FATIGUE AND CREEP OF SUPERALLOY SINGLE CRYSTALS CMSX-4

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Low cycle fatigue and creep tests were performed on superalloy single crystals CMSX-4 to determine the effect of orientation and temperature on the stress-strain response and on the lifetime. The resistance against fatigue at 700 °C decreases in the order of $\langle 001 \rangle, \langle 011 \rangle, \langle 111 \rangle$ orientations. For creep the ranking depends both on the temperature and on the applied stress. These results are correlated with the microstructural changes taking place during loading.

1. Introduction

The efficiency of the gas turbines is given mainly by the operating temperature. The limiting factor for increase of the operating temperature is the material of the critical parts. The blades are the most critical parts of the gas turbines. The actual service stress of the blades is a combination of static stress (due to the high centrifugal forces), cyclic stress (either low frequency stress due to start-up and shut-down cycles or high frequency stress due to vibrations) and thermomechanical stress (due to changes of temperature). From all the possible types of loading, we shall deal in this paper with the case of isothermal low-cycle fatigue simulating the above mentioned low-frequency cyclic stress and with the case of isothermal creep simulating the effect of static stress.

The blades have been made of polycrystalline superalloys for years. Steadily increasing temperatures and stresses together with corrosion resulted in increased danger of intercrystalline fracture. This led to the necessity to eliminate the weak spots in the material, i.e. to eliminate the grain boundaries. Now the use of single-crystal components is well established. Beginning in the early seventies with the Pratt&Whitney alloy PW 1480 several million parts have been produced, so far. Since several years ago, single-crystal components are no longer confined to military engines, but have entered service in the high-pressure turbines of civil engines [1]. Last years have also witnessed a great effort to develop and test monocrystalline

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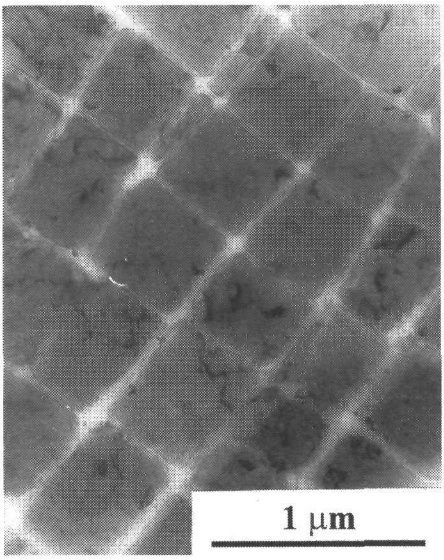

Fig. 1. Transmission electron micrograph showing two-phase structure of CMSX-4 single crystals.

superalloys for land-based gas turbines for use in advanced power engineering. One of the new monocrystalline superalloy material is the material CMSX-4. The aim of the present paper is to show the effect of orientation and temperature on the lifetime of this material under conditions of low-cycle fatigue and creep.

The microstructure of the single crystals CMSX-4 is a two-phase one, namely it consists of a γ matrix in which cuboidal γ' precipitates are coherently embedded. Fig. 1 shows this microstructure. The volume fraction of γ' precipitates is about 70%, the size of γ' cubes (measured along the cube edge) is about 0.4 to 0.5 μm, and γ/γ' interfaces are aligned to $\{001\}$ planes. This morphology itself indicates that the properties of the single crystals are orientation dependent.

2. Experimental

The single crystals were kindly provided by Howmet Ltd., England in the framework of COST 501 Round III collaborative programme. They were delivered as cast rods in fully heat-treated condition. The applied solution cycle resulted in solutioning of γ' better than 99% without incipient melting problems. The chemical composition of the single crystals is given in Table 1.

Table 1. Chemical composition of CMSX-4 [wt.%]

Cr	Mo	W	Co	Ta	Re	Hf	Al	Ti	Ni
6.5	0.6	6.4	9.7	6.5	2.9	0.1	5.7	1.0	bal.

The lattice parameter of the γ matrix a_γ is slightly higher than the lattice parameter of the γ' precipitates $a_{\gamma'}$. Thus the misfit parameter δ defined as $\delta = 2(a_{\gamma'} - a_\gamma)/(a_{\gamma'} + a_\gamma)$ is negative; its value is about $\delta = -1 \times 10^{-3}$ [2].

