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CREEP-FATIGUE INTERACTION IN AN AUSTENITIC Fe-Ni-Cr ALLOY AT 600°C

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INTRODUCTION

There is a growing interest in and demand for high temperature cyclic data regarding materials used in the power industry. The increased utilization of nuclear energy has emphasized the necessity to acknowledge the effects of cyclic deformation as a compliment to monotonic creep. Hence at high temperatures the interaction of fatigue and creep processes must be considered. Towards this end, a number of studies [1-8] have been carried out using Type 304 stainless steel and Alloy 800. Also, creep-fatigue design rules have been recommended by the American Society of Mechanical Engineers [9]. Although the rules, which imply a linear summation of creep and fatigue damage, were recommended for Types 304 and 316 stainless steels at temperature above 427°C, subsequent work [10,11] has indicated that care must be exercised in applying these design rules.

The present work was carried out to investigate the application of the design rules to fatigue-creep interaction in Alloy 800. The choice of alloy was made because of its engineering importance in the nuclear power industry, the relative lack of high temperature interactive data and its sensitivity to compositional variations [12,13]. This alloy is solid solution hardened by chromium and nickel additions, and the presence of carbon results in further hardening due to the formation of carbides. Provided sufficient stabilizing elements, such as titanium, are present then the formation of chromium carbides will be suppressed. Further high temperature strengthening may be introduced by the precipitation of the intermetallic compound based on $Ni_3(A\ell,Ti)$ and isomorphous with the face centred cubic matrix, known as γ', if amounts of titanium and aluminum are present up to the solubility limits. The maximum strengthening by γ' occurs at around 600°C.

It is evident then that the probability of γ' precipitation will depend upon the amount of titanium and aluminum remaining in solid solution after the formation of carbides and nitrides and this in turn will play an important role in the high temperature behaviour of the alloy.

EXPERIMENTAL PROCEDURE

Two alloys of type Sanicro 31 (trade name of Sandvik AB) based on Alloy 800 were used in this work and the analyses are given in Table 1. It will be noted that cast no. 5.68342 containing a high Ti/(C+N) ratio (9.5:1) also contained a high $(A\ell+Ti)$%(i.e. 1.04%).

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Samples of these alloys were taken from 25mm dia bar stock and cold pilgered to 16mm bar. The material was then solution heat treated at 1120°C for 15min and water quenched. Specimens for cyclic studies were machined with a diameter of 5mm over a gauge length of 7.5mm and the cyclic tests were carried out on an electrohydraulic,servo-controlled machine at frequencies of 10Hz. Accompanying tests were also conducted at 1Hz (342 and 202 series) and at 0.005Hz (202 series only). All these tests were done at 600°C under stroke control which was calibrated for an equivalent total strain range of 1.2%. All tests were conducted using the same setting and the stress response was monitored continuously.

Standard creep tests were carried out on the same type of specimen with a similar geometry as the fatigue specimens. All the tests were carried out at 600°C and one load level corresponding to 250 N/mm^2. In these cases, the strain was monitored continually with time.

A series of sequential tests were carried out such that the specimen was subjected to a predetermined number of cycles in fatigue or time under monotonic loading (creep), this was then followed by the other deformation process (i.e. creep or fatigue) until fracture occurred. Failure in fatigue was defined as the number of cycles required for 70% of the tensile saturation or maximum stress to be reached and creep fracture was defined as the time for complete separation.

Metallographic examination was carried out using optical and electron transmission microscopical technique.

RESULTS AND DISCUSSION

Microexamination and Hardness Tests

The results of hardness tests carried out at 600°C on solution heat treated coupons of each series is shown in Figure 1. The results shown are average values of at least five readings. It will be noticed that the hardness of the high Ti/(C+N) ratio 342 series increased markedly with time up to about 3000h after which, the hardness increased slowly to 10,000h and then decreased with time. Transmission electron microscopy revealed extensive homogeneous γ' precipitation. In addition, $M_{23}C_6$ formed within the grains as well as at the grain boundaries. The hardness of the 202 material (Ti/(C+N) = 4.5:1) increased slightly with time to about 500 h, and then decreased. Although some γ' precipitation occurred, chromium ($M_{23}C_6$-type) and titanium (TiC) carbides were predominant. After creep and even after fatigue testing, this material had a higher carbide dispersion owing to the fact that it contained twice the amount of carbon, when compared to the 342 series material.

