FRACTURE OF SINGLE CRYSTAL SUPERALLOYS UNDER CYCLIC LOADING AT HIGH TEMPERATURES

H. Frenz*, J. Kinder*, H. Klingelhöffer*, P.D. Portella*

The LCF-behaviour of two single crystal superalloys developed as blade materials for the use in aircraft engines, *viz.* SRR99 and CMSX-6, was investigated at 980°C. Special attention was given to the influence of hold periods at either the maximum (tension phase) or the minimum (compression phase) strain level. The introduction of a hold period in the compression phase led for both alloys to a pronounced reduction of the cycle number for crack initiation. This reduction was accentuated by reducing $\Delta\epsilon_t$. On the other hand, the influence of a hold period in the tension phase on N_A was much less pronounced. The evolution of the γ/γ'-microstructure and the fracture mechanisms characteristic for the different loading conditions were investigated using mainly SEM.

INTRODUCTION

Under normal service conditions, gas turbine blades are subjected to very complex stress-strain-temperature loading cycles in a non-inert environment. The identification of the predominant damage mechanisms requires careful testing under controlled conditions. In this sense, the introduction of more realistic thermal-mechanical fatigue testing contributes to a better understanding of the material behaviour in real blades (1). However, the high costs of such complex tests and the difficulties in interpretating their results keep a living interest in isothermal low-cycle fatigue testing (1,2). In this work we present some results concerning the LCF-behaviour of single crystal nickel-base superalloys with and without hold periods. Due to their relatively simple microstructure, single crystal superalloys permit a more detailed investigation of the microstructural modifications as well as of the fracture mechanisms and how they depend on cyclic loading.

*Federal Institute for Materials Reserach and Testing (BAM), Berlin, Germany

EXPERIMENTAL DETAILS

The specimens were cast by Thyssen Guß AG in Bochum, Germany, using a high gradient DS/SX-furnace. Six specimens were produced in each run by using helix selectors. The chemical composition of each master charge as determined by X-ray spectrometry or atomic absorption spectrometry is given in Table I. The heat treatment consisted of a multi-step solution treatment followed by a two-step ageing treatment according to the standard specification of each alloy.

TABLE 1 Chemical composition of the master charges (Mass fractions in %)

Alloy	Ni	Cr	Al	Ti	Mo	W	Co	Ta	others
SRR99	66.05	8.53	5.57	2.22	0.03	9.53	5.03	2.85	0.18
CMSX-6	70.48	9.76	4.78	4.68	3.00	0.03	5.02	2.08	0.17

TABLE 2 Microstructural parameters of the specimens after the standard heat treatment

<table>
<tr><th rowspan="2">Alloy</th><th colspan="2">γ'-phase</th><th colspan="2">porosity</th><th>γ/γ'-eutetics</th></tr>
<tr><th>V_V in %</th><th>edge length in μm</th><th>V_V in %</th><th>maximal feret in μm</th><th>V_V in %</th></tr>
<tr><td>SRR99</td><td>60</td><td>0.52</td><td>< 0.5</td><td>15</td><td>< 0.1</td></tr>
<tr><td>CMSX-6</td><td>62</td><td>0.57</td><td>< 0.5</td><td>10</td><td>2</td></tr>
</table>

The resulting microstructure consisted of a monomodal distribution of cuboidal γ'-particles for both. Table II summarizes the microstructural parameters. Metallographic specimens were conventionally prepared paying attention to the orientation of the specimen surface and by using etchant solutions which preferentially etched the γ'-phase. SEM was used to observe the γ/γ'-microstructure. The problems with the determination of the γ' volume fraction based on the measurement of the area fraction in etched metallographic specimens at the SEM were discussed elsewhere (3). The angle between the specimen symmetry axis and the [001] direction, χ, varied between 2° and 8° with a median of 5°. The specimens used in the mechanical tests had a total length of 115 mm and a gauge length of 26 mm with 9 mm diameter. Their final shape was given by circumferential grinding. Mechanical testing was carried out using closed loop system, computer assisted servohydraulic or electromechanical systems with a load capacity of 100 kN. The specimen grips were specially developed and allow a precise axial loading in both tension and compression (4).

The tests were carried out with uncoated specimens in air under total strain control with a triangular waveform ($R_\epsilon = -1$). The absolute value of the strain rate was in most experiments 10^{-3} s^{-1}, some results for 10^{-5} s^{-1} are also available. Hold periods of 300 s were introduced at either the maximum or the minimum strain level and are represented as t_t and t_c respectively. The specimen lifetime, N_A, was determined through a macroscopic crack initiation criterion (1 % deviation) from the diagram total stress range *versus* cycle number.