The low-cycle fatigue tests were performed in air under total strain control tests on specimens having gauge length 15 mm and diameter 6 mm in a computer controlled servohydraulic testing system at total strain rate $1 \times 10^{-3}s^{-1}$ and total strain cycle asymmetry R_ε either 0.05 or 0.5. The hysteresis loops were recorded and digitally stored at the pre-set numbers of loading cycles. This made it possible to determine the elastic moduli and the dependencies of the stress amplitude, plastic strain amplitude, and mean stress on the number of loading cycles.

The creep tests were performed either under constant load or under constant stress conditions in air. The elongation was measured as a function of time by means of a linear variable differential transformer. The data were recorded digitally by means of a PC.

3. Results and discussion

The cyclic hardening/softening at the beginning of cycling of the CMSX-4 single crystals is very inexpressive. In other words, the cyclic stress response is stable. This holds for all orientations and temperatures. The stable cyclic stress response makes it possible to construct easily the cyclic stress-strain curves (CSSCs). Fig. 2 shows the CSSCs for the investigated orientations at 700 °C in the shear stress vs. plastic shear strain representation for two strain cycle asymmetries. The full symbols in this diagram (as well as in Figs. 3, 5, and 6) correspond to the strain cycle asymmetry 0.5, while the open symbols correspond to the strain cycle asymmetry 0.05. The axial stress and plastic strain amplitudes were resolved into the slip system $\{111\}\langle 011\rangle$ having the highest Schmid factor. It can be seen that the CSSC does not depend on the orientation, but it does depend on the mean strain.

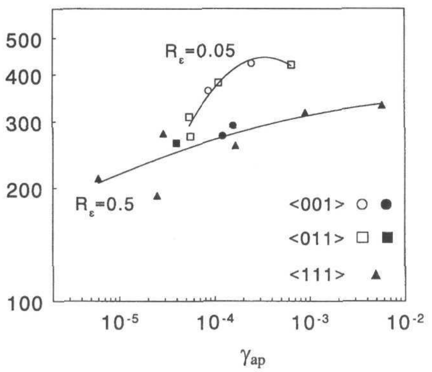

Fig. 2. Cyclic stress-strain curve for three multiple slip orientations at 700 °C.

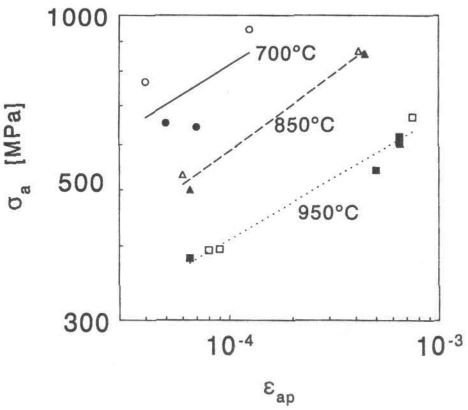

Fig. 3. Cyclic stress-strain curves for $\langle 001\rangle$ oriented crystals at three temperatures.

The CSSC is shifted towards lower stresses for higher strain cycle asymmetry. The temperature dependence of the CSSC for ⟨001⟩ oriented crystals is displayed in Fig. 3. It can be seen that the CSSC depends strongly on the temperature. For the given plastic strain amplitude the stress amplitude decreases with increasing temperature. A slight effect of the mean stress can be again stated. The cyclic stress-strain response is certainly closely related to the processes of the cyclic plastic deformation. These processes manifest themselves by the formation of the surface relief. Fig. 4 shows the SEM micrograph of the ⟨001⟩ specimen cycled at 700 ℃. Two sets of lines can be seen. The more expressive lines with large spacing – the persistent slip bands (PSBs) – lie along the trace of one of the active slip planes {111}. The less expressive lines with small spacing lie along the (001) plane perpendicular to the stress axis. The PSBs were observed only at 700 ℃ for higher strain amplitudes. The fine lines were observed at all temperatures and all strain amplitudes. The study by means of transmission electron microscopy [15] shows that the PSBs appear as very thin slabs (thickness below 0.1 μm) going through both the γ channels and the γ' particles. The dislocation within the PSBs cannot be resolved. It can be only speculated that the dislocation density within them is very high. Our finding that the PSBs are present only at 700 ℃ is in agreement with results of other authors on similar superalloys showing that there are no PSBs at temperatures above 760 ℃ [3, 4, 5, 6]. Chieragatti and Remy [7] found a clear plateau at the CSSC in the case of MAR-M200 single crystals tested in fully reversed cycle at 650 ℃. The reason why the presence of the PSBs in our case does not manifest itself by the plateau must be sought either in their low density or in the fact that they harden very quickly after their formation and do not thus represent zones of substantially higher cyclic slip activity under asymmetrical cycling. The main bearers of the cyclic plastic deformation are then the γ channels as the γ' particles are the harder phase. The misfit between the two phases results in the presence of the misfit stresses. The stress acting on the dislocations is given by the sum of the externally applied stress and the misfit stress. Due to the fact that the CMSX-4 single crystal is a negative misfit alloy, the stress