Basic Cyclic Tests

Figure 2 shows the stress response vs cycles for the uninterrupted (or basic) cyclic tests. Cyclic hardening was observed, after which saturation occurred, followed by failure. The 202 series specimens tended to show a negative strain rate (or frequency) response. This is typical of dynamic strain aging behaviour [14]. The 342 series specimens showed a similar behaviour for the 1 and 10Hz frequency tests. No tests at 0.005Hz frequency were carried out on the material. A higher stress response for a constant strain amplitude resulted in a smaller amount of plastic strain with an accompanying longer fatigue life.

In general, the 202 series material tended to have slightly longer fatigue lives for the same frequency, as shown in Table II. The longest lives were associated with a frequency of 1Hz. In all cases transcrystalline cracking was observed. The 202 material cycled at a frequency of 0.005Hz showed a large degree of oxidation in the cracks which could account for the decreased life at this low frequency [15]. Optical micro-examination of the surface revealed a relatively coarse slip distribution after cycling at 10Hz, whereas at the lowest frequency (0.005Hz) and also after creep testing, slip appeared to be more homogeneous. More uniform slip could also account for the longer lives at 1Hz [16]. Figure 3 shows an electron transmission image of the 342 series cycled at 10Hz. The conditions for this image were such that the majority of dislocations were in contrast yet the γ' precipitates were out of contrast. Clustering of the dislocations should be noted.

Basic Creep Tests

The difference in creep behaviour of the 342 and 202 series material can be seen in Figure 4 for a stress of 250 N/mm^2. The initial strain in the 202 series specimen was much greater than that for the 342 series specimen. Such an effect is to be expected since γ' precipitated more abundently in this latter alloy during the equilibration of temperature at 600°C under zero load conditions prior to starting the test. The 342 material displayed a much lower secondary creep rate (3×10^{-5} h^{-1} compared to 7×10^{-5} h^{-1} - see Figure 4) and relatively little tertiary creep. The fracture elongation was about 5% for the 342 alloy and approximately 35% for the low Ti/(C+N) ratio 202 alloy. Hence, γ' in the high Ti/(C+N) ratio 342 material lowered the creep ductility and the secondary creep rate.

Interaction Tests

The effect of prior creep testing on the cyclic stress response was found to depend upon the amount of creep damage (expressed as the time ratio [t/t_f] at σ = 250 N/mm^2). Very little hardening occurred after small amounts of creep damage ($t/t_f \sim 0.15$), no cyclic hardening was seen after intermediate amounts of creep damage ($t/t_f \sim 0.4$) and cyclic softening took place after large amounts of prior creep damage ($t/t_f \sim 0.6$). This behaviour indicated that the hardening mechanism occurring during creep (γ' and/or carbide precipitation, as well as plastic deformation) resulted in a similar stress level as that required for high frequency cycling. It is expected that the hardening or softening during cycling is associated with dislocation multiplication or annihilation, respectively.

A significant difference in the deformation mode was observed in the specimens subjected to prior creep. In this case, a change to homogeneous slip was noticed.

When creep was imposed first, all the failures were transcrystalline indicating that time independent damage was the operative failure mechanism. It is important to note that only small, minor inter-crystalline cracks had developed after imposing a creep damage of 0.6.

Prior cyclic straining at high frequency tended to decrease the initial creep strain and lower the creep rate. As the amount of fatigue damage (expressed in terms of the cyclic ratio, N/N_f) increased prior to creep testing, then the initial creep strain decreased. In general, the effect of prior fatigue appeared to be the same as that due to prior monotonic (tensile) deformation, which indicates the similarity between these two time independent plasticity mechanisms. There was a tendency for relatively small and medium amounts of fatigue damage ($N/N_f < 0.5$) to increase the rupture time, thereby enhancing the creep performance. However, when large amounts of prior fatigue damage ($N/N_f < 0.5$) were imposed, the presence of small fatigue cracks caused the ensuing creep life to be reduced.

Figure 5 is a transmission electron image of a 342 series specimen subjected to a moderate amount of fatigue damage ($N/N_f \sim 0.4$) prior to creep testing. In comparison with Figure 3 it is apparent that subsequent creep allowed recovery mechanisms to operate and reduce the dislocation density and also enhance the precipitation of $M_{23}C_6$-type carbides. The interaction of these carbides with dislocations can be seen in Figure 5. It is presumed that the presence of a high dislocation density after the fatigue stage, together with the constant load during creep enhanced the precipitation of these fine carbides.

