LOW CYCLE FATIGUE BEHAVIOUR OF NIMONIC PE 16 AT TEMPERATURES
UP TO 650° C

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SYNOPSIS:
Cyclic stress response of a nickel base alloy Nimonic PE 16 has been in­
vestigated in two initial microstructural conditions. Strain controlled,
fully reversed tests under low cyclic fatigue (LCF) loading were conduc­
ted at temperatures up to 650° C. Dislocation arrangements , densities
and mechanisms of interaction with particles have been investigated with
the help of transmission electron microscopy ( TEM ). The deformation
behaviour is interpreted in terms of the microstructural observations.

Notation:

- \( d \) Average diameter of ordered \( \gamma' \) particles in nm
- \( T \) Test temperature in \( ^\circ \) C
- \( \varepsilon \) Strain rate in \( s^{-1} \)
- \( \Delta \varepsilon_t \) Total strain range in %
- \( \Delta \varepsilon_p \) Plastic strain range in %
- \( \Delta \varepsilon_{p_{\text{min}}} \) Minimum plastic strain range in %
- \( \Sigma \Delta \varepsilon_p \) Cumulative plastic strain in %
- \( \Delta \sigma_{\text{max}} \) Maximum stress range in MPa
- \( \rho \) Dislocation density in \( \text{cm}^{-2} \)
- \( N \) Number of cycles
- \( N_f \) Number of cycles to failure

Introduction:
Deformation behaviour of the Nickel base alloy Nimonic PE 16 has been
studied in recent years by many investigators. Most of the existing work
on this alloy is summarised in ref. (1) . These investigations are essen­
tially concerned with the tensile (2,3) and creep (4,5) behavior of the
alloy . In earlier investigations of age hardened alloys under cyclic
loading , formation of persistent slip bands (6,7) and a pronounced sof­
tening in some cases have been reported ( 8-10 ) both in single crystal
and in polycrystalline materials . A detailed study of the deformation
and fracture behaviour of Nimonic PE 16 and its correlation with the
evolving microstructure under different loading modes is presently under
way in our laboratories . In the present paper we report the results on
the LCF behaviour.

Experiment:
The alloy was heat treated to produce two different average sizes of the
ordered \( \gamma' \) precipitates i.e. , \( d = 21 \) and 30 nm respectively with a con­
tant volume fraction of 7 %. These sizes correspond to slightly under
and over aged conditions respectively at room temperature (3). Fully re­
versed axial strain controlled LCF tests were conducted at room tempera­
ture, 4000 , 5000 and 650° C employing strain rates of \( 4.10^{-3} \) and
\( 4.10^{-5} \) s\(^{-1} \). Total strain range was kept constant during a test . Five
different \( \Delta \varepsilon_t \) in the range of 0.88 % to 5 % were employed . \( \Delta \varepsilon_p \) chanc­
ged slightly from cycle to cycle. The values used in the Coffin – Manson
plots are $\Delta \varepsilon_p\min$, the minimum value corresponding to $\Delta \varepsilon_{\text{max}}$. All the tests were conducted in air. Microstructural development due to deformation was characterised with the help of TEM.

Results:
In this paper the results of the tests only at 500°C and 650°C are reported since the behaviour at 500°C is essentially representative of that at the lower temperatures.

An example of the cyclic stress response of the two initial microstructural states is shown in Figs. 1 and 2. Materials in both the states first harden to a maximum value of stress, $\Delta \varepsilon_{\text{max}}/2$, then the under aged material begins to soften whereas the over aged one continues to deform at nearly constant $\Delta \varepsilon_{\text{max}}/2$ before a rapid fall in the stress due to initiation and growth of cracks in both the materials. A similar difference in their behaviour was found also at other combinations of $T$ and $\varepsilon$ used in this study, but not shown here due to lack of space. An example of the influence of $T$ and $\varepsilon$ on the cyclic stress-strain behaviour is shown in Fig. 3. The extent of hardening in all the cases increases with increasing strain amplitude. For a given $\Delta \varepsilon_p$ the extent of hardening is larger at the lower test temperature of 500°C than that at 650°C. The influence of $\varepsilon$ on the cyclic strength at 650°C is large and positive whereas that at 500°C is relatively small and negative.

The TEM studies showed that deformation at small $\Delta \varepsilon$ is inhomogeneous, being essentially concentrated in planar slip bands parallel to $\{111\}$ planes of the matrix and the interband regions being relatively free of dislocations. The density of these bands increased with increasing $N$. The dislocation arrangement within the bands was made visible by suitable tilting of the specimens in TEM. An example of the average density of dislocations in the slip bands, based on at least four measurements for each average value, and the morphology of the corresponding slip bands is shown in Fig. 5. The deformation in both the states was found to become increasingly homogeneous at higher $T$, $\Delta \varepsilon$, and lower $\varepsilon$. In the under aged material paired dislocations were always observed in the beginning of deformation indicating shearing of the ordered $\gamma'$ precipitates. With increasing cumulative strain the number of paired dislocations decreased and became negligible at larger $\Sigma \Delta \varepsilon_p$ and Orowan loops appeared around $\gamma'$ precipitates (Fig. 6). However, in the over aged material Orowan loops were observed under all the test conditions.

Figure 4 shows an example of the fracture life of the over aged material as a function of $\Delta \varepsilon_p\min$. Within the accuracy of measurements, no appreciable difference was observed in the fatigue life of the under and over aged materials tested under identical conditions.

Discussion:
Our observation of Orowan mechanism during cyclic loading of the over aged material, even in beginning of its deformation, is consistent with that made under tensile loading at those temperatures in our laboratory. These observations are, however, in contrast to those made under tensile loading at room temperature, where shearing of $\gamma'$ precipitates ($d=30\text{nm}$) by dislocation pairs has been reported (3). We have estimated the threshold stresses for the two mechanisms according to the modified approach discussed in ref. (3) and using temperature dependent dislocation line energy. These calculations show that for temperatures of 500°C and above, Orowan stress for the over aged material is smaller than the stress for weak dislocation pair cutting and is approximately equal to that for weak dislocation pair cutting in the under aged material.