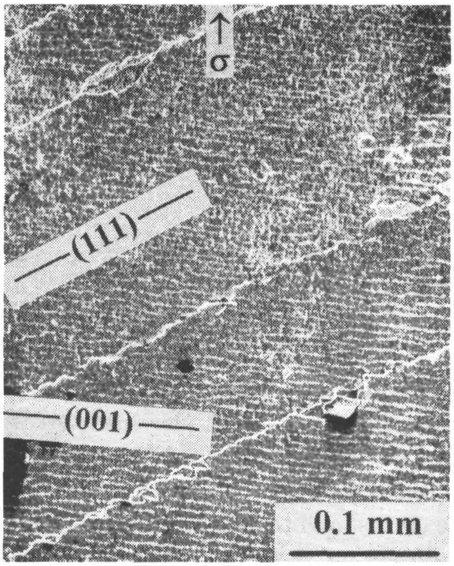

Fig. 4. Surface relief of ⟨001⟩ crystal tested at 700 ℃.

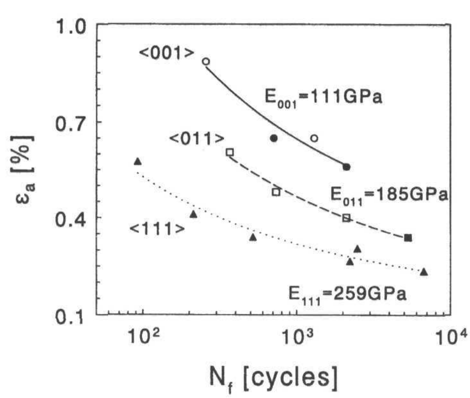

Fig. 5. Total strain amplitude vs. number of cycles to fracture for three multiple slip orientations at 700 °C.

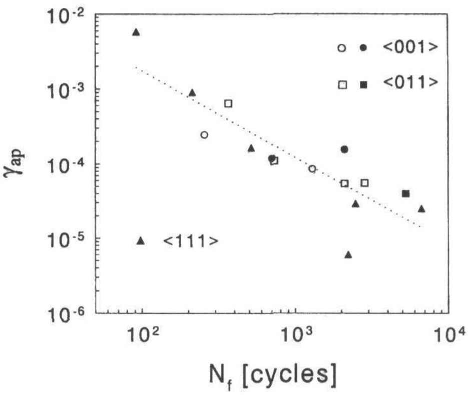

Fig. 6. Coffin-Manson plot for three multiple slip orientations at 700 °C.

acting in the horizontal γ channels (channels perpendicular to the stress axis) is higher then the stress acting in the vertical γ channels (channels parallel with the stress axis). The cyclic plastic deformation takes place on all the eight available $\{111\}\langle 011\rangle$ slip systems just in these horizontal γ channels. As the amplitude of the cyclic plastic deformation is small (below 0.1% – see Figs. 2 and 3), the activity of the vertical γ channels is not necessary at all. The reason, why approximately every 20^{th} horizontal γ channel (see Fig. 4) produces a visible surface relief, could lie in the inhomogeneous distribution of the thickness of the horizontal γ channels. The fatigue life plotted in terms of the total strain amplitude vs. number of cycles to fracture at 700 °C (Fig. 5) is very strongly orientation dependent. The values of the Young modulus presented in Fig. 5 were determined from the hysteresis loops. The orientation dependence of the fatigue life curves in Fig. 5 is due mainly to the orientation dependence of the Young modulus. On the other hand, the fatigue life plotted in terms of resolved cyclic plastic strain amplitude vs. number of cycles to fracture, i.e. the Coffin-Manson diagram (Fig. 6), is independent of orientation.