A summary of the effect of sequential fatigue and creep testing for the 342 and 202 series material is shown in Figures 6(a) and 6(b) respectively. The striking feature about both these figures is that enhancement of creep life takes place after moderate amounts of prior fatigue ($N/N_f \leq 0.5$) and that enhancement of fatigue life occurs after each alloy has been prior creep tested to about half life (i.e. creep damage $[t/t_f] \sim 0.5$). The former effect is due to the introduction of a high dislocation density at the start of the creep test, together with inhomogeneous carbide and some homogeneous γ' precipitation in the case of 202 series material, and γ' with less carbide precipitation in the 342 series material. The latter effect (mentioned above) is caused by homogeneous γ' (principally in the 342 material) and strain induced carbide (in the 202 material) precipitation during the creep stage. This results in an improved cyclic strength. Consequently, the cyclic plastic strain component is lower for a fixed total strain and the fatigue life is increased. In general, Figure 6 indicates that γ' precipitation in the 342 series material is a more potent mechanism than carbide precipitation in the 202 series material for enhancing the fatigue or creep behaviour.

The linear damage summation rule is included in Figures 6(a) and 6(b). For both types of material it appears to be too conservative. Small amounts of prior fatigue and creep brought about microstructural changes similar to those induced by thermal treatment, which improved the mechanical properties. Accompanying work with sequential low frequency (0.005Hz) and high frequency (10Hz) tests on the 202 series material has indicated a similar trend. Relatively followed by high frequency cycling resulted in an enhancement of the large amounts of low frequency damage ($N/N_f \sim 0.6$), high frequency life, in a similar manner to that observed by prior creep testing.

CONCLUSIONS

Simple sequential tests at 600°C involving monotonic creep and high frequency cycling of two types of Sanicro 31 (342 and 202 series) based on Alloy 800 resulted in an enhancement of life. Under these conditions, the linear damage summation rule was found to be too conservative.

The 342 series material containing a high Ti/(C+N) ratio exhibited precipitation (γ') hardening which was not apparent to the same extent as in the low Ti/(C+N) ratio 202 series material. Although the cyclic behaviour of the 342 series material was significantly enhanced by prior creep testing, that of the 202 series material was enhanced to a lesser degree by the formation of $M_{23}C_6$ carbides.

Prior cyclic deformation tended to improve creep behaviour through the introduction of a high dislocation density, and subsequent γ' and/or carbide formation, provided that no large fatigue cracks formed during the first stage.

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Table I Chemical Analysis (wt %) of Sanicro 31 (trade name of Sandvik AB) Alloy Based on Alloy 800.

Cast No.	C%	N%	Si%	Mn%	P%	S%	Cr%	Ni%	Ti%	Aℓ%	Ti/(C+N)	(Aℓ+Ti)%
5.68342	0.043	0.011	0.69	1.16	0.009	0.004	21.1	34.1	0.51	0.53	9.5:1	1.04
7.72202	0.071	0.021	0.60	0.59	0.006	0.003	20.8	31.0	0.41	0.27	4.5:1	0.68

Table II Effect of Frequency on Fatigue Life at 600°C ($\Delta\varepsilon_T$ = 1.2%).

Cast No.	Test Frequency ν		
	0.005 Hz	1 Hz	10 Hz
5.68342	*	5989	2321
7.72202	2600	5175	3711

