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DIFFUSION CREEP IN A COARSE GRAINED ODS SUPERALLOY UNDER TRANSVERSE LOADING

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Introduction

Oxide dispersion strengthened (ODS) superalloys are candidate materials for high performance applications in gas turbines. Their excellent high temperature strength is derived from a combination of a fine dispersion of oxide particles and a highly elongated grain structure. The high-temperature creep behaviour of such alloys is generally characterized by a highly stress-sensitive creep rate which can be approximately described in terms of a "threshold stress" below which the creep rates due to dislocation motion are negligible. This creep behaviour can be explained on the basis of recent models for the interaction of dislocations with dispersoids at high temperature (1-3).

A highly elongated, textured grain structure is expected to result in anisotropic mechanical behaviour. However, the creep data available for these alloys have largely been generated in the longitudinal grain direction. This note reports some recent results on creep in the transverse grain direction in the ODS superalloy INCONEL* MA 6000. This alloy is a dispersion-strengthened Ni-Cr based superalloy containing a nominal dispersion of 2.5 Vol.% Y_2O_3 and a γ' volume fraction of approximately 50 %. The elongated grain structure, with the long grain dimension reaching up to several millimetres, is achieved by thermomechanical processing including annealing in a moving temperature gradient (4).

Whittenberger (5) has conducted constant velocity compression tests on MA 6000 at temperatures between 1144 and 1366 K in the longitudinal, long and short transverse grain directions. He found that the strengths in the transverse directions are comparable to that in the longitudinal direction (actually the short transverse direction was found to be the strongest). However, these tests were conducted under relatively fast strain rates ($> 10^{-7}\ s^{-1}$) whereas the present results were obtained under compression creep at lower stress levels where diffusional processes are expected to play a more significant role.

Experimental Techniques

INCONEL alloy MA 6000, in the form of a rectangular bar, was used having the following standard heat treatment, 1505 K/0.5 h, 1228 K/2 h and 1118 K/24 h. Cylindrical specimens with dimensions 16 mm long and 8 mm diameter were creep tested in compression at 1323 K (this corresponds to 84 % of the absolute solidus temperature) and stresses between 120 and 230 MPa, with the stress axis parallel to the long transverse grain direction. Compression creep was chosen for this test series in order to suppress the formation of creep cavity damage on the grain boundaries perpendicular to a tensile stress. Ceramic extensometers mounted axially onto the specimen surface allowed for continuous monitoring of displacement during creep. Following creep the specimens were sectioned longitudinally, polished and etched to reveal the transverse grain structure and the γ' precipitate distribution.

Results

Figure 1 shows the microstructure of MA 6000 in the long transverse direction in the as-received fully heat treated condition. The grains are of irregular shape having lengths between 100-300 μm and a grain

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aspect ratio of between 1 and 3. In this orientation the long grain dimension is normal to the plane of the micrograph.

Figure 2 shows the microstructure following creep at 120 MPa to a strain of 0.5 %. In comparison to figure 1 it is noticeable that zones free of γ' have developed adjacent to those grain boundaries parallel to the compression stress axis. This is confirmed by observation in the SEM as shown in figure 3. Similar observations were made in other specimens tested in this stress range, although no evidence of γ' free zones was found in a specimen tested at a higher stress of 230 MPa after 3 % strain. Further, no γ' free zones were detected in material that had undergone stress-free annealing at 1323 K for times comparable to those for creep testing.

Minimum creep rates are plotted against applied stress as shown in figure 4 and compared with tensile creep data for the longitudinal grain direction (from Ref. 6). At high stress both sets of data are comparable whereas at lower stress the creep rate in the long transverse direction is higher; at 120 MPa the creep rate is over two orders of magnitude greater.

Discussion

The observation of precipitate free zones adjacent to grain boundaries parallel to the compression stress axis is strong evidence for a diffusion creep deformation mechanism. Higher creep rates at low stress in comparison to the longitudinal creep data gives further support to the belief that an additional deformation mechanism is operative in the long transverse direction.

At first sight it might be considered that diffusion creep rates would be negligible in these highly elongated grain structures because of the long diffusion distances involved. However, although this is indeed true for creep with the stress applied in the longitudinal direction, this is not the case for transverse creep testing; as indicated by Greenwood (7), lines of vacancy flux now adopt a two dimensional form resulting in a creep rate dependent on the short grain dimensions and independent of the long grain length. In this situation the rate equation for diffusion creep controlled by vacancy migration through the lattice is given by (7,8)

$$\dot{\epsilon} = 12 \left[\frac{D\Omega}{kT}\right] \left[\frac{\sigma \; (L_3^2 + L_1^2)}{L_1^2 L_2^2 + L_2^2 L_3^2 + L_1^2 L_3^2}\right]$$

