

THE EFFECT OF DIRECTIONAL RECRYSTALLIZATION ON THE LCF CHARACTERISTICS OF PM

NICKEL-BASED SUPERALLOY APK-6

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Abstract

The object of the present work has been to compare the elevated temperature fatigue characteristics of APK-6 manufactured by the direct extrusion of loose powder (DE/LP) with that which has been directionally recrystallized (DR). DE/LP material consists of 20 μm grains with high-angle boundaries containing massive γ' phase, whereas DR has a $\langle 110 \rangle$ fibre texture of low-angle longitudinal boundaries, which are not associated with coarse γ' precipitation.

LCF tests were conducted with $R = -1$ at 300, 500 and 700°C on the DE/LP material, and DR material has been tested at 700°C. It is shown that the elastic strain amplitude dominates the fatigue life over most of the data, arising from the combination of high yield strength and low ductility exhibited by these materials.

The DE/LP material showed prolific subsidiary grain boundary cracks. The main fracture was predominantly transgranular in character, however, lying parallel to active slip bands. The DR material fails wholly transgranularly, with the fracture appearing to nucleate on intense slip bands. It is suggested that, due to the coarse grain size, crack nucleation occurs after fewer cycles in DR than in DE/LP material, but propagation to final failure is slower due to the longer, highly serrated crack profile imposed by the grain dimensions. The result is that the total LCF lives of the two microstructures are comparable at 700°C.

Introduction

The PM superalloy APK-6 has been developed for the rear row blades of industrial gas turbines. The alloy possesses a creep rupture strength superior to that of the casting alloy IN-792 in the temperature range 650°C-750°C, together with 2½ times the fatigue resistance of IN-738 at 650°C. Shaw (1) gives details of the development of the material.

Creep fracture and thermal fatigue failures in alloys that have equiaxed grain structures are almost always associated with grain boundaries that are transverse to the applied stress. Versnyder and Shank (2) have reasoned that by alignment of the grain boundaries parallel to the principal stress direction (i.e. producing grains elongated parallel to the stress axis), grain boundary fracture might be inhibited and ductility increased.

Zone annealing (gradient annealing) has been successfully used in APK-6 to produce grains of high aspect ratio, and their crystallographic texture has been identified (3). The object of the present work has been to compare the elevated temperature fatigue characteristics of the material manufactured by the direct extrusion of loose powder (DE/LP) with that which has been directionally recrystallized (DR).

Experimental Materials and Methods

The composition (wt %) of APK-6 is as follows:

C(0.03)-Cr(12.5)-Co(9.0)-Mo(2.0)-W(3.9)-Ta(4.6)-Al(3.4)-Zr(0.1)-B(0.01)-balance Ni

The material studied (supplied by INCO Alloys Ltd.) was in the form of 16 mm diameter bars produced by the direct extrusion of loose powder (DE/LP). One set of specimens were zone recrystallized by passing through an induction coil at a controlled speed, achieving a maximum temperature of 1220°C, which is above the γ' solvus temperature (1205°C) of the alloy.

Both as-extruded and zone annealed bars were given the following heat-treatment: 2 h at 1230°C, furnace cool at 3° min⁻¹ to 1195°C, air cool, 24 h at 650°C, air cool and 8 h at 760°C air cool.

Cylindrical LCF testpieces were machined having a gauge length of 10 mm and a gauge diameter of 5 mm. LCF tests were carried out at a constant strain rate of $5 \times 10^{-3} \text{ s}^{-1}$, which defined an upper test frequency of 0.5 Hz, corresponding to a minimum strain range of 0.5%. Tests were conducted under strain control to define a curve between 10^2 and 5×10^4 cycles, carried out in accordance with ASTM E606-80.

Experimental Results

1. Characterization of Microstructure

In DE/LP material the matrix grains are equiaxed and of average diameter 20 μm as shown in Figure 1. There is a duplex dispersion of the γ' phase, with coarse angular particles in the grain boundaries.

In DR material, zone annealing has resulted in the formation of grains of high aspect ratio of width of approximately 1 mm. Figure 2 shows that a duplex γ' distribution is again present, but the longitudinal boundaries do not contain the coarse angular particles present in the DE/LP material. As described in Reference (3), a DR specimen was scanned in a STEM, and a Selected Area Channelling Pattern (SACP) generated for each grain across the section. It was shown that in every case the longitudinal axis of the grains was close ($\pm 5^\circ$) to $\langle 110 \rangle$, so the longitudinal boundaries are essentially of tilt character.