*No tests carried out at this frequency

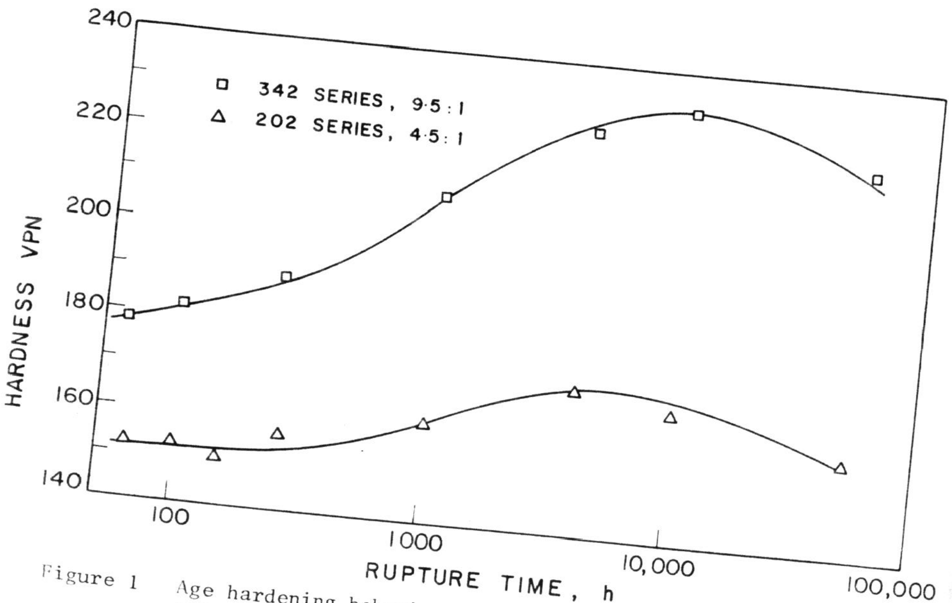

Figure 1 Age hardening behaviour at 600°C of high Ti/(C+N) [9.5:1] 342 series and low Ti/(C+N) [4.5:1] 202 series Sanicro 31 alloy.

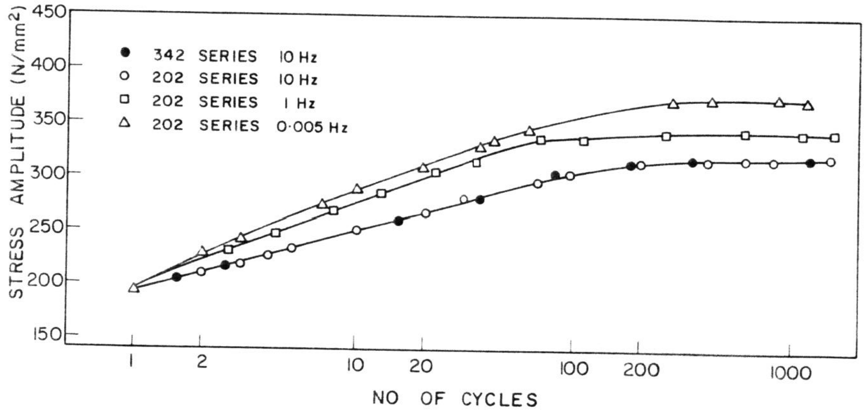

Figure 2 Cyclic Stress Response ($\Delta\varepsilon_T$ = 1.2%) at 600°C

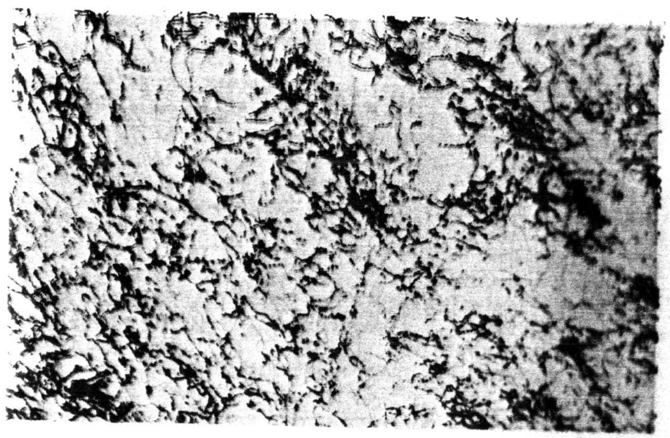

Figure 3 Transmission Electron Image of High Ti/(C+N) [9.5:1] Alloy After Cycling to Failure at 10 Hz. Test Temperature = 600°C. X20,000.

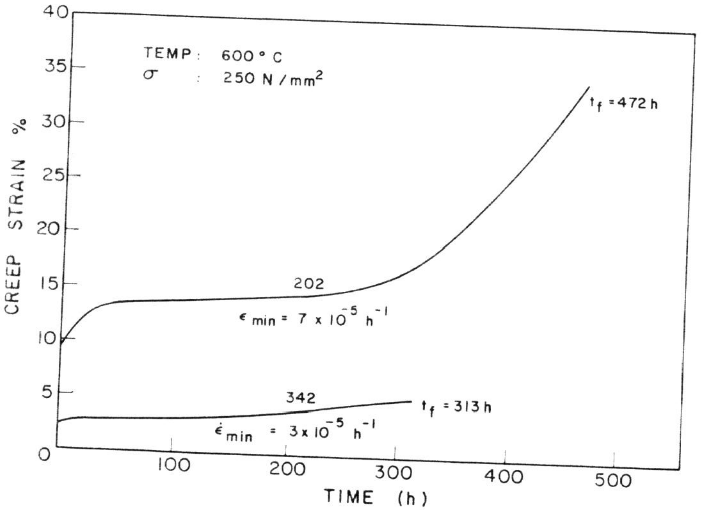

Figure 4 Creep Curves for Both Alloys Tested at 600°C and a Stress of 250N/mm².