where L_1, L_2, and L_3 are the grain lengths in the longitudinal, long transverse and short transverse directions respectively, D is the volume diffusion coefficient and Ω the atomic volume. When $L_1 >> L_2$ and $L_1 >> L_3$ this equation reduces to

$$\dot{\epsilon} = 12 \left[\frac{D\Omega}{kT}\right] \frac{\sigma}{L_2^2 + L_3^2}$$

which is shown as a dashed line in figure 4 using values of $L_2 = 300\ \mu m$, $L_3 = 100\ \mu m$ and $D = 1.16 \times 10^{-15}\ m^2 s^{-1}$ (9). This indicates that diffusion creep can readily account for the creep rates observed although the stress dependence is greater than the predicted linear relationship. This contribution by diffusion creep is clearly not subject to a threshold stress of similar magnitude as in dislocation creep.

The occurrence of diffusion creep in these alloys is of interest both from a technical and a scientific standpoint. Technically, the operation of an additional deformation mechanism in a specific loading direction increases the anisotropy in mechanical behaviour which must be accounted for in design since components are rarely subjected to conditions of uniaxial stress. In addition, the development of precipitate free (and presumably oxide dispersion free) zones leads to a locally weakened structure which may have deleterious effects on residual strength properties (10). A similar contribution by diffusion creep is expected to arise under tensile creep in the transverse direction; but as will be shown elsewhere (11) premature grain boundary failure limits the tensile strain achievable to low values at which diffusion zones do not become visible.

Scientifically this observation is of interest since diffusion creep has rarely been reported in particle hardened systems in stress and temperature ranges of engineering interest. The reason is that at low stresses diffusion creep tends to be inhibited or slowed down by the presence of particles on the grain boundaries, e.g. (12), while at higher stresses it is masked by power-law creep processes. In ODS alloys like the one studied here the particle dispersion acts to suppress power-law creep, even at moderate stress levels and high homologous temperatures at which diffusion rates are high. This effect increases the relative importance of diffusion creep and makes ODS alloys convenient materials in which to study deformation by diffusion creep.

Conclusion

Diffusion creep deformation occurs in the ODS superalloy INCONEL MA 6000 when creep tested in the transverse grain direction even though the material is coarse grained and possesses a highly elongated grain structure. This additional mechanism can give rise to considerable creep deformation at stresses below the "threshold stress" for dislocation creep in the longitudinal direction and should not be neglected in potential design applications.

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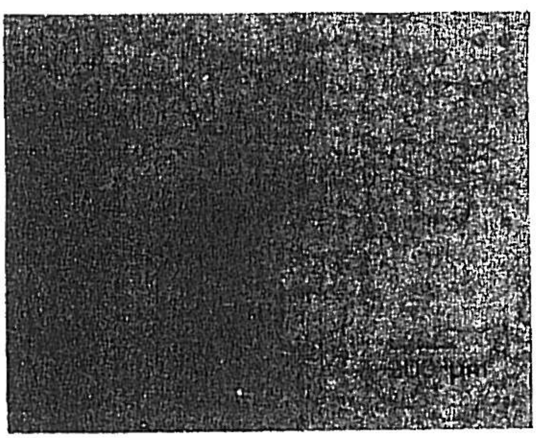

FIG. 1: As-received microstructure of MA 6000 in the transverse grain direction.

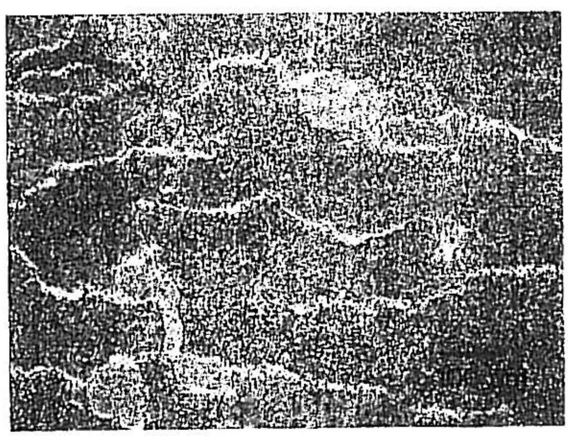

FIG. 2: Microstructure following compression creep at 1323 K and 120 MPa showing γ' free zones adjacent to grain boundaries parallel to the compression stress axis (horizontal).