2. LCF Tests

DE/LP Material. In order to establish the LCF characteristics of the conventional APK-6, tests have been conducted at 300°C, 500°C and 700°C with $R = -1$. The resultant data are shown in Figure 3 in the form of total strain range versus number of load reversals to failure (taken as a 20% fall in the saturation stress).

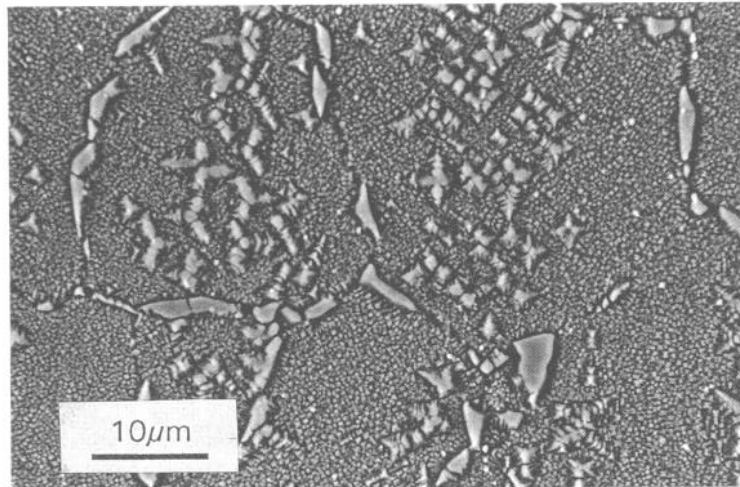


Figure 1 - SEM micrograph of etched section of heat treated DE/LP material.

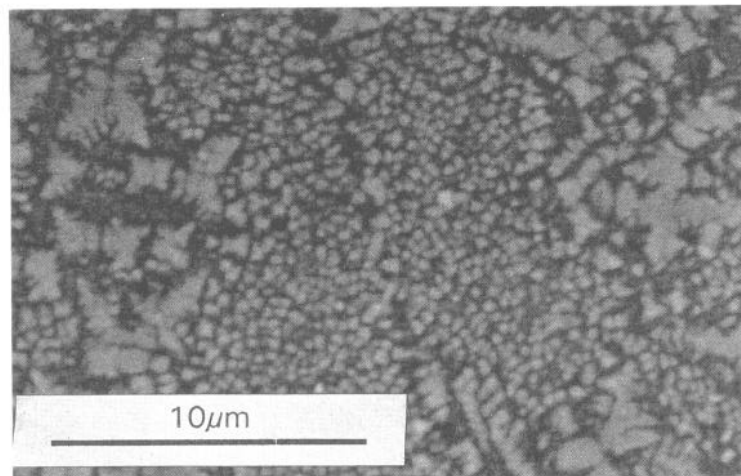


Figure 2 - SEM micrograph of etched section of heat treated DR material.

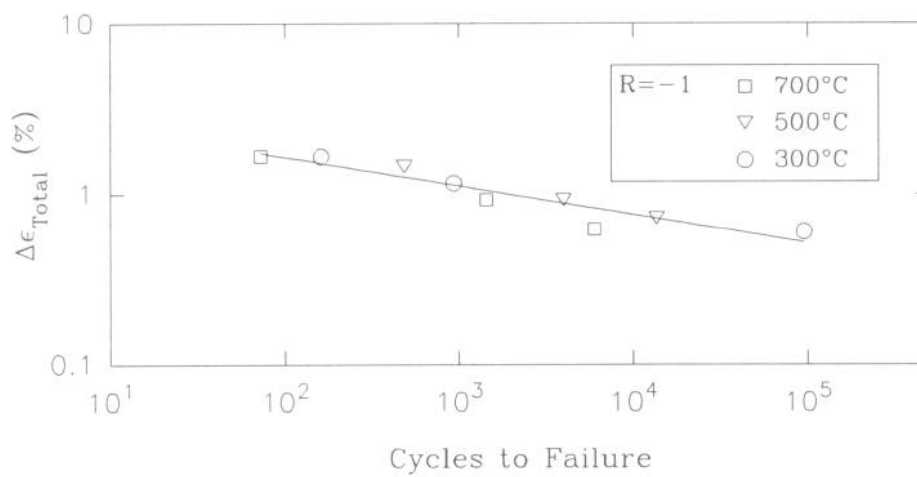


Figure 3 - LCF characteristics of DE/LP material.

