Available online at www.sciencedirect.com

ScienceDirect

Acta Materialia 83 (2015) 256–268

Acta MATERIALIA

www.elsevier.com/locate/actamat

Cyclic behaviour of a 6061 aluminium alloy: Coupling precipitation and elastoplastic modelling

D. Bardel,[a,b,c] M. Perez,[b,*] D. Nelias,[a] S. Dancette,[b] P. Chaudet[a] and V. Massardier[b]

[a] *Université de Lyon, INSA-Lyon, LaMCoS UMR CNRS 5259, F69621 Villeurbanne, France*
[b] *Université de Lyon, INSA-Lyon, MATEIS UMR CNRS 5510, F69621 Villeurbanne, France*
[c] *AREVA NP, Département d'ingénierie mécanique, Lyon, France*

Received 1 August 2014; revised 5 September 2014; accepted 5 September 2014

Abstract—Multi-level cyclic loading is performed on an aluminium 6061 alloy. From an initial fully precipitated T6 state, various non-isothermal heat treatments are performed, leading to various precipitation states. This paper focuses on the effect of precipitates on yield stress, and on kinematic and isotropic hardening. In parallel, the elastoplastic behaviour is modelled coupling a recently developed multi-class precipitation model to an adaptation of the classical Kocks–Mecking–Estrin formalism. In addition to the classical isotropic effect of solid solution, precipitates and dislocation forests, the proposed model takes into account the kinematic contribution of grain boundaries as well as precipitates, thus providing a new physical meaning to the Armstrong–Frederick law. The resulting cyclic stress–strain curves compare well with the experimental ones for all treatments and strain levels.

Keywords: Isotropic hardening; Kinematic hardening; Precipitation; Age hardening; Cyclic loading

1. Introduction

Understanding of the microstructural evolutions and associated deformation mechanisms in age-hardening aluminium alloys has greatly progressed in the last decade (see for example the recent review of Simar et al. [1]). In their pioneering contribution, Myhr et al. [2,3] coupled a Kampmann–Wagner numerical (KWN) precipitation model with a dislocation strengthening model in 6XXX alloys after non-isothermal heat treatments, typical of that used for welding. The aim of this kind of studies is generally to predict yield stress, hardness [2,4,5] and, sometimes, strain hardening during a tensile test [1,6]. Nevertheless, despite this progress, the literature is more sparse on the cyclic behaviour of 6XXX alloys, for which accurate constitutive laws are needed for several applications such as fatigue or welding (especially for multi-pass processes).

Beyond practical applications, the use of cyclic behaviour enables some limitations attached with monotonous testing to be overcome. For example, kinematic hardening can be erroneously attributed to isotropic mechanisms, based on monotonous loading. The use of cyclic loading is then fundamental to separate the kinematic and isotropic contributions and thus better understand the hardening behaviour of age-hardening alloys.

In the literature, several authors have studied the impact of microstructural evolutions on the kinematic hardening of age-hardening aluminium alloys. Proudhon et al. [7] investigated the Bauschinger effect induced by isothermal treatments and proposed some elements of kinematic hardening modelling inspired by the pioneer contributions of Ashby [8], Brown and Stobbs [9]. Later, several teams took over these early studies: e.g. Fribourg et al. [10] on 7XXX series, and Teixeira et al. [11] and Han et al. [12] for Al–Cu–Sn alloys. However, these papers share a common drawback: the entire kinematic hardening is attributed to the precipitates, thus neglecting the potential impact of grain boundaries (as studied by Sinclair et al. [13]).

In this study a cyclic elastoplastic model is coupled to a recently developed precipitation model [14]. This coupling aims at understanding and describing the variety of cyclic behaviour that can be encountered in the heat-affected zone of a 6061-T6 weld joint. The modelling approach is based on:

- a robust precipitation model (KWN-type) detailed in previous papers [15,16] that has been recently adapted for rod-shaped precipitates and validated by transmission electron Microscopy (TEM) as well as small-angle neutron scattering (SANS) [14],
- an isotropic hardening model based on the Kocks–Mecking–Estrin (KME) formalism [17–19] embellished by the consideration of the entire precipitate