MECHANICAL BEHAVIOUR

Figure 1 shows the dependence of the cycle number for crack initiation, N_A, on the total strain range, $\Delta\epsilon_t$, for SRR99 at 980°C. This log-log-diagramm shows the results of LCF tests without hold periods (▲), with hold periods of $t_t = 300$ s at the maximum tensile strain (□) or with hold periods of $t_c = 300$ s at the maximum compressive strain (⊠). For the sake of simplicity, the results for these three loading types were connected by straigth lines, which do not involve any theoretical consideration. The introduction of a hold period in the compressive phase led in comparison to the tests without hold periods to a drastic reduction in N_A up to one order of magnitude in the range investigated. On the other hand, the introduction of a hold period in the tensile phase led to a moderate reduction in N_A for large values of $\Delta\epsilon_t$, whereas for lower values of the total strain range an increase in lifetime was observed. The mean stress during tests without hold periods was less than 1% of the total stress range. The introduction of hold periods in the compressive phase led to a shift of the hysteresis loop in the tensile region, so that the mean stress reached values of about 15% of the total stress range after few cycles and kept approximately constant up to N_A. The inverse tendency was observed for tests with a hold period in the tensile phase. The total stress ranges for tests with the same value of $\Delta\epsilon_t$ was nearly independent of the specific cycle waveform. Similar results were found for CMSX-6 (5).

FRACTURE MECHANISMS

The light micrographs in Figure 2 show the evolution of the damage mechanism under LCF loading without hold times. The formation of a complex oxide layer (mainly containing chromium and aluminium) after few cycles depletes a surface near region, resulting in a γ'-free layer. Both layers grow steadily with increasing value of N, but at some preferential sites distributed homogeneously over the specimen surface, the formation of nickel oxide speeds up. At these sites we observe protusions on the surface, under which small cracks perpendicular to the specimen axis are hidden. The initial stages of damage under LCF loading with hold periods are identical. However, the behaviour of the surface cracks after being formed changes radically in these cases. With hold periods in the compressive phase, the surface cracks stop growing laterally at some point. Sharp inclined cracks are generated at their extremities, some of them grow more rapidly and determine the rupture. The fracture surface consists of two or more inclined surfaces which are nearly ((111)) oriented. With hold periods in the tensile phase, surface cracks do form but did not lead to failure. Instead of them, cracks originating from bulk pores grow and become predominant. The surface fracture is nearly plane and perpendicular to the specimen axis but it shows typical features of creep fracture in these alloys. In the two other loading types we did not observe any damage at the bulk pores.

DISCUSSION

The evolution of the γ/γ'-microstructure in single crystal superalloys is classically considered to be a diffusional process which depends strongly on the misfit between the γ and the γ' phases as well as on the applied stress (6). Our results concerning the evolution of the γ/γ'-microstructure in SRR99 and CMSX-6 under LCF loading with hold periods are in accordance with this approach (5). Both alloys have a negative misfit and show platelets perpendicular to the specimen axis when hold periods are introduced in the tensile phase, since in this case the specimen was submitted the far most long time to a tensile stress. *Mutatis mutandis* they present platelets parallel to the specimen axis when the predominant stress is compressive. When considering the LCF behaviour of superalloys, hold periods in the compressive phase are more damaging than those in the tensile phase, which is usually associated with the high mean stress levels resulting from asymmetric loading (2). The single crystal superalloys SRR99 and CMSX-6 show at 980°C the same behaviour as reported in the literature. However, the shift in the mean stress seems to be connected with the changes observed in the γ/γ'-microstructure and the consequent formation of internal stresses. The radically different fracture mechanisms observed under these loading types are currently being investigated in more detail. We expect to derive from these investigations more concrete clues to the behaviour of superalloys under cyclic loading.

ACKNOWLEDGEMENTS

This work was supported by the *Bundesministerium für Bildung und Forschung* (03 M3038 D). We are grateful for the experimental support given by Bärbel Bogel, Uwe Chrzanowski, Klaus Naseband and Jörg Wuttke.

References

(1) Ziebs, J., Meersmann, J., Kühn, H.-J., Hülsmann, N. and Olschewski, J., Proceedings of the 4th International Conference on Biaxial/Multiaxial Fatigue, vol. 2, (European Structural Integrity Society, 1994), 247-259.

(2) Plumbridge, W.J. and Ellison, E.G., Materials Science and Technology 3(9)(1987), 706-715.

(3) Portella, P.D., Breitkreutz, K. and Bierwagen, V., Sonderbände der Praktischen Metallographie, vol. 23, ed. W.-U. Kopp et al. (Munich, BY: Carl Hanser Verlag, 1992), 93-106.

(4) Naseband, K., Ledworuski, S., Kühn, H.-J. and Frenz, H., Proceedings of the 6th International Fatigue Congress 1996 (London: Elsevier Applied Science, in press).