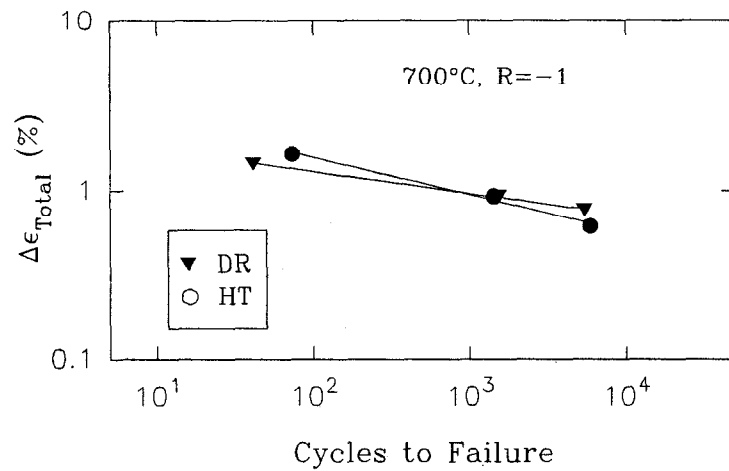


Figure 4 - Comparison of LCF responses of DE/LP and DR materials.

Directionally Recrystallized (DR) Material. LCF tests have been conducted at 700°C, and the results are compared with those from the DE/LP material in Figure 4. It is seen that at this temperature there is little significant difference between the curves of total strain range vs. cycles to failure for the two microstructures.

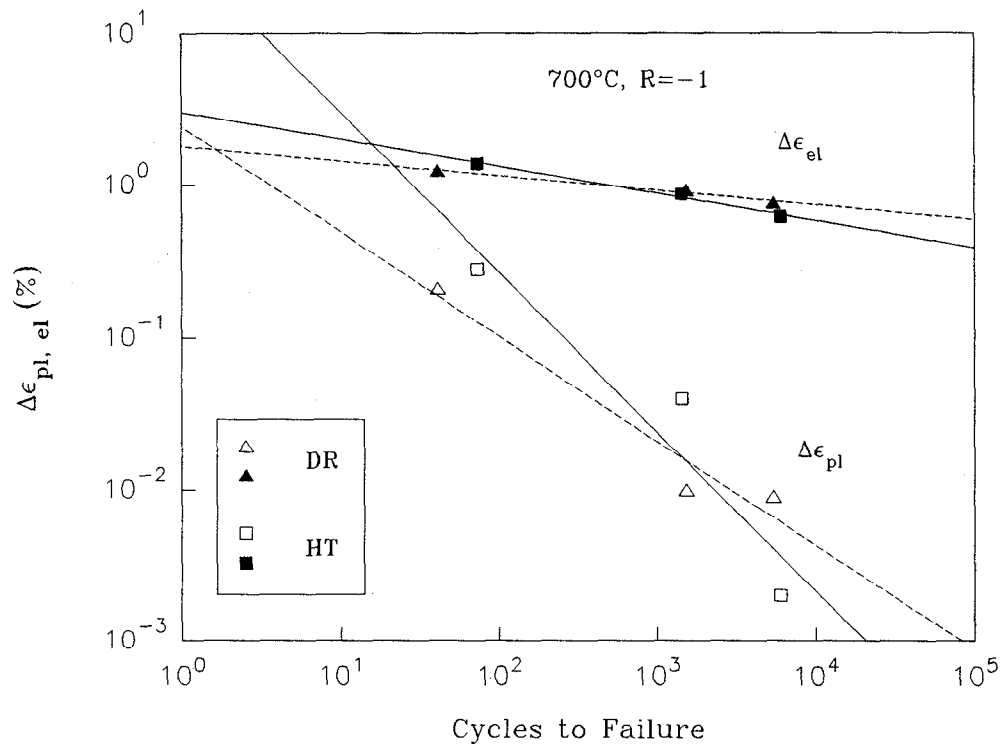


Figure 5 - Data of Figure 4 showing elastic and plastic strain components.

