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Dynamic strain ageing in Inconel® Alloy 783 under tension and low cycle fatigue

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ABSTRACT

Low cycle fatigue (LCF) tests were performed on Inconel®[1] Alloy 783 at a strain rate of $3 \times 10^{-3}\ s^{-1}$ and a strain amplitude of ±0.6%, employing various temperatures in the range 300–923 K. A continuous reduction in the LCF life was observed with increase in the test temperature. The material generally showed a stable stress response followed by a region of continuous softening up to failure. However, in the temperature range of 573–723 K, the alloy was seen to exhibit dynamic strain ageing (DSA) which was observed to reduce the extent of cyclic softening. With a view to identifying the operative mechanisms responsible for DSA, tensile tests were conducted at temperatures in the range, 473–798 K with strain rates varying from $3 \times 10^{-5}\ s^{-1}$ to $3 \times 10^{-3}\ s^{-1}$. Interaction of dislocations with interstitial (C) and substitutional (Cr) atoms respectively, in the lower and higher temperature regimes was found to be responsible for DSA. Further, the friction stress, as determined using the stabilised stress–strain hysteresis loops, was seen to show a more prominent peak in the DSA range, compared to the maximum tensile stress.

1. Introduction

Inconel® Alloy 783 is a new class of Ni–Co based superalloys with a low coefficient of thermal expansion (CTE) [1–4]. The alloy was developed with an objective of achieving a low CTE while maintaining a high strength and a good corrosion resistance so that it can be used in aircraft gas turbine components such as rings, casings and shrouds that can maintain tightened blade tip clearances at different operating temperatures, leading to an increased turbine efficiency [5,6]. The lowering of CTE is attributed to a reduced Cr content in the alloy which ensures that the Curie temperature stays high enough thereby avoiding the lattice thermal expansion associated with magnetic transformation [5]. Besides gas turbine engine parts, the low CTE superalloys have potential usage in the superconductive magnets for fusion reactors. The alloy contains a higher Al content of about 5% compared to the more conventional and better known variants of the above class of superalloys such as Incoloy 903, 907, 908 and 909 [5]. The increased Al addition facilitates the formation of incoherent NiAl-type β-phase in an austenitic matrix in addition to the coherent Ni_3Al-type γ′ precipitates. The β-phase that occurs discontinuously at both inter- and intra-granular locations, can be processed to resist stress accelerated grain boundary oxidation (SAGBO), a particular form of stress corrosion cracking to which these class of superalloys are usually susceptible [1–4,6]. The alloy also possesses an improved resistance against salt spray corrosion compared to other low CTE alloys, which makes it a suitable candidate for offshore turbine applications as well [7]. While the austenitic matrix accounts for a good combination of mechanical properties and workability, the γ′ imparts precipitation strengthening, to the alloy.

Components, such as turbine blades and vanes in gas turbine and aero engines are subjected to repeated cyclic thermal stresses resulting from startup and shutdown operations. The high rotational speeds and the associated centrifugal stresses experienced by the turbine discs call for good elevated temperature tensile strength and toughness. Furthermore, stresses that are associated with changes in the rotational speed of the turbine and the stresses that are of thermal origin are cyclic in nature, underlining the need for such alloys to possess a good resistance to low cycle fatigue (LCF) [8]. Though the fatigue crack growth behaviour of the alloy under different microstructural conditions has been studied in detail [2,6], literature on LCF is limited [9]. The present investigation is aimed at investigating the influence of DSA under LCF and tensile deformation at different temperature–strain rate combinations.

2. Experimental

2.1. Material and heat treatment

Detailed chemical composition of the alloy in wt.% is provided in Table 1. The alloy, received in hot worked condition, was machined

[1] Inconel is the registered trademark of Special Metals Corporation, USA.

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Table 1
Chemical composition (wt.%) of Inconel® Alloy 783.

Ni	Co	Fe	Al	Cr	Nb	Ti	Mo	Si	Mn	Cu	C	B	P	S
28.11	34.75	25.05	5.37	3.21	3.00	0.20	0.14	0.08	0.04	0.03	0.01	0.005	0.004	<0.001

into bars, which were subsequently given a three-step heat treatment as detailed below:

1. Annealing at 1393 K for 1 h and air-cool.
2. Ageing at 1116 K for 4 h and air-cool (referred to as β-ageing).
3. Ageing at 991 K for 8 h and furnace cooling at 328 K per hour to 894 K, held for 8 h at this temperature followed by air cooling to room temperature (γ′-ageing).

The β-phase in this alloy has been reported to contain approximately 31% Al, 30% Ni, 24% Co and 15% Fe (atom%) [10]. The γ′ precipitates formed in step-3 above have an average size of 30–40 nm [2].

