plastic flow around the short diagonal of the indenter. This is at variance with the hitherto held view that the geometry of the indenter resulted in predominantly elastic deformation adjacent to the short diagonal [10, 11].

(3) that the $\{h 0 \bar{h} l\}$ type of slip plane is more active during plastic deformation than the $\{h h \overline{2h} l\}$ type. This is deduced from the relatively higher rate of growth of the etch pit along the long or short diagonals of the indentation when these coincide with the $\langle 1 1 \bar{2} 0\rangle$ directions.

To the authors' knowledge this particular technique would appear to be a powerful means of studying the anisotropic distribution of stored plastic energy in brittle solids. However, further work is necessary to critically assess the application of the technique in examining the spatial distribution of plastic strain as a function of depth, load etc.

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The effect of environment on the creep and stress rupture behaviour of Rene 95

Previous work on Udimet 700 has indicated that an air environment could result in lower rupture life and ductility in specimens tested under conditions of creep and stress-rupture at elevated temperature [1]. Also, in cast Udimet 500, localized oxidation at grain boundaries due to the air environment has been found to play an important role in crack nucleation and propagation under conditions of elevated temperature low-cycle fatigue [2]. In addition to the above class of alloys, such effects have also been reported in steels, in which specimens tested in air were found to be prone to cavitation [3]. The present study was undertaken as a prelude to a detailed investigation of creep-fatigue interaction in Rene 95, which is a high strength nickel-base superalloy used primarily for compressor and turbine disc applications in advanced gas turbine engines. It was desired to obtain a clearer idea of the effects of air environment on the creep and stress rupture behaviour of Rene 95.

In addition to the conventional strengthening mechanisms involving precipitation of a high volume fraction of gamma-prime and, to a smaller degree, solid solution strengthening, Rene 95 derives part of its strength from the residual dislocation substructure introduced into the alloy during a thermomechanical processing treatment (TMT). This TMT is responsible for the duplex structure of Rene 95, referred to as the necklace structure, in which large warm-worked grains are surrounded by a necklace of very small recrystallized grains (Fig. 1). The necklace grains are very fine and are pinned by over-aged gamma-prime particles (Fig. 2). The warm-worked grains contain

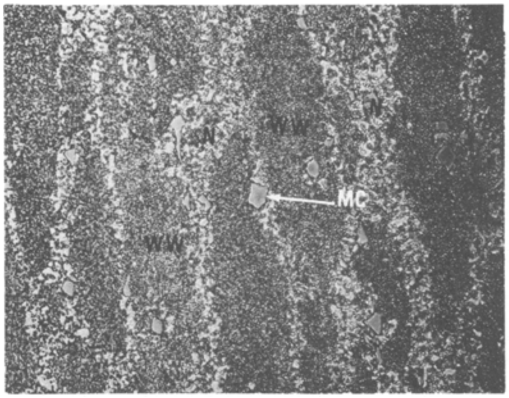

Figure 1 Optical micrograph of necklace Rene 95, X 400. WW – warm-worked grains, N – necklace region.

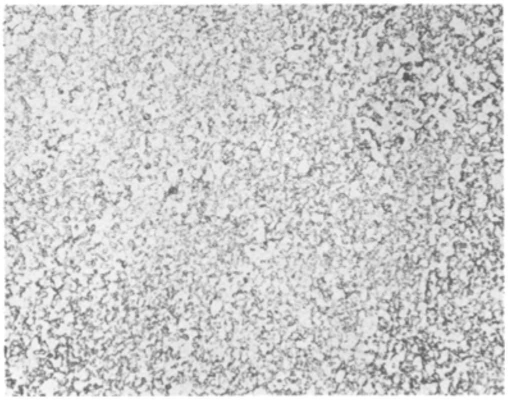

Figure 3 Optical micrograph of fine grained Rene 95, X 400.