---

* Corresponding author; e-mail addresses: michel.perez@insa-lyon.fr; daniel.nelias@insa-lyon.fr

http://dx.doi.org/10.1016/j.actamat.2014.09.034

1359-6462/

Nomenclature

b	Burgers vector
C^{AF}	constant of the Armstrong–Frederick model
D	grain size
E	Young's modulus
f	yield surface
f_V	volume fraction of the $\beta'' - \beta'$ hardening phase
f_V^{bp}	volume fraction of bypassed precipitates
i_c	index of the class corresponding to the transition radius
k	strength constant for precipitate shearing calculation
k_1	multiplication constant in the KME model
k_2^0, k_2^p	dynamic recovery coefficients in the KME model
k_j	solid-solution strengthening constant for element "j"
$\overline{L_{bp}}$	mean distance between bypassed precipitates
l_i	length of the precipitate rod in the class "i"
l_{bp}	mean length of bypassed precipitates
M	Taylor factor
N_i	precipitate density in the class "i"
n_G	number of dislocation stored at grain boundaries
n_G^*	maximum number of dislocation stored at grain boundaries
n_{ppt}	number of dislocations stored around precipitates
n_{ppt}^*	maximum number of dislocations stored around precipitates
R	total isotropic hardening coefficient
$\overline{R}$	mean radius of the precipitate distribution
$\overline{R_{bp}}$	mean radius of the bypassed distribution
r^c	transition radius between sheared and bypassed precipitates
S_{ijkl}	component "$ijkl$" of the Eshelby tensor S
X_G	kinematic stress due to grain boundaries
X_{ppt}	kinematic stress due to Orowan storage
α	constant related to the forest hardening
β	constant related to dislocation line tension
γ^{AF}	constant of the Armstrong–Frederick model
$\Delta\sigma^{bp}$	bypassed precipitate contribution to strength
$\Delta\sigma_p$	precipitate contribution to strength
$\Delta\sigma^{sh}$	sheared precipitate contribution to strength
$\Delta\sigma_{SS}$	solid-solution contribution to strength
ϵ	uniaxial total strain
ϵ_e	elastic part of the strain
ϵ_p	uniaxial plastic strain
ϵ_p^*	unrelaxed plastic strain
κ	ratio of the length of the precipitate by its diameter
$\dot{\lambda}$	plastic multiplier
λ_G	mean spacing between slip lines at grain boundaries
μ	Shear modulus of the matrix
μ^*	shear modulus of the precipitates
v	Poisson coefficient
ξ	effective stress ($\xi = \sigma - X_G - X_{ppt}$)
Ω	Brown and Stobbs accommodation factor
φ	efficiency parameter for Orowan storage ($\in [0, 1]$)
ρ	dislocation density statistically stored
ρ_0	initial dislocation density
ρ_{ppt}	dislocation density stored in form of Orowan loops
σ_0	pure aluminium yield stress
$\sigma^y_{0.02\%}$	yield stress for 0.02% of plastic strain
χ	constant in X_{ppt} expression

distribution, solid-solution strengthening (as presented in Ref. [14]) as well as a precipitate-induced recovery mechanism [6],

- a kinematic hardening model based on grain and precipitate contributions, adapted from the work of Sinclair et al. [13], Brown and Stobbs [9] and Proudhon et al. [7] for cyclic hardening.

This approach will be validated by uniaxial multilevel cyclic loadings performed on specimens that were subjected beforehand to non-isothermal heat treatments, representative of welding thermal histories in a heat-affected zone as in Ref. [14]. The slip irreversibility mentioned in Ref. [12] is assumed negligible in this work, which simplifies the treatment of isotropic and kinematic contributions to the hardening. We indeed believe here that a clear description of slip irreversibility should come after a proper description of isotropic and kinematic effects, on which this paper is focused.

2. Materials and experimental methods

2.1. Materials and heat treatments

Uniaxial specimens were extracted from a 6061-T6 rolled plate of 50 mm thickness. The alloy composition is given in Table 1. In order to mimic the thermal cycles occurring in a heat-affected zone, two kinds of controlled heating cycles were performed on a home-made Joule thermomechanical simulator presented in Ref. [20] and improved for this study. Each cycle was composed of a heating stage (at constant heating rate) up to a maximum temperature, followed by natural cooling, as in the welding process (cooling rate between 30 and 50 °C s^{-1} depending on treatment). The specimen dilatation and contraction was free during these thermal cycles. In order to study the effect of both heating rate and maximal temperature, two types of treatments will be presented as detailed in Ref. [14]: