CREEP AND CREEP-FATIGUE BEHAVIOUR OF UDIMET 720 AT 850°C

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The object of this study is to identify damage mechanisms operating at high temperature (850°C) in Udimet 720, a nickel-based superalloy strengthened by γ' Ni_3Al precipitates. In addition to environmental effects, the extension of viscoplasticity may result in specific damage mechanisms, such as intergranular cavitation, wedge cracking and/or thermal coarsening of γ' particles. The major mechanisms have been investigated using tensile smooth specimens, for creep and creep-fatigue loadings. The introduction of the relevant damage parameters in a model describing the viscoplastic behaviour of the material is tentatively discusssed.

INTRODUCTION

Nickel based wrought superalloys are widely used for components operating at high temperature, such as gas turbine discs. However, intergranular cracking occurs in these alloys above 650°C. To achieve better performances, the latest developments of gas turbines require alloys for discs working at temperatures ranging from 700 to 900°C. An optimized version of Udimet 720 LI superalloy has been provided by TURBOMECA for this study.

Crack growth tests were conducted at 850°C on CT specimens, in air and under vacuum (5.10^{-5} mbar), for two kinds of mechanical loadings : creep and creep-fatigue, with a 900 seconds hold-time at maximum load. For the same value of the loading parameter K_{max}, crack growth rates measured in air under creep loading are higher than those measured under creep-fatigue. Under vacuum, crack growth rates decrease by one order of magnitude for similar loading conditions, and the difference observed in air between creep and creep-fatigue tends to be minimized.

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These preliminary results show the essential role played by environment (especially by oxygen diffusion in grain boundaries at crack tip) in intergranular crack growth in Udimet 720 at 850°C.

Previous studies on wrought and powder-metallurgy Ni-based superalloys (1, 2) at temperatures below 700°C have shown that the interaction between oxidation and mechanical loading was the driving parameter responsible for intergranular crack growth in such alloys. However, at 850°C, crack propagation under creep and creep-fatigue loadings was only observed on CT specimens at elevated values of the maximum applied load ; then, in addition to oxidation-deformation interaction, the extension of viscoplasticity at crack tip may result in specific damage mechanisms. Since the analysis in term of stress-strain field in the process zone near the crack tip appears to be complex, the identification of the operating damage mechanisms in an extended viscoplastic field has been realized using smooth tensile specimens.

EXPERIMENTAL PROCEDURE

Original tensile smooth specimens, featuring several cross-sections, were designed for the identification of damage mechanisms and material behaviour at 850°C. Creep and creep-fatigue tests were conducted in air and under vacuum until the minimal section of each specimen failed, the thicker sections of the specimen remaining unbroken. Then, each test provided us a creep curve and a lifetime value measured on the section of the specimen with the smallest radius, and four unbroken sections presenting various damage rates for different stress levels. Longitudinal polished sections of the specimens were observed using scanning electron microscopy.

The different lifetime values obtained from creep (air and vacuum) and creep-fatigue tests are plotted on figure 1. The stress versus lifetime curve for creep tests in air shows a breaking point around a stress level of 300 MPa, lifetime for lower stress levels being shorter than what we can expect from the results obtained at elevated stress levels (assuming Kachanov's description of the curve). Although lifetimes measured for creep-fatigue tests appear to be slightly shorter than those observed for creep tests at the same stress level, no significant difference can be found between these two kinds of mechanical loadings in term of lifetime. However, creep-fatigue tests were only performed at elevated stress levels, above the level for which a transition has been observed for creep. One creep test was performed under vacuum : the lifetime measured is then twice the value of the lifetime for creep at the same stress level in air.

Fracture surfaces of all specimens are mainly intergranular, even for the highest stress levels. Observations of the longitudinal sections of the tests specimens, polished and etched, allowed us to identify several damage mechanisms operating at 850°C :

Matrix oxidation : addition elements in solid solution in the γ phase (mainly Al, Ti and Cr) form an oxide scale at the metal surface. The diffusion of aluminium towards the specimen surface results in the dissolution of γ' particles under the oxidized surface. The thickness of the oxide scale, and the depth of the γ' depleted zone under the surface obey a $t^{1/2}$ kinetics, and are controlled by volume diffusion of oxidizing elements in the γ phase. Observations of samples oxidized at 850°C in air show that no interaction exists between matrix oxidation and mechanical loading.

Intergranular oxidation : grain boundaries appear to be oxidized from the specimen surface. The depth of penetration of oxidation along grain boundaries is much greater than the depth of internal oxidation. No preferential oxidation at grain boundaries can be observed when no mechanical loading is applied to the sample. This suggests that a strong interaction exists between grain boundary oxidation and mechanical strain, as it was previously shown at lower temperatures. On the most damaged sections, we observed that grain boundary oxidation results in intergranular crack initiation and multiple cracking, until a major crack grows and leads to sample failure.

