatigue did not affect the creep properties at 220MPa (Table 1). Figure 1 shows the creep curves obtained at 255MPa and it can be seen that prior fatigue still results in a normal three stage creep curve. In fact, as far as the specimen is concerned, it is equivalent to testing at a higher creep stress.

At 220MPa creep failure occurred by inter-granular cavitation but when prior fatigue reduced the life at this stress level, failure was transgranular with a large reduction in area ($\sim$70%). At higher stress levels, all failures were ductile and transgranular. In Figure 2, creep damage is plotted against fatigue damage on a fractional basis. This shows that, in most instances, linear summation of damage is less than unity (c.f. equation (1)). Also, the deleterious effect of prior fatigue is mainly a result of the initial fatigue cycles and continued cycling produces smaller further reductions in the creep resistance of the material. One prior fatigue test at a lower strain range of 0.5% had a far less drastic effect on the creep behaviour and gave a linear summation of unity. Other workers [4] have also noted that lowering the strain range reduces the damaging effect on the creep behaviour.

Prior creep + fatigue

Specimens were pre-crept at 255MPa to the early and late stages of teriary-creep before fatigue testing at $\Delta\varepsilon_t$ = 1.0%. At this creep stress no inter-granular cracking is produced nor are any surface cracks formed which could act as initiation sites in subsequent fatigue tests. Prior creep reduced the fatigue life slightly but when damage was considered in terms of equation (1) linear summations greatly in excess of unity were obtained (Figure 2). Figure 3 shows that prior creep reduced the amount of cyclic softening e.g. at 50% N_f virgin material softened 21% from its initial state whereas only 14% softening occurred after prior creep. In fact, the material tended to soften to the same stress range under all circumstances, but the initial stress range was reduced by prior creep.

DISCUSSION

The present results indicate that even relatively small amounts of prior fatigue can reduce the creep resistance of this low alloy steel. Two forms of structural changes produced in the alloy by fatigue are cyclic softening of the bulk material and crack initiation and propagation. After 50% N_f at $\Delta\varepsilon_t$ = 1.0% surface cracks considerably less than one grain in depth are observed distributed randomly along the gauge length. It is not expected that the presence of such small localised cracks would have any significant effect on the creep behaviour.

Since creep deformation is controlled by the bulk properties of the material, the detrimental effect of prior fatigue must be a result of cyclic softening. The evidence suggests that prior fatigue does not alter the creep mechanisms but merely their rate of operation. Creep deformation in this alloy at the present stress levels is recovery controlled [5] so that cyclic softening must produce a dislocation structure which is less resistant to recovery processes. At this stage, there is no evidence available of the substructure formed during cyclic softening in this material. In this context, it would be interesting to determine the effect of a cyclically hardened structure on the creep properties. Further evidence is given for the importance of cyclic softening by the fact that a reduction in the strain range of the prior fatigue gives a structure less deleterious in creep; as the strain range is lowered, the amount of softening is reduced.

In order to compare the effect of prior fatigue with that of a tensile prestrain, a specimen was prestressed to a level equal to the maximum tensile stress obtained during fatigue cycling (i.e. 1/4 cycle fatigue test) before being creep tested at a lower stress. In this case, not only were the steady creep rate increased and the time to rupture decreased slightly, but also primary creep was eliminated. This confirms the importance of the substructure in controlling the creep properties since different substructures are produced by the two forms of prestraining.

The reduction in the time to fracture as a result of prior fatigue is directly related to the increase in the steady creep rate since the product $\dot{\varepsilon}_s \cdot t_f$ was constant in all cases. The dependence of the fracture processes on the deformation rate was also demonstrated by the fact that at the lowest creep stress, prior fatigue changed the fracture mode from intergranular to transgranular through its effect in enhancing the steady creep rate.

The major influence of prior creep on fatigue is to reduce the initial cyclic stress range without affecting the range at half-life. Thus creep, in effect, has partly softened the material as far as the fatigue process is concerned. It is known that in high stacking fault energy materials the saturation stress range level tends to be the same independent of the initial structure of the material [6]. Therefore, in the present case, where creep damage is associated solely with bulk deformation, it is not surprising that even extensive prior creep has only a minor effect on the low cycle fatigue properties. Work is in progress to determine whether the presence of inter-granular creep cracks is capable of influencing the fatigue behaviour.