Figure 5 illustrates the data of Figure 4 when the total strain range ($\Delta\epsilon_{tot}$) is separated into the elastic ($\Delta\epsilon_{el}$) and the plastic ($\Delta\epsilon_{pl}$) strain components. It is seen that, apart from the tests giving very short lives, the LCF behaviour is dominated by $\Delta\epsilon_{el}$. The dominant effect of $\Delta\epsilon_{el}$ occurs at shorter lives in

the DR material than in the DE/LP material.

Suresh (4) points out that it is useful to consider a transition life, which is defined as the number of reversals to failure at which the elastic and plastic strain amplitudes are equal. At short fatigue lives, plastic strain amplitude is more dominant than the elastic strain amplitude and the fatigue life is controlled by ductility. When, at longer fatigue lives, the elastic strain amplitude is more significant, the fatigue life is dictated by the fracture strength.

As pointed out by Plumbridge and Ellison (5), this pattern of behaviour is characteristic of many superalloys, and it may be attributed to their possessing a combination of a high yield strength and a low ductility at elevated temperatures.

3. Metallography of Fracture.

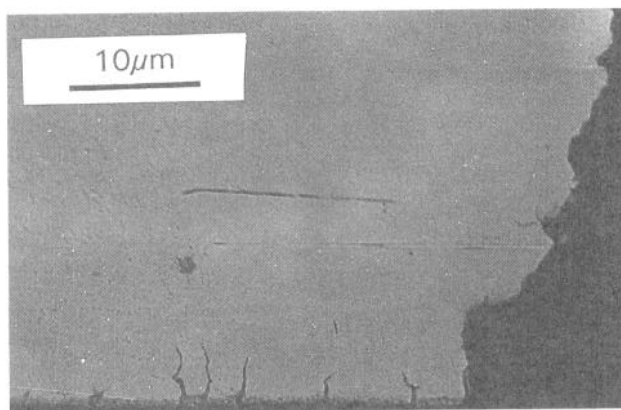


Figure 6 - Optical micrograph showing secondary cracking in DE/LP material.

DE/LP Material Figure 6 is an optical micrograph of a longitudinal section through the fracture surface formed at 700°C in the DE/LP material. Prolific subsidiary grain boundary cracks are observed to be propagating from the surface, but the main fracture is seen to propagate transgranularly.

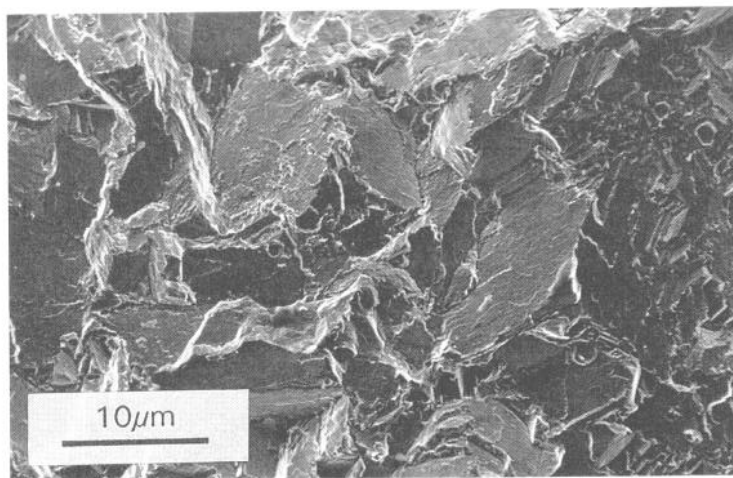


Figure 7 - SEM fractograph of DE/LP specimen.

Figure 7 is an SEM image of the fracture surface which is seen to be highly faceted on a scale comparable with the grain size.

Figure 8 is an SEM image of an etched longitudinal section, showing one of the subsidiary surface cracks visible in Figure 6 at higher magnification. After being nucleated at a grain boundary, the propagation is seen to be transgranular. Figure 9 illustrates the tip of a subsidiary crack in this