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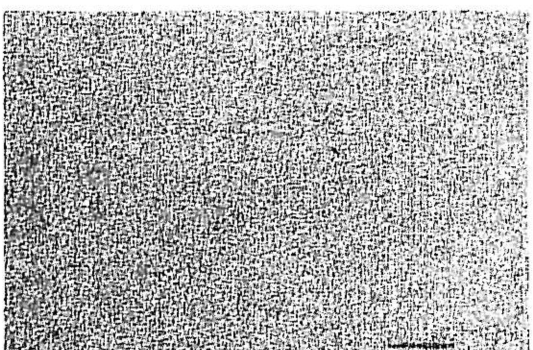

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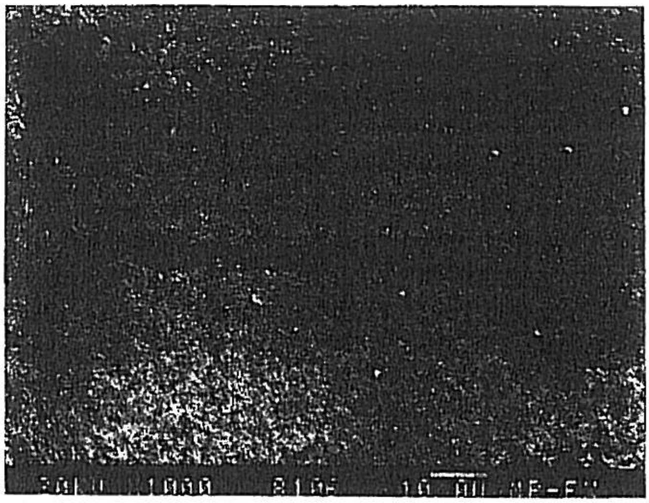


FIG. 3: SEM micrograph confirming that the zones adjacent to grain boundaries are free of γ'.

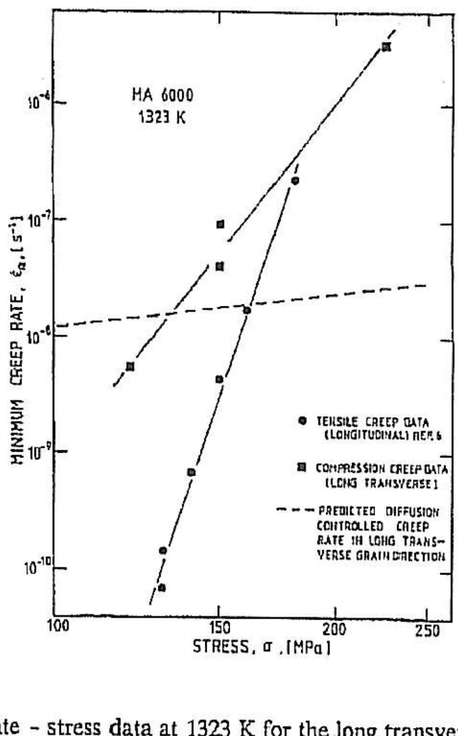
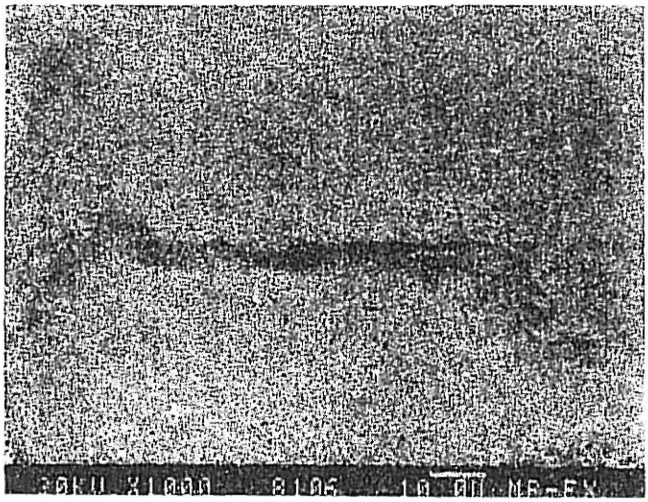


FIG. 4: Compression creep rate - stress data at 1323 K for the long transverse grain direction in comparison to the longitudinal direction. The dashed line shows the predicted diffusion creep rate.



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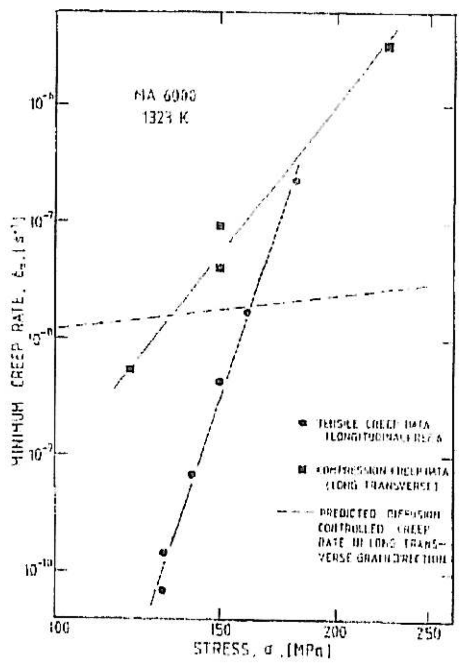

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