CONCLUSIONS

High temperature low cycle fatigue and static creep produce structural changes in a material which can affect its subsequent behaviour. In this instance, it was found that cyclically softening a 1% Cr.Mo.V. steel reduced its creep resistance at 838 K, the extent decreasing with smaller amounts of softening. The presence of creep damage without any cracking had little effect on the high temperature low cycle fatigue properties of this steel.

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Table 1 The effects of prior fatigue on the steady state creep rates and times to fracture at various creep stresses at 838 K.

% PRIOR FATIGUE	STRESS = 285 MN/m^2		STRESS = 255 MN/m^2		STRESS = 220 MN/m^2	
	$\dot{\varepsilon}_s (s^{-1})$	t_f(ks)	$\dot{\varepsilon}_s (s^{-1})$	t_f(ks)	$\dot{\varepsilon}_s (s^{-1})$	t_f(ks)
0	2.7×10^{-8}	533	4.7×10^{-9}	2880	9.5×10^{-10}	20029
5	1.3×10^{-7}	158	-	-	-	-
10	3.5×10^{-7}	72	2.3×10^{-8}	810	8.6×10^{-10}	19180
25	7.2×10^{-7}	32	2.8×10^{-8}	634	-	-
50	8.4×10^{-6}	7	5.2×10^{-8}	436	4.5×10^{-9}	2203

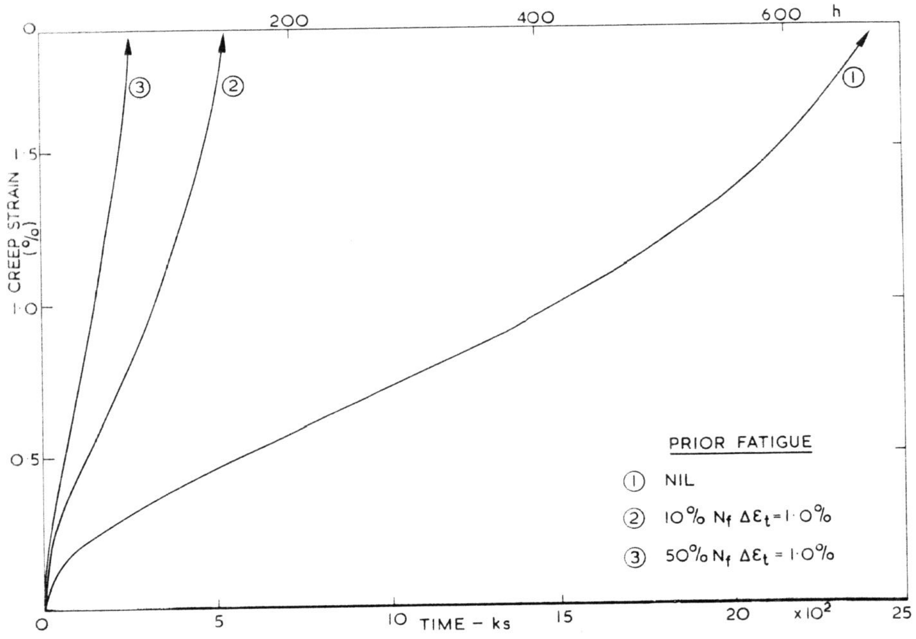

Figure 1 Creep curves at 255 MN/m^2 after 0%, 10% and 50% prior fatigue at $\Delta\varepsilon_t$ = 1.0%

