Mechanics of Materials 109 (2017) 34–41

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Research paper

1D cyclic yield model independent of load spectrum characteristics and its application to Inconel 718

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ARTICLE INFO

Article history:
Received 31 August 2016
Revised 20 March 2017
Available online 28 March 2017

Keywords:
Inconel 718
Cyclic yielding
Low cycle fatigue
Constitutive equations
Softening

ABSTRACT

At room temperature, nickel-based superalloy Inconel 718 softens under fully reversed plastic deformation cycles. Chaboche's unified constitutive equations have been previously used in the literature to predict nickel-based superalloy cyclic softening behavior. To better fit our results, the constitutive equations were modified to account for continuous softening. Moreover, applying the model to results gathered from two different loading spectrum indicates that the isotropic evolution is solely dependent on the accumulated plastic strain and can be applied to a variety of number of cycles and strain amplitudes combinations without adjusting the parameters. This new information is significant and has a considerable impact on material testing and modeling. It implies that a unique set of parameters extracted from any fully reversed strain controlled test can characterize the material flow stress evolution with accumulated plastic strain independently of the strain sequence, for $R_\varepsilon = -1$. This flexible prediction method could lead to significant experimental costs reductions.

1. Introduction

Inconel 718 hardens during the first cycles (Fournier and Pineau, 1977; Merrick, 1974) when tested under room temperature low cycle fatigue (LCF) conditions at a strain ratio $R_\varepsilon = -1$. However, Inconel 718 continuously softens after several strain cycles since second particles shearing occurs (Xiao et al., 2008). At half its fatigue life, its yield strength can decrease as much as 40% for a 1% strain amplitude (Sudarshan Rao et al., 2012).

The flow stress evolution of a metal under cyclic plastic deformation can be predicted using unified Chaboche's constitutive equations (Chaboche and Rousselier, 1983) that account for inelastic behaviors such as Bauschinger effect, ratcheting, cyclic hardening and creep (Lemaitre et al., 2009). The elastic domain is commonly defined with the flow function f expressed as (Chaboche et al., 2012)

$$f = J(\sigma - \chi) - R - k, \tag{1}$$

where χ is the back stress, k the initial yield strength and J is a stress space invariant function commonly chosen as the von Mises invariant J_2. In 1D, the von Mises stress space invariant is defined as

$$J_2(\sigma - \chi) = |\sigma - \chi|. \tag{2}$$

The elastic domain is classically defined as $f < 0$ and the plastic domain as $f = 0$. R represents the isotropic hardening component (yield surface evolution) and is commonly defined as a function of the accumulated plastic strain p as

$$R(p) = Q(1 - e^{-bp}), \tag{3}$$

where Q and b represent respectively the saturation value and the hardening rate. This relation was successfully used on stainless steel 316 (Goodall et al., 1981). The back stress χ is defined as a sum of independent variables χ_i. Each one governs a different domain of the plastic deformation. For a nickel-based superalloy, two such kinematic variables are sufficient (Zhao et al., 2001) and can be expressed as a Armstrong and Frederick (Armstrong and Frederick, 1966) kinematic hardening rule as

$$\chi = \chi_1 + \chi_2$$
$$\chi_i = a_i(1 - e^{-C_i \varepsilon_p}) \qquad i = 1, 2, \tag{4}$$

Abbreviations: E, Young modulus; ν, Poisson's ratio; $\sigma_{y0.2\%}$, 0.2% offset tensile yield strength; $\sigma_{y0.05\%}$, 0.05% offset tensile yield strength; σ_u, ultimate strength; El., elongation; AR., area reduction; Bal., balance; R_ε, strain ratio; $\dot{\varepsilon}$, strain rate; f, flow function; N, total number of experiments; σ_{num}, predicted stress; $\Delta\varepsilon_{tot}/2$, strain amplitude; $\Delta\sigma/2$, stress amplitude; σ, applied stress; χ, back stress; R, yield surface evolution; k, initial yield strength; a_i, C_i, back stress parameters; ε_p, plastic strain within a half cycle; p, total accumulated plastic strain; Q, elastic field size saturation value; b, elastic field size hardening rate; α, β, elastic field size evolution parameters; F, cost function; M, total number of data point; $\sigma_{\exp}$, experimentally measured stress.

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http://dx.doi.org/10.1016/j.mechmat.2017.03.011

Table 1
Inconel 718 chemical composition obtained by optical spectrometry (weight %).

Elements	Ni	Cr	Nb	Mo	Ti	Al	Co	Si	Mn	Cu
Composition	Bal.	17.93	5.23	3.24	1.19	0.60	0.30	0.07	0.06	0.05

Table 2
Inconel 718 monotonic tensile properties following ASTM E8M-13a methodology.

E (GPa)	ν	$\sigma_{y0.2\%}$ (MPa)	$\sigma_{y0.05\%}$ (MPa)	σ_u (MPa)	El. (%)	AR. (%)
205	0.32	1253	1125	1413	24	39

where a_1, a_2, C_1 and C_2 are material constants and ε_p is the plastic strain within a half cycle.

Zhan and Tong (2007) and Tong et al. (2004) used Chaboche's constitutive model to predict nickel-based alloys behavior when submitted to constant $R_\varepsilon = 0$ cyclic strain amplitude and creep tests at 650 °C. They developed an algorithm based on a least square minimization to determine a set of parameters best fitting experimentally measured behavior. However, the validity of the fitting parameters could be questioned since the initial yield strength was identified as 150 MPa while it was of 1000 MPa in monotonous tensile tests.