Creep tests of single crystals CMSX-4 of orientations $\langle 001\rangle, \langle 011\rangle$ and $\langle 111\rangle$ were performed at 750 °C, 800 °C, 850 °C, and 1000 °C, both at constant axial load as well as at constant axial stress. The range of applied loads was chosen in such a way that it covers the range of rupture lives $t_f \in (\approx 10\text{ h}, \approx 5000\text{ h})$. Figs. 7 to 10 show creep rupture curves for different temperatures. The constant load data are shown by full symbols, the constant stress data by open symbols. At 750 °C (Fig. 7) the constant load data for $\langle 001\rangle$ and $\langle 111\rangle$ orientations can be fitted by one line. These orientations are superior to $\langle 011\rangle$. The lifetime of $\langle 011\rangle$ crystals is (for the same stress) by the factor of 100 shorter than the lifetime of $\langle 001\rangle$ crystals. At

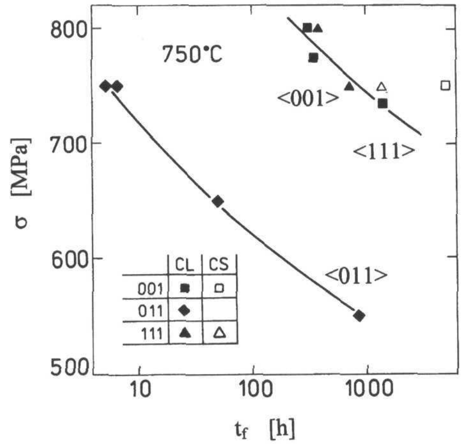

Fig. 7. Creep rupture curves for 750 °C. CL – constant load; CS – constant stress.

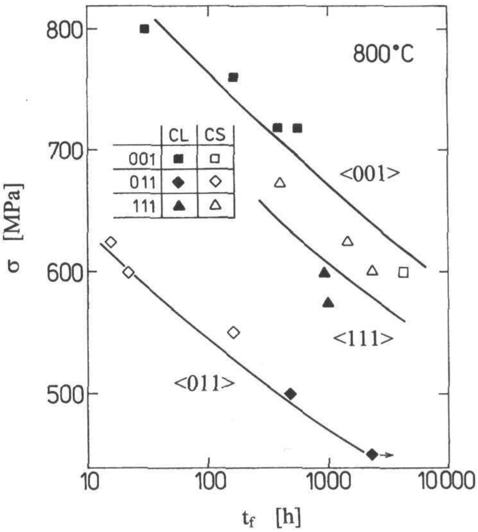

Fig. 8. Creep rupture curves for 800 °C.

800 °C (Fig. 8) there is a slight difference between orientations of ⟨001⟩ and ⟨111⟩; both these orientations display substantially higher lifetime than the orientation ⟨011⟩. At 850 °C (Fig. 9) the curves for ⟨001⟩ and ⟨111⟩ orientations cross at about 470 MPa ($t_f \approx 2000$ h). It proves that the ranking of the orientations depends also on the applied stress. At 1000 °C (Fig. 10) the data indicate that there is no effect of orientation. The data presented in Figs. 7 to 10 also show that the constant-stress tests are longer than the constant-load tests. This effect can be explained by the increase of true stress with elongation in the case of constant-load tests.