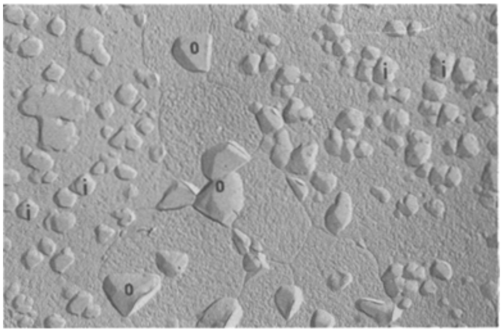

Figure 2 Replica micrograph of necklace region, X 6400. O – over aged gamma-prime, i – intermediate sized gamma prime.

the dislocation substructure which are in the form of cell networks anchored by the intermediate sized gamma-prime precipitate [4. 5]. The finest gamma-prime particles responsible for most of the strength, are uniformly distributed in the warm-worked and necklace grains.

Increasing the amount of work put into the material during the TMT increases the volume fraction of the necklace grains. Thus, it is possible to produce a structure which is fully recrystallized and fine grained (the grains having the same size as those in the necklace region shown in Fig. 1). Fig. 3 is an optical micrograph of such fine-grained Rene 95.

In the present study, both necklace Rene 95 (20% necklace, 80% warm-worked) and fine-grained Rene 95 were creep tested at 1200° F/ 150×10^3 psi (922 K, 1034 MN m^{-2}) (constant load test) in air and vacuum (10^{-6} Torr). The creep (elongation) strain as a function of time is shown in Fig. 4. Specimens tested in air showed higher minimum creep rates, shorter steady state creep periods and lower rupture lives. The uniform reduction in area at fracture for necklace Rene 95 in air and vacuum were 9.3% and 18.2% and those for fine grained Rene 95 were 4.4% and 9.9% respectively.

The fracture surfaces of the creep specimens of both necklace and fine-grained Rene 95 tested in air showed dictinctly two regions, one which was associated with the initiation and propagation of an intergranular crack initiated from the surface, while the other was associated with the overloaded region (Fig. 5). Further examination showed that the mechanism of fracture was influenced by environment. Fig. 6 shows a micrograph of a typical crack, originated from the surface, propagating through the necklace region. Many such cracks initiating from the surface indicated that air tested specimens were prone to surface cracking. MC carbides situated at the surface were seen to be oxidized and many cracks were seen to originate from the oxidized carbides. Besides the surface carbide oxidation, many carbides below the surface were also seen to be in the oxidized condition (Fig. 7). This effect was also noted in the results on fine-grained Rene 95, which has considerably smaller MC carbides. (The fine-grained Rene 95 was made from powder stock; the necklace Rene 95 was made from cast and wrought stock.) In contrast to the surface of the specimens, no such extensive cracking along the necklace regions were found in the middle of the specimens in spite of the fact that many carbides were found in a fractured condition as a result of

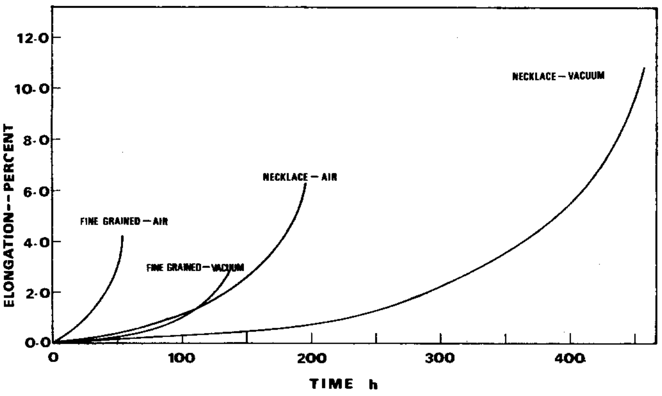

Figure 4 Creep curves of necklace and fine grained Rene 95 in air and vacuum.