2.2. Tensile and low cycle fatigue tests

Tensile tests were performed on cylindrical samples with a gauge length of 28.6 mm and a gauge diameter of 4 mm (Fig. 1a). Tests were conducted at different temperatures in the range, 473–798 K at strain rates varying from $3 \times 10^{-5}\,s^{-1}$ to $3 \times 10^{-3}\,s^{-1}$. Smooth specimens of 25 mm gauge length and 10 mm gauge diameter were used for carrying out total axial strain controlled LCF tests in air. Fig. 1(b) presents the specimen geometry employed for the LCF tests. All tests were performed at a constant strain rate of $3 \times 10^{-3}\,s^{-1}$ and a strain amplitude of ±0.6% in the temperature range, 300–923 K, using an Instron 1342 servohydraulic machine, equipped with a radiant heating furnace. The failure life was taken as the cycle number corresponding to a 20% drop in the peak tensile stress at half-life in LCF tests.

2.3. Metallography

Optical metallography was carried out on samples swab etched for about 30 s using Kalling's reagent (6 g $CuCl_2$, 100 ml HCl, 100 ml H_2O and 100 ml CH_3OH). Samples for transmission electron microscopy were initially mechanically polished down to about 70 μm, followed by electropolishing using a solution containing 10% perchloric acid and 90% methanol at 243 K using a d.c. supply of 20 V.

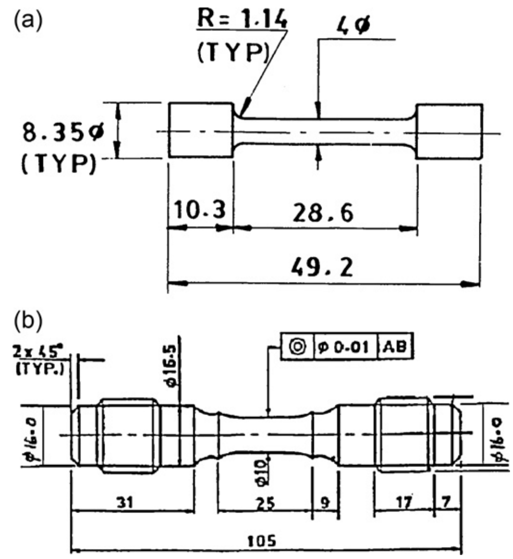

Fig. 1. (a) Specimen geometry used for tensile tests. (b) Specimen geometry used for LCF tests.

3. Results and discussion

3.1. Prior microstructure

The prior microstructure of the alloy subjected to the heat treatment detailed earlier consisted of three phases, an austenitic matrix, intra- and intergranularly distributed NiAl β-phase and a fine distribution of γ′ precipitates. Fig. 2 presents the typical microstructure of the untested material that shows the γ′

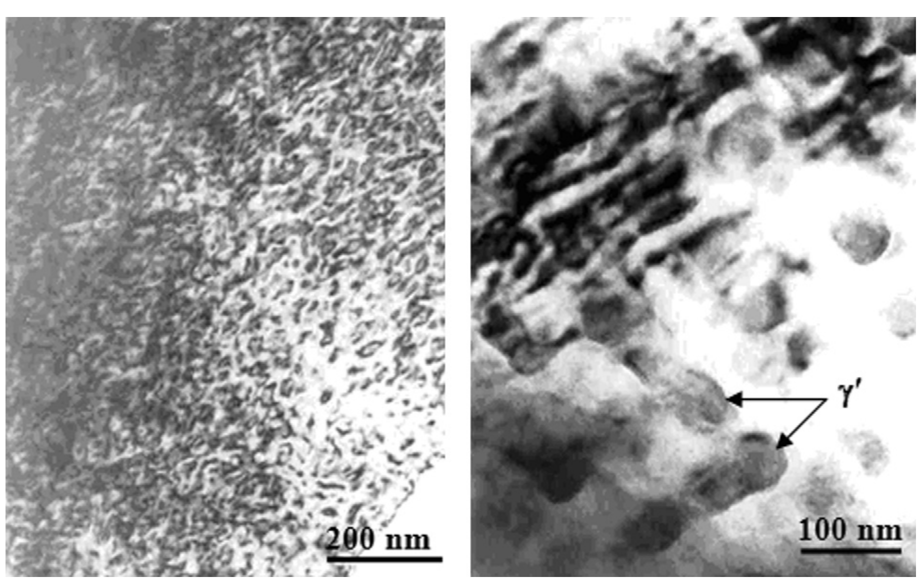

Fig. 2. Prior microstructure of the alloy in the heat-treated condition showing γ′.