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Plain and notched fatigue in nickel single crystal alloys

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ABSTRACT

The paper focuses on CMSX-4 and two experimental alloys, LDSX-5 and LDSX-6, developed to provide alternative performance attributes. The specific objective in this work was an exploration of the low cycle fatigue (LCF) characteristics of these three alloy variants and the assessment of methods for predicting the observed lives. A comparison of the alloys is presented in relation to their strain control fatigue response and notch fatigue behaviour. Predictions of notch lives are made from the plain specimen data but found to be extremely pessimistic at the lower temperature studied, 650 °C. The inaccuracies are attributed to the presence of casting pores. Using measured crack growth data and pore sizes, it is shown that fracture mechanics calculations of residual lives are more appropriate. At 800 °C, the higher temperature studied, Walker strain predictions of notch lives are more meaningful. This is explained in terms of the relaxation of stresses at the defects.

1. Introduction

The research programme set out to explore the LCF behaviour of experimental single crystal nickel alloys. The alloys specifically focused on alternative compositions to CMSX-4 that offer various performance attributes. The two alloys highlighted in the present paper were chosen because of lower densities, improved stability (LDSX-5) and enhanced creep strength (LDSX-6). Data generated on CMSX-4 were used for comparison. All alloys were produced with a [1 0 0] orientation using conventional single crystal casting technology. The experiments involved plain and notched test-pieces with K_t values of 2.38 for a centre hole plus 2.3 and 3.6 for double edge notch geometries. Plain specimens were subjected to 15 cpm strain control fatigue with R values of 0 and −1. From these tests, hysteresis loops were recorded and cyclic stress–strain curves constructed. The notch specimens were tested with the same waveform at $R = 0$. Plain and notched specimens were evaluated at 650 °C and 800 °C. The orientations of test-pieces and notches were confirmed to be consistent by means of Electron Back-Scatter Diffraction (EBSD) measurements.

A prime objective of the work was the assessment of methods for predicting fatigue performance. In particular, the Walker strain relationship has previously been shown to provide an effective means of predicting notch behaviour [1,2]. In the present situation, however, inconsistencies were identified which were attributed to the presence of casting pores. These defects introduced the need to consider an alternative damage tolerance approach based on fracture mechanics and the application of crack growth rate data. Both life prediction methods are highlighted and discussed.

2. Experimental procedures

2.1. The alloys

The compositions of the LDSX-5 and LDSX-6 alloys are summarised in Table 1 in relation to CMSX-4.

The principal differences from CMSX-4 are higher rhenium content, the addition of ruthenium, greater amount of molybdenum and reduced tungsten particularly for LDSX-5. This is illustrated in Fig. 1. These changes influenced density, stability, creep strength and castability. The relative benefits are highlighted in Table 2.

Following casting the alloys were solution treated at 1340 °C, gas-fan quenched, primary aged at 1150 °C, quenched and finally aged at 870 °C. Microstructures were defined by etching in 10 ml HNO_3, 50 ml HCl, 2.5 g $CuCl_2$ and 40 ml H_2O. Scanning Electron Microscopy (SEM) comparisons of CMSX-4, LDSX-5 and LDSX-6 at the same magnification are reproduced in Figs. 2a–2c.

The average measured widths of the γ' precipitates and γ channels are recorded in Table 3.

All the alloys contained casting pores. A typical example is illustrated in Fig. 3. These pores played an important role in the observed fatigue behaviour. They will be considered in more detail during the discussion.

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2.2. Fatigue procedures

The core fatigue tests were carried out under strain control on a plain cylindrical specimen with a gauge length of 15 mm and a nominal 5.5 mm diameter. Two sets of the notched specimens had a DEN (double edge notch) configuration with K_t values of 3.6 and 2.3. The third set had a 'flat plate' geometry with a K_t value of 2.38. The three notch specimens are shown in Fig. 4.

Additional crack propagation measurements were made on corner crack specimens with a 7 × 7 mm cross section and a 0.35 mm deep slit machined into one corner. The cast bars from which all specimens were machined were aligned so that their primary axis

Table 1
Alloy Compositions (wt%).

	Co	Cr	Mo	W	Re	Ru	Al	Ti	Ta	Hf
LDSX-5	8.4	3.1	2.7	2.9	6.4	4.6	5.6	0.3	6.5	0.1
LDSX-6	3.1	3.3	2.7	4.8	6.4	4.7	5.6	0.3	6.5	0.1
CMSX-4	9	6.4	0.6	6.4	3	0	5.6	1	6.5	0.1