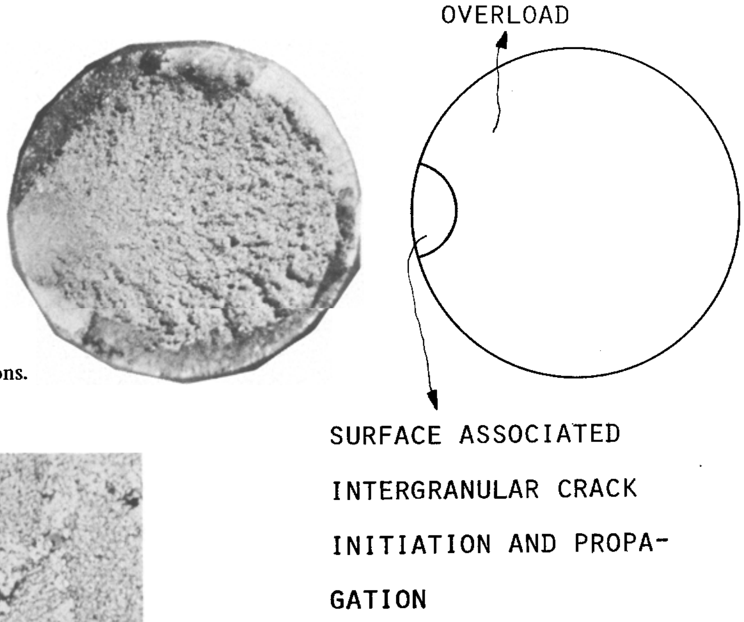

Figure 5 Fracture surface indicating intergranular cracking and overload regions.

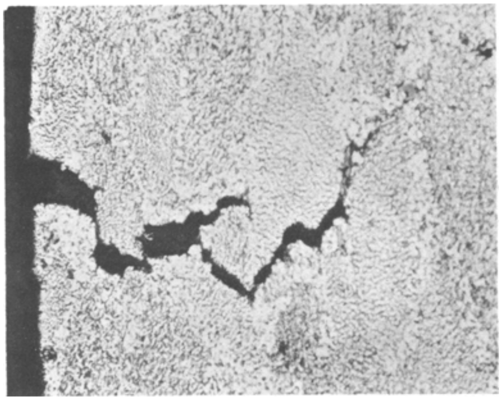

Figure 6 Surface cracking and propagation through the necklace region, × 400.

deformation (Fig. 8). However, the replica micrographs did show that microvoid formation had commenced in the specimen interior. Fig. 9 shows the SEM fractograph of a typical intergranular crack initiated from the surface in an air test. Since the initiation and propagation of the crack is in the necklace region of the microstructure, the crack path is quite wavy and rough as it assumes the tortuosity of the necklace around the elongated warm-worked grains.

In comparison, metallographic examination of specimens tested in vacuum showed that the surface was not prone to cracking any more than the inside of the specimen. Fig. 10 shows an optical micrograph of a specimen of necklace Rene 95 near the surface (longitudinal section) which shows no evidence of oxidation of the carbides. The interior of the specimen was found to have many cracks in the necklace region which were intergranular in nature (Fig. 11). Also the fracture surface showed no evidence of the propagation of a single crack; rather it was a mixture of intergranular plus dimple rupture (Fig. 12). Similar observations were noted for the fine grained Rene 95.

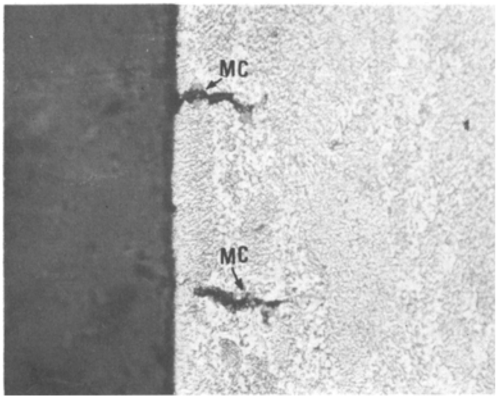

Figure 7 Crack propagating from an oxidized MC carbide situated below the surface, × 400.