γ' particles coarsening : high resolution SEM observations of etched longitudinal sections of various tests specimens were made. These observations allowed us to identify microstructural transformations of the superalloy at 850°C. Ageing results in a coarsening of the hardening γ' particles, which are uniformly distributed in the γ phase. It can be observed on samples aged at 850°C without any applied load. Particles shape remains roughly circular and no rafting has been observed on loaded specimens. Nanometric γ' particles which can be observed in the initial microstructure are disappearing after 50 hours at 850°C.

DISCUSSION

The elevated temperature considered in this study, higher than conventional service temperature used for wrought Ni-based superalloys, sets several problems. Thermal activation of damage mechanisms and the development of an extended viscoplatic strain field at crack tip does not allow a simple description of crack growth kinetics for creep and creep-fatigue loadings.

The main problem raised for the modelization of crack growth kinetics is the description of the viscoplastic strain field at crack tip. We have observed an important evolution of the microstructure of Udimet 720 with time at 850°C. γ' coarsening results in an increase of inter-particle spacing, assuming that the volume fraction of hardening particles remains constant.

In order to appreciate the importance of the microstructural evolution of the alloy on its creep behaviour, we have performed additional relaxation tests on tensile smooth specimens at 850 °C. Relaxation times have been limited to 24 hours to prevent any coarsening effect during the test.

Figure 2 shows the shape of the inital loading curve for each relaxation test (with an initial loading rate of $\dot{\varepsilon} = 6.10^{-4} s^{-1}$). Ageing (500hours at 850°C) results in a strong decrease of the material yield-strength as shown in figure 2. Assuming that particles are not cut by dislocations, the dispersion of hardening particles introduces a threshold stress for dislocation glide, known as Orowan stress :

$$\sigma_{th.} = \frac{Gb}{l} \qquad (1)$$

where G is the shear modulus, b the Burgers vector, and l the spacing between hardening particles. Considering this approach, a good agreement has been found between the increase in the inter-particle spacing l and the yield-strength decrease for Udimet 720 aged at 850°C.

Arzt and Ashby have shown that a stable particle distribution also introduces a threshold stress for creep (3). Modelling this threshold is complicated by the fact that, at creep temperatures, strain results from dislocations glide and climb. However, creep rate may be described by a modified form of Norton's law (4) :

$$\dot{\varepsilon} = \dot{\varepsilon}_o\left(\frac{\sigma - \sigma_p}{\sigma_o}\right)^n \qquad (2)$$

where the threshold creep stress σ_p has a form close to the Orowan stress :

$$\sigma_p \approx \alpha\frac{Gb}{l} \qquad (3)$$

where α is a constant.

Assuming that the particles coarsen with time, following a diffusion-controlled coarsening law :

$$\frac{dr}{dt} = \frac{K}{3r^2} \qquad (4)$$

the spacing between particles increases with time, assuming a constant volume fraction of the hardening phase :

$$l^3 = l_o^3 + K't \quad (5)$$

where l_o is the initial spacing. Assembling these results allows to describe the time dependency of the creep law (5) :

$$\dot{\varepsilon} = \dot{\varepsilon}_0\left(\frac{\sigma}{\sigma_0}\right)^n\left\{1 - \frac{\sigma_p^o\sigma}{(1 + K't)^{\frac{1}{3}}}\right\}^n \qquad (6)$$

where $\sigma_p^o = \alpha Gb / l_o$.

Then, ageing of the material should result in a decrease of the threshold creep stress with time : dislocation mobility (by glide or termally activated climb) increases with the spacing between γ' hardening particles.

However, relaxation tests results do not show a large difference between virgin material and material aged at 850°C for 500 hours. Inelastic strain rates measured for aged and virgin material can be described (for stress values higher than 300 MPa) by an Arrhenius law, instead of Norton's law:

$$\dot{\varepsilon} = A\exp\left\{-\frac{\Delta H - V\sigma}{kT}\right\} \qquad (7)$$

where V is an activation volume. This suggests that thermally activated dislocation climb is weakly affected by the coarsening of γ' particles.

Figure 3 shows inelastic strain rates measured for relaxation, fatigue-relaxation (with a 900 seconds hold-time at maximum strain) and creep tests (considering an average value of the stabilized creep rate), conducted on virgin material. In the stress range 300-500 MPa, a good agreement is found between inelastic strain rates measured for creep and relaxation loadings. However, for lower stress values (corresponding to long lifetimes), the average creep rate tends to be larger than the relaxation strain rate. This suggests an increasing effect of ageing and possibly environmental contributions at the lower stress levels. Modelling long creep lifetimes requires therefore to account for the different effects, which is underway. The combination of fatigue and relaxation loadings results in an important increase of inelastic strain rates , but relaxation during hold-times is still well described by the form of equation (7).

CONCLUSION

Ageing of the material results in an important decrease of Orowan's threshold stress with time, as a result of the increase of the average spacing between γ' hardening particles. However, thermally activated dislocations climb (and then, viscoplastic strain rates) does not appear to be strongly affected by γ' particles coarsening, for elevated stress levels (above 300MPa). Inelastic strain rates seem to be affected by γ' particles coarsening for lower stress levels and elevated lifetimes.

We have here considered the effects of a single damage mechanism, knowing that creep rate and lifetime of Udimet 720 at 850°C result from different operating damage mechanisms (γ' particles coarsening but also intergranular and matrix oxidation). As it is shown in reference (5), each operating damage mechanism considered separately can be integrated in a modified Norton's law, based on physical observations. But we can think that the identification of all operating mechanism considered separately, and the application of a life-fraction Robinsons rule would not lead to a satisfying description of the global creep behaviour of the alloy. Previous studies realized at lower temperatures (1,2) have shown that grain boundary strength decreases as a result of a strong interaction between intergranular oxidation and deformation. Such interactions between the different damage mechanisms and viscoplasticity have to be considered in the case studied here.

ACKNOWLEDGEMENTS

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REFERENCES

(1) Bernède P. « Effet de l'oxydation sur la fissuration en fatigue-fluage d'un superalliage pour disques de turbines, l'Astroloy », PhD Thesis, ENSMP, 1994.

(2) Hochstetter G. « Propagation de fissures à haute température dans un superalliage pour disque de turbomachine (N18). Interactions entre la nature des sollicitations mécaniques et des effets d'oxydation », PhD Thesis, ENSMP, 1994.

(3) Arzt E., Ashby M.F., Scripta Met., vol. 16, pp.1285-1290, 1982

(4) Evans W.J., Harrison G.F., Met. Sci., vol. 10, pp. 307-313

(5) Ashby M.F., Dyson B.F « Creep damage mechanics and micromechanisms », Advances in Fracture Research, 6th International Conference on Fracture, New Dehli, India, vol. 1, pp. 3-30, 1984.

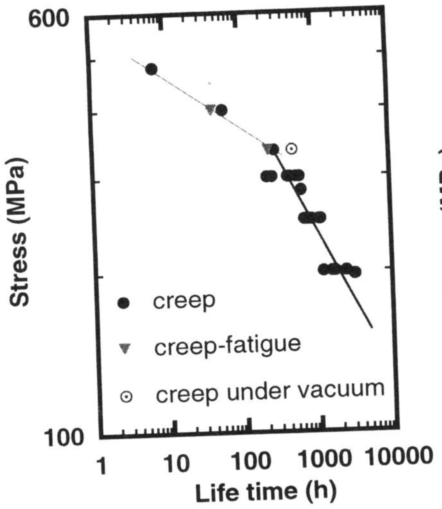

Figure 1 Stress vs. lifetime for creep and creep-fatigue tests at 850°C.

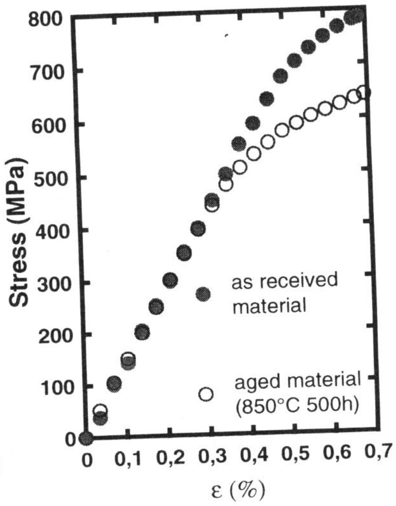

Figure 2 Tensile stress-strain curves for virgin and aged material.

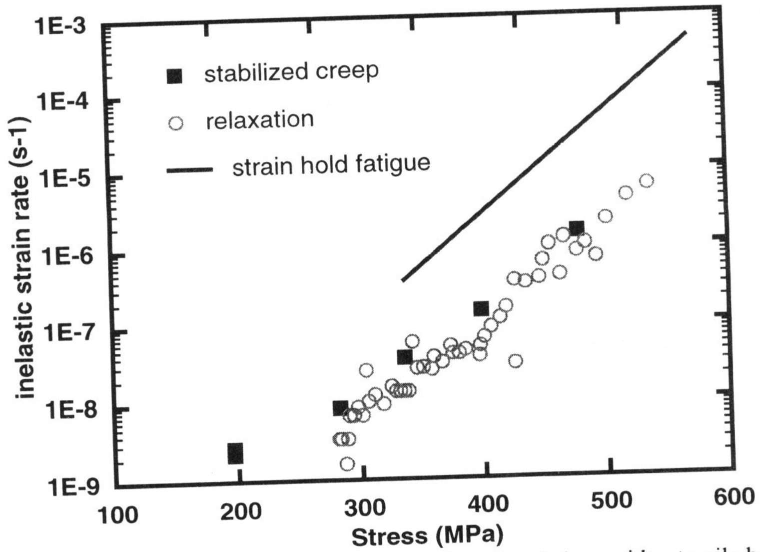

Figure 3 Inelastic strain rates measured for relaxation, fatigue with a tensile hold strain and creep tests conducted on virgin material.