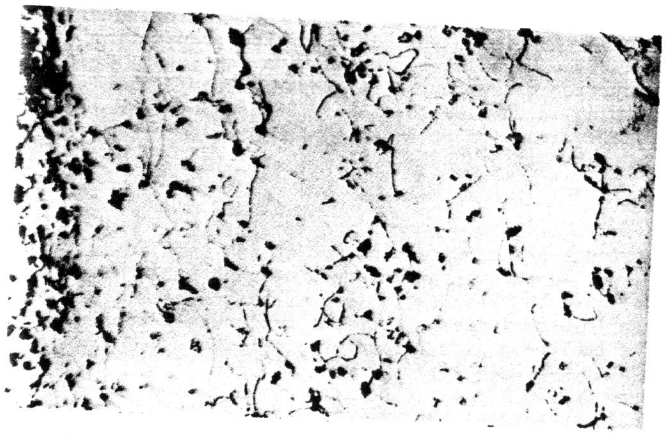

Figure 5 Transmission Electron Image of High Ti/(C+N) [9.5:1] 342 Series Material Cycled to 0.4 Life at 10 Hz and then Creep Tested at 250N/mm² to Failure. Test Temperature = 600°C. X20,000.

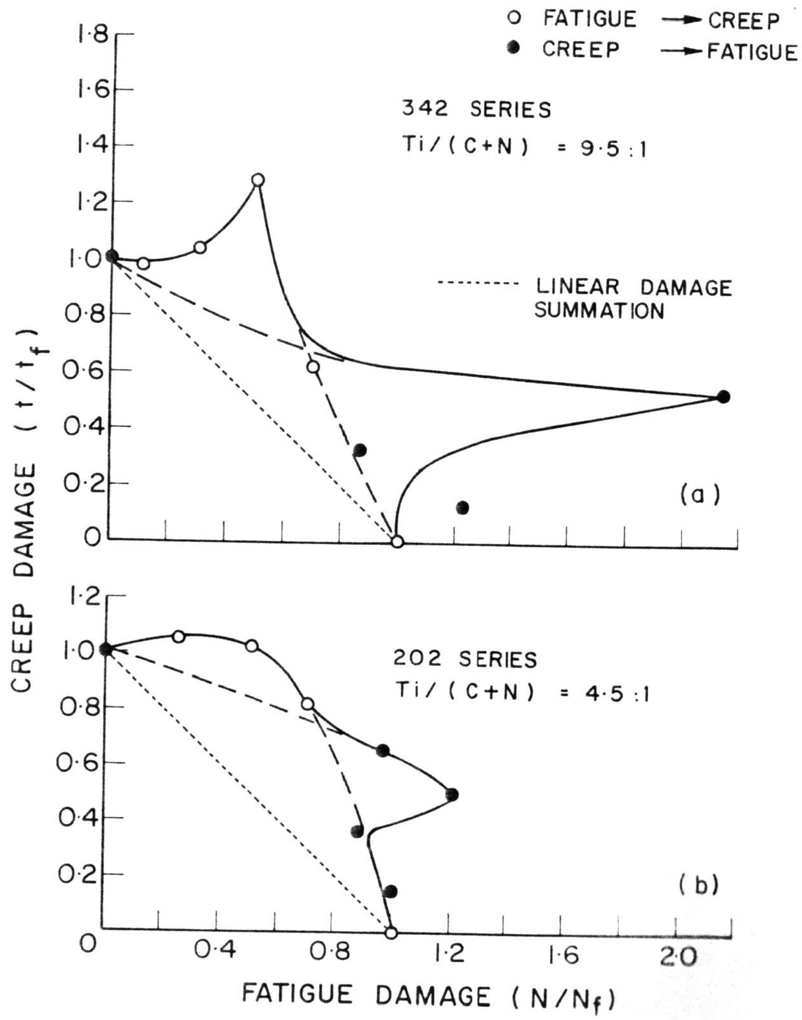

Figure 6 Creep (250N/mm²) - Fatigue (10 Hz) Damage Interaction Curves at 600°C.
a) 342 Series Sanicro 31 Alloy - Ti/(C+N) Ratio = 9.5:1.
b) 202 Series Sanicro 31 Alloy - Ti/(C+N) Ratio = 4.5:1.