(5) Frenz, H., Kinder, J., Klingelhöffer, H. and Portella P.D., Proceedings of the 8th International Conference on Superalloys, Seven Springs, USA, 1996, in press.

(6) Pineau, A., Acta metall. 24 (1976), 559-564.

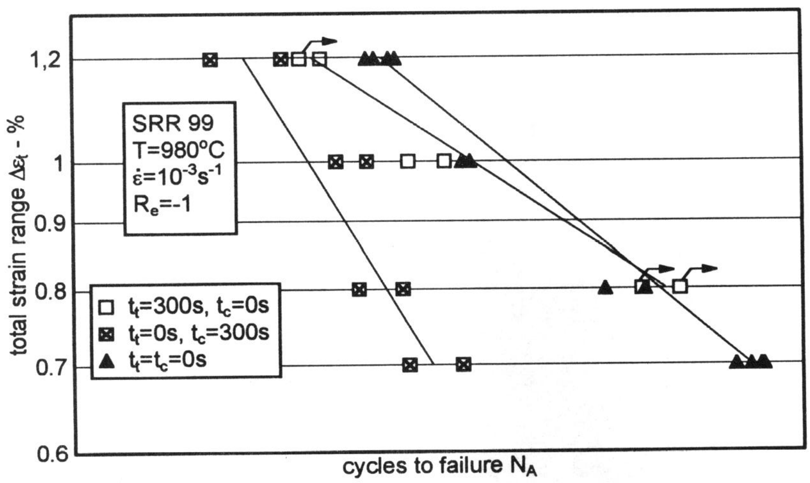

Figure 1 LCF-test results of SRR 99 at 980 °C

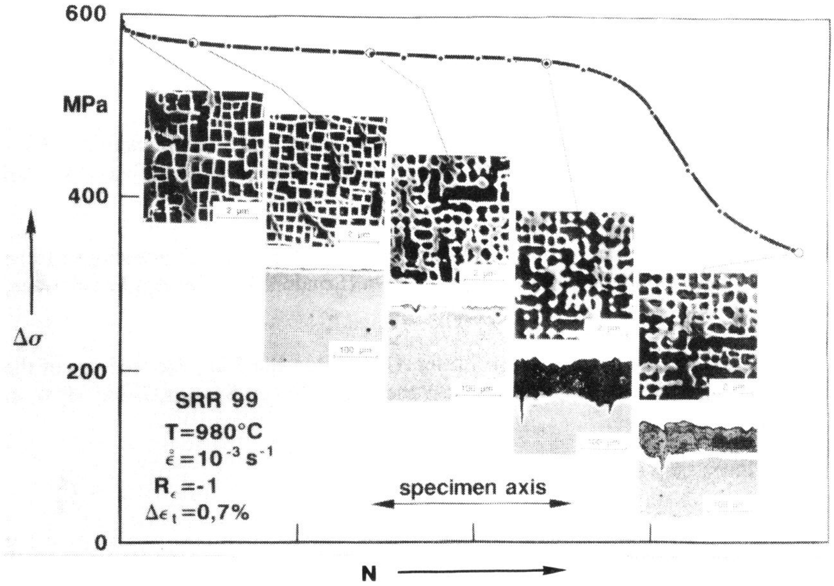

Figure 2 Microstructural evolution of SRR 99 during LCF-tests

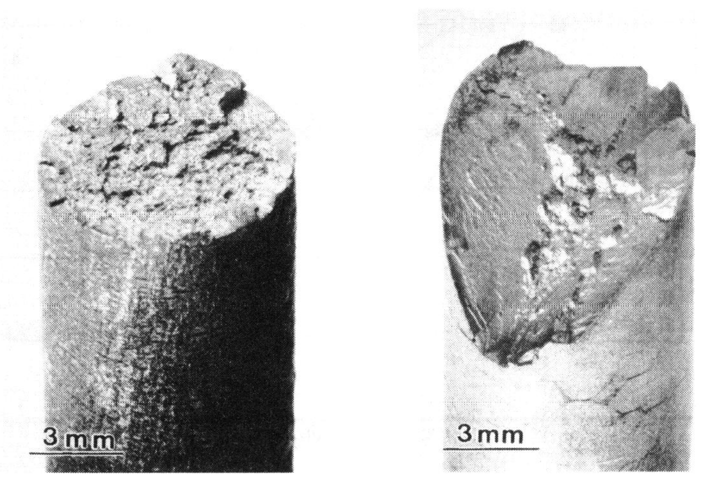

Figure 3 Fracture surfaces of SRR 99 at 980 °C, left: hold period in tensile phase, right: hold period in compression phase