The main conclusion of the above presented results is that the effect of orientation on the creep resistance depends strongly on temperature and applied stress. The crystallographic orientation of the monocrystalline components is usually chosen in such a way that one of the crystallographic directions ⟨001⟩ coincides with or lies near to the load axis. There are indications based on laboratory tests that the ⟨001⟩ oriented single crystals do not necessarily exhibit the best resistance to high temperature deformation. For example, MacKay and Maier [9] found for MAR-M247 and MAR-M200 single crystals tested in the temperature range 760–774 °C that the rupture life was the longest for ⟨111⟩ orientation, somewhat shorter for ⟨001⟩ orientation and the shortest for ⟨011⟩ orientation. On the other hand, Caron et al. [10] found for CMSX-2 single crystals tested at 760 °C considerably shorter creep lives for ⟨111⟩ orientation than for ⟨001⟩ orientation. Later they showed [11]

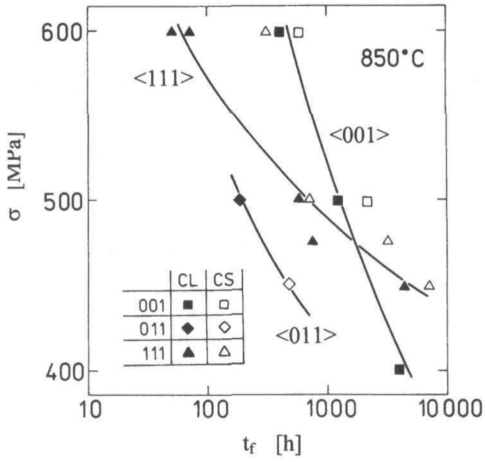

Fig. 9. Creep rupture curves for 850 °C.

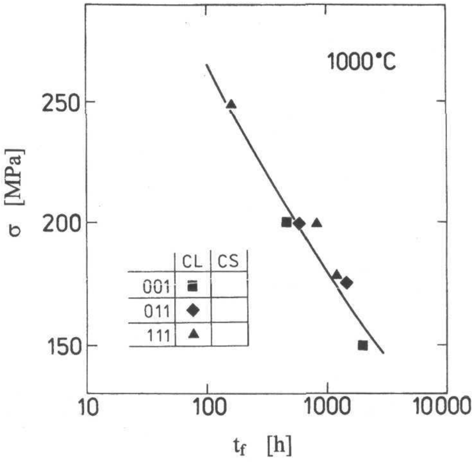

Fig. 10. Creep rupture curves for 1000 °C.

that the creep life of ⟨111⟩ oriented crystals is highly dependent on the size of the γ' precipitates while the creep life of ⟨001⟩ oriented crystals depends on the size of γ' precipitates weakly. The creep life of ⟨111⟩ crystals can be longer or shorter than that of ⟨001⟩ crystals in dependence on the γ' particle size. There are several papers showing a drop in creep rupture lives for crystals having orientation near to ⟨001⟩ with increasing disorientation from the exact ⟨001⟩ orientation. Sass et al. [12] tested CMSX-4 single crystals at 800 °C under a constant stress of 767 MPa. The longest lives were reached by crystals with an orientation in close proximity of ⟨001⟩. With increasing disorientation from ⟨001⟩ the creep strength significantly dropped. The explanation of all these seemingly controversial effects probably lies in distribution of resolved shear local stresses in this γ/γ' composite material [8, 13, 14].

Summing up the discussion, it can be said that the high resistance of the CMSX-4 single crystals against fatigue and creep is due to their „clever" structure. The harder γ' particles are embedded in the softer framework of the γ matrix; the channels of this γ matrix are very thin, the γ' particles are relatively large. Thus the dislocations which can move predominantly in the γ matrix must undergo torturous paths, and moreover, their bowing out through the γ channels requires high stresses. The fact that the CMSX-4 single crystals exhibit very good characteristics both for the high temperature fatigue and the creep behaviour makes them a very attractive material.

4. Conclusions

1. Cyclic shear stress-strain curve at 700 °C does not depend on orientation but depends on strain cycle asymmetry. The Coffin-Manson curve is also independent of orientation.

2. Cyclic stress-strain curve of ⟨001⟩ oriented crystals depends systematically on temperature. Temperature dependence of fatigue life curves is not systematic.

3. The ranking of orientations from the point of view of the resistance against creep depends on both the temperature and the applied stress. At low temperatures (at and below 800 °C) the orientation ⟨001⟩ is superior, at high temperatures (at and above 1000 °C) the orientations are equivalent and at medium temperatures the ranking depends on the applied stress.

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