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Cyclic deformation response of AISI 316L at room temperature: Mechanical behaviour, microstructural evolution, physically-based evolutionary constitutive modelling

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ABSTRACT

Deformation (e.g. cyclic hardening, softening and saturation) response and the corresponding microstructural evolution of AISI 316L during cyclic loading at room temperature are exhaustively studied. In particular, the physical interpretation and the role of internal stresses are thoroughly evaluated in order to better comprehend the relationship between microstructural evolution and cyclic deformation response. The understanding obtained provides a basis for the development of a physically-based evolutionary constitutive model which aims to accurately represent the complex cyclic deformation response of the material. The developed constitutive model represents the change in microstructural condition and its relationship with internal stress variables. The model parameters are identified by a systematic evaluation of mechanical and microstructural observations from a number of experimental tests. The proposed model is shown to effectively represent the complex cyclic elasto-plastic deformation behaviour of the material for a range of strain amplitudes.

1. Introduction

In many modern practical applications, in order to improve the reliability of lifetime assessment procedures, it is desirable to have a constitutive model which accurately describes the history dependence of long-term mechanical response, e.g. cyclic deformation response. This demand can be met by developing evolutionary constitutive model equations. As a consequence of taking insufficient account of underlying physical mechanisms, phenomenological constitutive models can be incapable of accurately simulating material mechanical behaviour once the boundary conditions extend beyond the considered mechanism range. In particular, considerable changes in the cyclic response of many polycrystalline materials are observed during early loading cycles (Feltner and Laird, 1967; Grosskreutz and Mughrabi, 1975; Pham et al., 2011). This makes phenomenological models unable to accurately describe the history dependence of cyclic deformation response (even when the boundary conditions do not change), since they often simply characterise the situation at the saturated response stage. In order to improve the descriptive capability, one can still use phenomenological models, but there is then the need to repeatedly identify parameters for every cycle. This approach is time-consuming and requires a lot of computational power to model cyclic deformation behaviour for thousands of cycles. Moreover, it still cannot improve predictive capability. An alternative approach to improve both descriptive and predictive capabilities is to provide a satisfactory physical basis for the

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Nomenclature

AISI American Iron and Steel Institute (material grading system)
b magnitude of Burger's vector
C_{inter}/g_{inter}, and C_{intra}/g_{intra} saturation magnitudes of inter-granular, and intra-granular back stress during a cycle
D_g, d_w, and d_c. grain size, dislocation wall thickness, and dislocation cell size (i.e. channel width), respectively
FCC face-centered cubic
f_b, and f_w the area fractions of boundary dislocations, and dislocation walls
f_j fraction factor
E, G elastic, shear moduli
GNDs geometrically necessary dislocations
k_1, and k_2 coefficients characterising the process of dislocation storage and dislocation annihilation during plastic deformation.
k_{1-b}/k_{2-b} and k_{1-I}/k_{2-I}. the square root densities of boundary dislocations and interior dislocations at the end of the cyclic hardening stage, respectively.
k_{1-j}/k_{2-j} the square root density of dislocation sessile junctions at stablised condition.
k_{2-b}, k_{2-I} and k_{2-j} the rates of annihilation of dislocations, boundary dislocations, interior dislocations and sessile junctions, with respect to p, respectively
k_{2-w} a coefficient characterising the rate of formation of dislocation walls.
k_L proportionality constant describing the relationship between the mean free path and the density of dislocations.
L dislocation mean free path
LCF low cycle fatigue
LD loading direction
M Taylor factor
N, and $N_{2\%}$ number of cycles, and number of cycles to 2% of maximum stress drop (crack initiation criterion), respectively
PSBs persistent slip bands
p the accumulated plastic strain
SODS a self-organised dislocation structure
TEM transmission electron microscope
X, X_{inter}, and X_{intra} back stress, Inter-granular back stress, and Intra-granular back stress
α a geometric constant of the elastic interaction of dislocations
ε_e, ε_p, ε_p^a and ε^a elastic strain, plastic strain, plastic strain amplitude, and total strain amplitude, respectively
κ geometrical factor of dislocation cell structures
ρ_t, ρ_b, ρ_I, ρ_j, ρ_w, and ρ_c the density of total dislocations, dislocations present close to grain boundaries, interior dislocations, dislocation sessile junctions, wall dislocations, and channel dislocations, respectively
$\rho_{GNDs\text{-}inter}$, and $\rho_{GNDs\text{-}intra}$ densities of GNDs required to accommodate the plastic strain incompatibility between grains, and between dislocation high/low density regions
$\Delta\sqrt{\rho_{w-c}^{bal}}$ the difference between square root density of dislocations within walls and within channels
σ_{max}, and σ_0 maximum stress of every cycle, and yield stress
σ_E, σ_E^0, and σ_E^R effective stress, initial effective stress, and the increment of effective stress
θ cell-to-cell misorientation

Superscripts or Subscripts
(c), and (t): reversal loading from compression and tension peaks
gen, and *ann*: generation, and annihilation
hard, *soft*, and *midlife*: hardening, softening, the mid-life cycle
peak, *hom*, and *sat*: the values of parameters at conditions of: the end of cyclic hardening stage, quite homogeneous distribution of dislocations over grains, the stabilised response condition

internal state variables so that the evolutionary constitutive model relates to any change in important physical quantities. This study adopts the latter approach, and aims to develop evolutionary constitutive model equations with internal state variables based on physical mechanisms.

In order to develop such an evolutionary constitutive model, it is necessary to have: (1) suitable internal state variables characterising the plastic deformation behaviour of the material, and (2) a relationship between physical features and the internal state variables during cyclic loading. Internal state variable theory was first established in a thermodynamics framework by Coleman and Gurtin (1967), and then further developed to solve problems in metal plasticity (Rice, 1971). The introduction of isotropic and kinematic hardening rules (Hill, 1950; Prager, 1956; Shield and Ziegler, 1958) to model the elasto-plastic behaviour of metallic materials led to the adoption of internal stress variables (i.e. isotropic (or effective) stress, and back stresses) with some sense of physical mechanisms (Armstrong and Frederick, 1966; Chaboche, 1997; Chaboche and Rousselier, 1983; Lemaitre, 1990). Evolutionary model equations with back stresses during cyclic loading were also developed (Armstrong and Frederick, 1966; Chaboche, 2008; Choteau et al., 2005; Mayama et al., 2007; Voyiadjis and