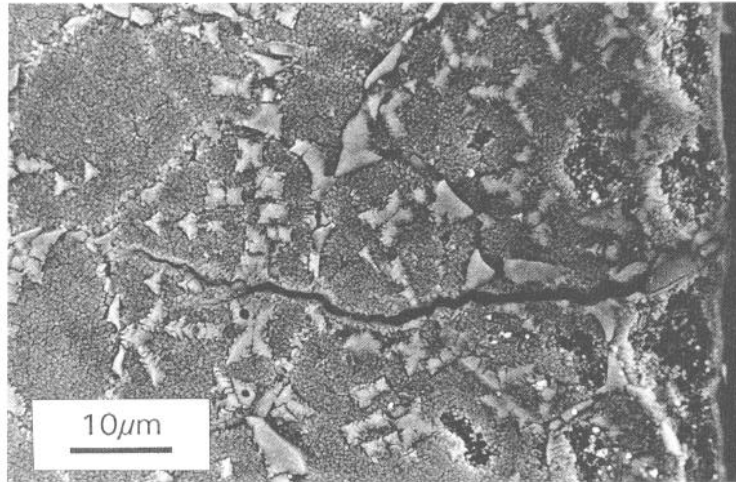


Figure 8 - SEM micrograph showing change in crack propagation path in DE/LP specimen.

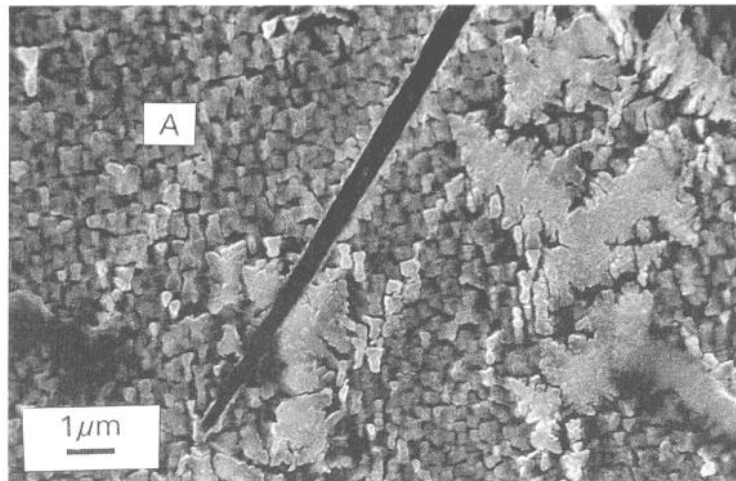


Figure 9 - SEM micrograph showing crack lying parallel to slip band (A).

material: lying parallel to the crack is an intense slip band (A), in which shearing of the γ' particles can be discerned. It therefore appears that, having nucleated in the grain boundaries, the crack propagates on shear bands in the material.

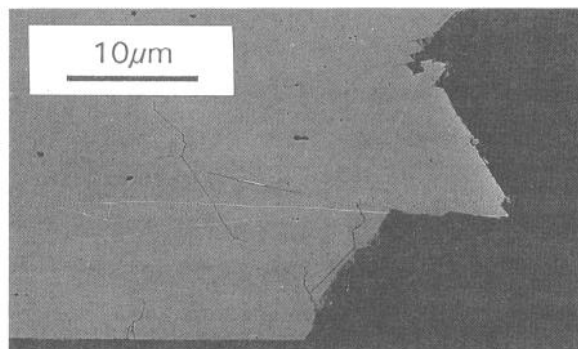


Figure 10 - Optical micrograph of DR fracture profile.

DR Material Figure 10 is an optical micrograph of a longitudinal section through the fracture surface of a DR specimen. The crack surface is seen to be highly serrated, and the propagation path appears to be crystallographic. Figure 11 is an SEM fractograph which suggests a similar mechanism to that

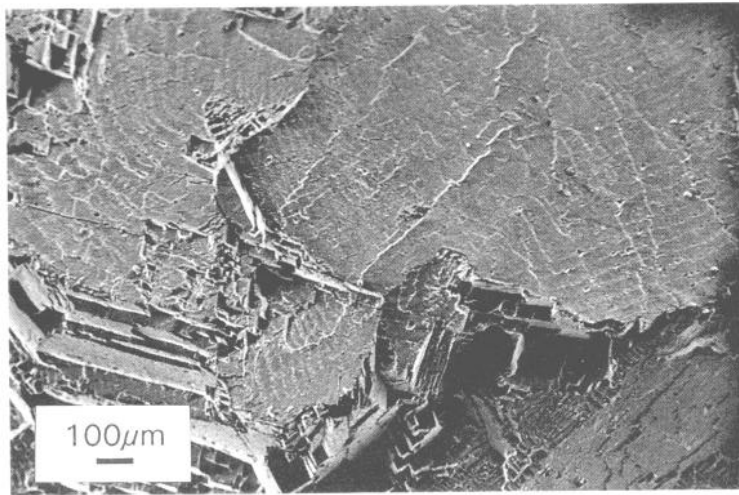


Figure 11 - SEM fractograph of DR specimen.

illustrated in Figure 7 for DE/LP material, but of a much coarser scale because of the increased grain size.