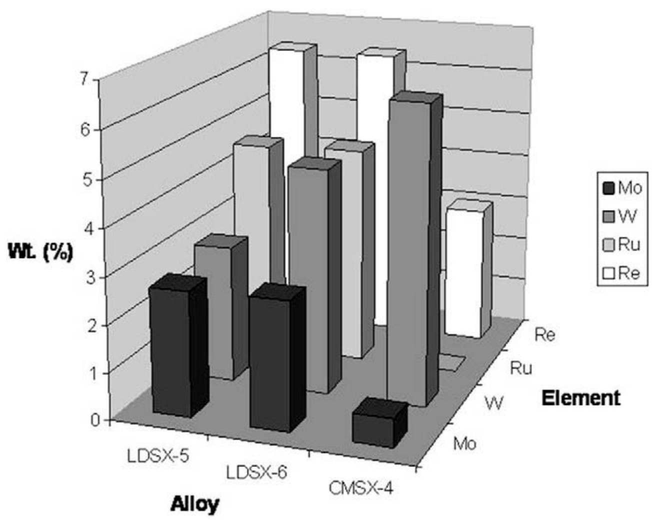

Fig. 1. Single crystal material compositions.

Table 2
Relative attributes of the alloys.

Stability	LDSX-5 > LDSX-6 > CMSX-4
Creep strength	CMSX-4 > LDSX-6 > LDSX-5
Castability	CMSX-4 > LDSX-5 > LDSX-6

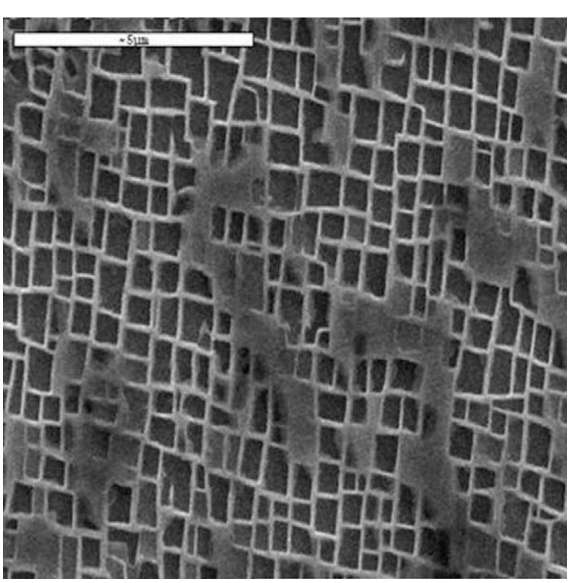

Fig. 2a. Microstructure of CMSX-4.

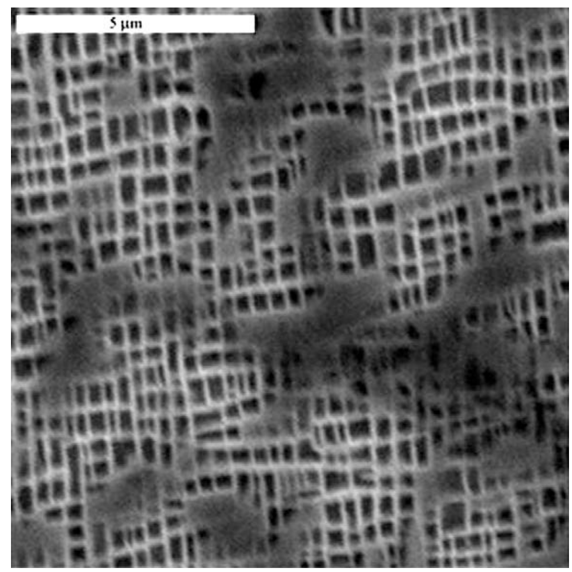

Fig. 2b. Microstructure of LDSX-5.

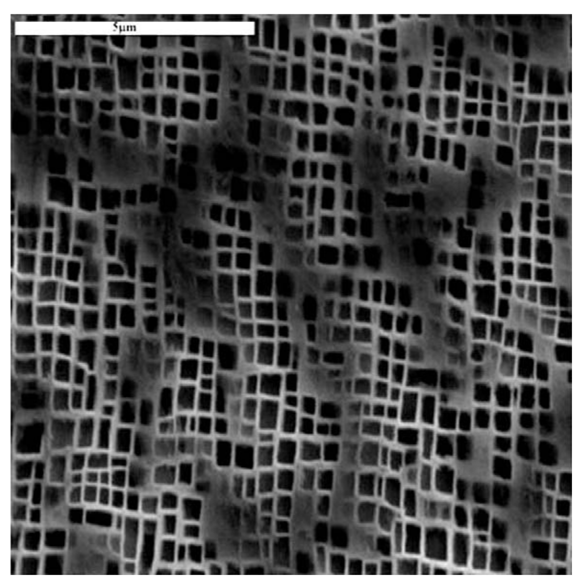

Fig. 2c. Microstructure of LDSX-6.

Table 3
Microstructural measurements.

Alloy	Average width of γ' (μm)	Average width of γ channels (μm)
LDSX-5	0.36	0.136
LDSX-6	0.41	0.136
CMSX-4	0.45	0.15