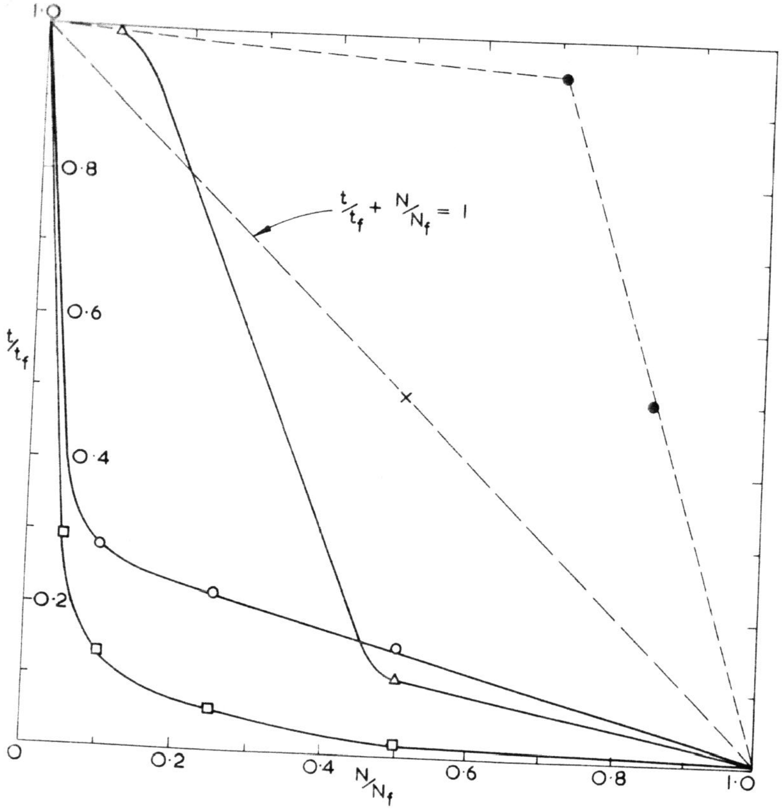

Figure 2 Plot of creep damage t/t_f versus fatigue damage N/N_f. Open symbols represent fatigue + creep tests, closed symbols represent creep + fatigue tests.

Creep stresses: Δ = 220 O = 255 □ = 285 MN/m²

Fatigue: $\Delta\varepsilon_t$ = 1.0%

X - $\Delta\varepsilon_t$ = 0.5% + CREEP AT 255 MN/m²

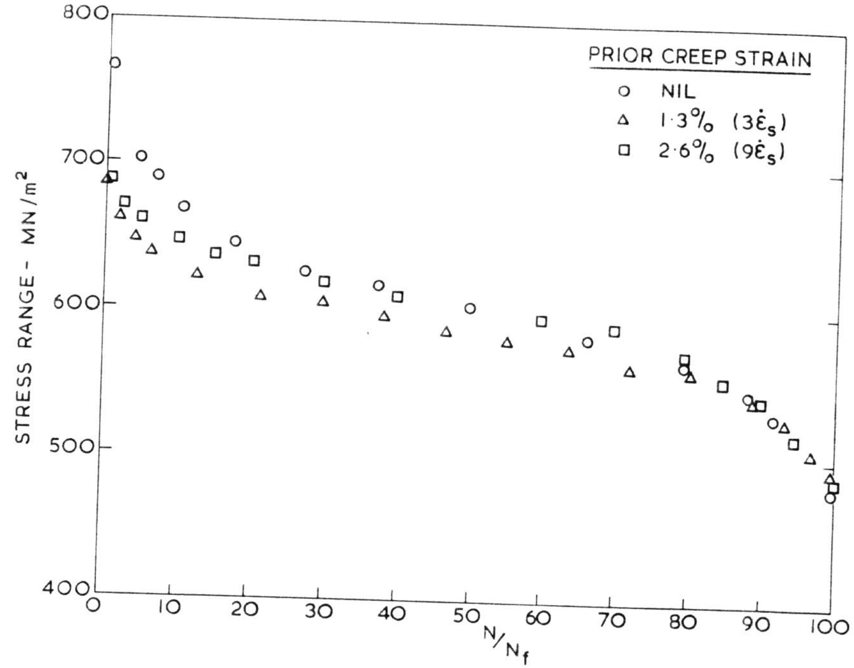

Figure 3 The effect of prior creep strain on the stress range versus N/N_f curves at $\Delta\varepsilon_t$ = 1.0%