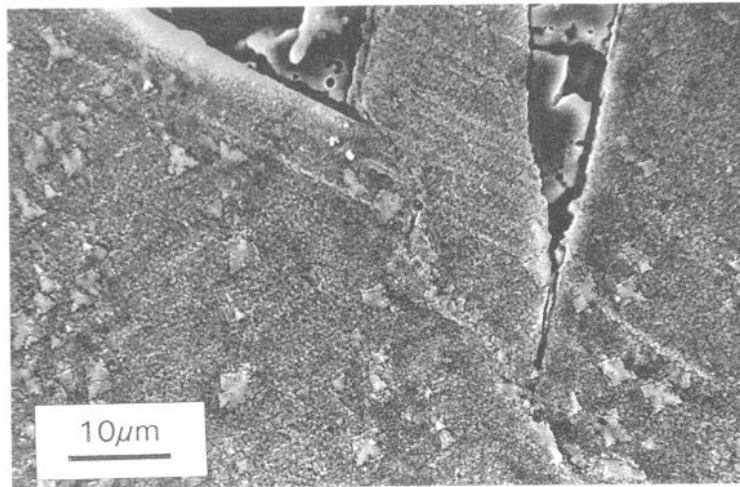


Figure 12 - SEM micrograph of DR fracture profile.

Figure 12 is an SEM image of an etched longitudinal section showing part of the (nickel-plated) fracture surface. The size of the γ' precipitates in the grain boundary is clearly much finer than that in DE/LP material (Figure 8). Some slip bands are visible, and part of the fracture surface is seen to lie parallel to these.

Discussion and Conclusions

The data of Figure 4 suggest that the profound change in microstructure brought about by directional recrystallization has no influence on the LCF characteristics of APK-6 at 700°C. Closer inspection reveals that this is not so, and when the elastic and plastic strain ranges are considered separately, as shown in Figure 5, it is obvious that ϵ_{el} dominates the LCF response in DR material after fewer cycles than in DE/LP material. This observation suggests that the fatigue cracks nucleate earlier in DR material than in DE/LP material.

The cracks appear to be slip-band nucleated in DR material, and this may not be unexpected in view of the very coarse grain size. This provides a long slip band length, and thus a large displacement per band.

Crack nucleation in DE/LP material is seen to be intergranular. The grain boundary structure of the DE/LP material differs significantly from that of the

DR material. In the former the fine grains are separated by high-angle boundaries, and within these it is apparent from Figure 1 that they are decorated by a coarse, dense array of γ' particles. Cracks are observed to nucleate at these boundaries (Figure 8), and it is suggested that this occurs at a point where a slip band impinges on the boundary. In view of the very fine grain size of DE/LP material in comparison with the DR material, the slip band length and hence the local shear displacement per band will be less, and it is reasonable to expect that crack nucleation will take a greater number of strain cycles than in DR material.

Since the total lifetime of DE/LP and DR materials are comparable, if the cracks nucleate earlier in DR material they must thereafter propagate more slowly. In both alloys the propagation path is along slip bands, and comparison of Figures 6 and 10 shows that for the DE/LP material the fine grain size allows the crack propagate macroscopically normally across the diameter of the test-piece, with frequent local changes in direction as it passes from grain to grain. The DR specimen again fails by stage I crack growth, but since the grain size is so large, serrations of large amplitude are developed. The total crack length is thus much greater than in the DE/LP specimen, so that the time spent in propagation (by the same mechanism) will inevitably be increased.

The results may thus be summarized by the following conclusions:

1. Directional recrystallization does not appear to affect the LCF life of APK-6 at 700°C.
2. In DE/LP material the grain boundaries contain coarse precipitates of γ' -phase. The fatigue cracks nucleate intergranularly, and propagate transgranularly along slip bands.
3. In DR material the grain boundaries are essentially of tilt character, and contain a finer γ' precipitate than DE/LP material. Both the nucleation and the propagation of fatigue cracks are associated with slip bands, giving rise to a serrated fracture path whose scale is dictated by the very large grain size.

References

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