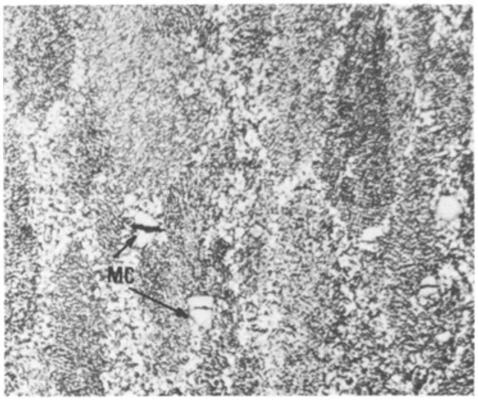

Figure 8 Fractured carbides in the middle of the air-tested specimens of necklace Rene 95, × 400.

Figure 9 SEM fractograph of intergranular fracture in necklace Rene 95, × 500.

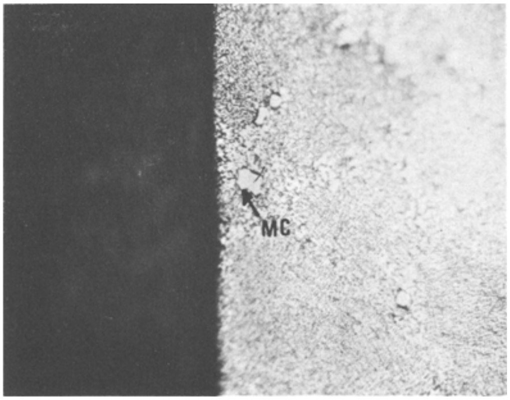

Figure 10 Optical of a longitudinal section of necklace Rene 95. Vacuum test, × 400.

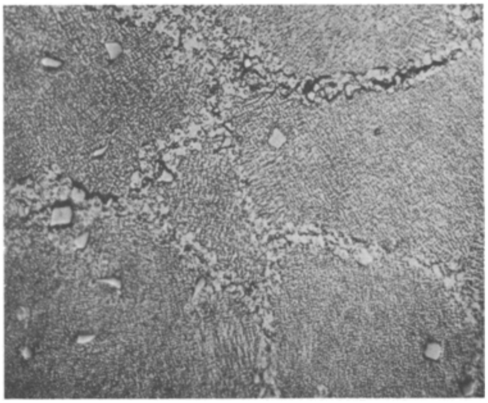

Figure 11 Intergranular cracking in the middle of the specimen – vacuum test, × 400.

Figure 12 Fracture surface in a vacuum stress rupture test. Necklace Rene 95, × 500.

The above results thus indicate that the inherent creep strength of Rene 95 can be realized only in vacuum and that the presence of an oxidizing environment causes premature fracture of creep specimens due to oxidation and accompanying surface cracking. The fracture of specimens tested in vacuum resembles classical creep rupture, with the reduction in cross-sectional area and the intergranular cracking accompanying creep deformation resulting in the material exceeding its tensile strength. On the other hand, fracture in the air environment resembles stress corrosion, with one single crack being responsible for the final failure. Our observations indicate that oxidation enhances crack nucleation and propagation at the grain boundaries

The higher life of necklace Rene 95 in air over that of fine-grained Rene 95 can be explained by the following: (a) the necklace Rene 95 has less grain boundaries exposed to the surface by virtue of its structure. Therefore, there is less area for crack nucleation. (b) more importantly, the necklace structure provides higher crack propagation resistance by forcing the crack to follow the necklace region, thus imparting a tortuosity to crack path.

Such environmentally induced surface cracking then contributes additional displacements to that measured in the longitudinal direction by the extensometer, which eventually shows up as higher creep rates in the creep curves (Fig. 4). The surface cracking also increases the stress supported by the remainder of the cross-section of the specimen in a constant load test at an earlier stage resulting in a shorter duration of secondary creep.

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