A material's cyclic yield behavior can be characterized through three main testing procedures (Hales et al., 2002). The single step test consists of performing fully reverse cyclic tests at constant strain amplitude. The incremental step test introduced by Landgraf et al. (1969) consists of loading blocks in which the strain amplitude is incremented every cycle to reach a maximum and then progressively decremented to its initial value. The multiple step test, similar to the single step test, consists of increasing the strain amplitude after every chosen number of cycles. Polak and Hajek (1991) proved that a single incremental test on copper and low carbon steel can be used to approximate their cyclic stress–strain curves. This observation can lead to experimental costs reductions since one incremental tests could provide the same information as several constant amplitude tests. To the best of our knowledge, incremental test results have never been compared to constant strain amplitude tests results for Inconel 718.

This study aims at demonstrating that Inconel 718 behavior, when submitted to $R_\varepsilon = -1$ strain controlled LCF, can be fully characterized by the accumulated plastic strain independently of the strain spectrum characteristics. The paper is organized as follows: Section 2 presents the studied material and the experimental procedures used to extract Inconel 718 stress–strain curves under single step and incremental tests. The experimental results are analyzed in Section 3. Section 3 also compares the proposed model's predictions to experimentally measured behavior while Section 4 concludes this work.

2. Material and experimental procedure

2.1. Material

The material studied is a nickel-based superalloy Inconel 718 that underwent a solution and precipitation heat treatment. Its chemistry, measured by optical spectrometry, is given in Table 1. The microstructure consisted of an austenitic FCC matrix strenghened by γ' ($Ni_3(Ti - Al)$) and γ'' ($Ni_3(Ti - Al)$) particles (Alexandre et al., 2004). The grain size was heterogeneous and mainly bi-modal with two median groups having mean diameters of 10 and 30 µm. It should be noted, however, that some grains could have diameters as large as 100 µm. The presence of NbC carbides, titanium carbo-nitride (TiCN) and δ phase (Ni_3Nb) particules located along the grain boundaries can be observed on Fig. 1. Aluminum and magnesium oxides were often found in the TiCN particles, as can be seen in Fig. 1. Monotonic tensile properties, measured according to ASTM E8M-13a standard (ASTM Standard E8M-13a, 2013), are presented in Table 2.

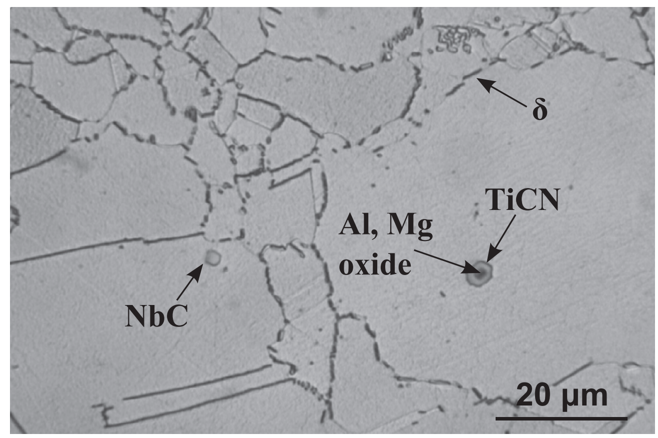

Fig. 1. Micrograph showing Inconel 718 microstructure. Titanium carbo-nitride (TiCN) and NbC carbides are present within the grains. An Al, Mg oxide can be observed inside the TiCN particle. δ phase (Ni_3Nb) is located along the grain boundaries. The grain size's heterogeneity is visible.

2.2. Cyclic tests

Specimens were extracted from the longitudinal direction of a 90 mm diameter bar. Samples had a dog bone shape with a 11.4 mm square reduced cross section and a 9 mm gage length. Specimens were designed in agreement with standards ASTM E9-09 (ASTM Standard E09-09, 2009) and E606M-12 (ASTM Standard E606M-12, 2012). Strain controlled tests were performed at room temperature on a MTS 318.25 equipped with a 250 kN MTS 661.22c-01 load cell with MTS 793 software and a FlexTest 60 (5.9A) controller. Tests were performed at a strain ratio $R_\varepsilon = -1$. The load path was triangular with a strain rate $\dot{\varepsilon} = 0.1$ %/s. Displacements were measured with a 8 mm gage length MTS 632.26C-20 extensometer.

Two types of cyclic yield tests were performed: four single step tests and one incremental test. A constant strain amplitude with a strain ratio $R_\varepsilon = -1$ was applied during single step tests. An example of a single step test strain command can be seen on Fig. 2(a). Four samples were tested at strain amplitudes $\Delta\varepsilon_{tot}/2 = 0.6,$ 1.0, 1.6 and 2%, respectively. The tests were performed until a qualitative sharp drop in the maximal stress was visually detected (see Fig. 3(a)). The sample tested with 1% strain amplitude was tested until failure.

Incremental tests consisted of a strain spectrum in which the initial strain amplitude of 0.4% was increased by 0.2% for each cycle until reaching an amplitude of 2%. In the second half of the spectrum, the strain was decreased back to 0.4% by steps of 0.2%. This strain spectrum, also called block, was repeated 18 times. Two such strain blocks are shown on Fig. 2(b).