International Journal of Mechanical Sciences 144 (2018) 118–133

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

A modification of the multicomponent Armstrong–Frederick model with multiplier for the enhanced simulation of aerospace aluminium elastoplasticity

Dylan Agius[a,b], Kyriakos I. Kourousis[c,*], Chris Wallbrink[b]

[a] School of Engineering, RMIT University, Melbourne, Australia
[b] Defence Science and Technology Group, Fishermans Bend, Melbourne, Australia
[c] School of Engineering, University of Limerick, Limerick, Ireland

ARTICLE INFO

Keywords:
Cyclic plasticity
Kinematic hardening
Hysteresis loops
Mean stress relaxation
Multiplicative AF model
Aerospace aluminium

ABSTRACT

The Multicomponent Armstrong–Frederick (AF) model with Multiplier (MAFM) has demonstrated high simulation accuracy for uniaxial and multiaxial loading conditions for a number of different materials. In this study the MAFM model is modified to improve the phenomenological modelling of aerospace aluminium alloys 7075-T6 and 7050-T7451 under uniaxial constant and variable amplitude loading. In order to recognise the experimentally observed strain amplitude dependency of mean stress relaxation rate, the coefficient of the linear kinematic backstress was modified from a constant to a strain amplitude dependent dynamic term. This modification improved the mean stress relaxation capability of the MAFM model. Additionally, the hysteresis loop evolution has been enhanced via further modification of the MAFM model by improving the monotonic stress-strain evolution of the initial loading branch of cyclic load cases by separating the kinematic backstress coefficients into two parts, the contributions from cyclic and monotonic micro-mechanisms. The monotonic coefficients were allowed to decay with continued cycling, which captured the monotonic to cyclic transition of stress-strain development. Finally, the experimentally observed reversibility of the monotonic stress-strain evolution has been also incorporated successfully through the introduction of a decaying strain range memory parameter, which improved the variable amplitude hysteresis loop evolution. Overall, the modified MAFM model has been successful in improving simulation accuracy of the cyclic elastoplastic response exhibited by both aluminium alloys examined.

1. Introduction

Recent studies [2–4,21,31] have demonstrated the potential improvements that can be achieved in strain-life fatigue predictions through the application of phenomenological constitutive models which are capable of accounting for transient cyclic effects. These models belong to a branch of modelling approach which uses nonlinear kinematic hardening to predict the macroscopic stress and strain, with the most widely employed models being those based on the original Armstrong-Frederick (AF) model [8]. The AF-based models are favoured for strain-life applications due to their numerical implementation simplicity and computational efficiency, which is particularly important when performing fatigue life predictions requiring the input and analysis of in-service aircraft complex spectra. When applying constitutive models to strain-life predictions it was shown by Agius et al. [2] that the hysteresis loop development is very important in the accurate prediction of fatigue life. In particular, the combination of the applied isotropic hardening and kinematic hardening coefficients has been shown to have a considerable influence on the hysteresis loop predictions and simulation accuracy of both strain ratcheting and mean stress relaxation. Therefore, accurate simulation of not only the mean stress relaxation but also of the hysteresis loop development is of outmost importance in strain-life fatigue analysis methods.

One of the interesting features of the elastoplastic behaviour of many metallic materials is the stress-strain progression from the initial (monotonic) loading branch to the subsequent stress-strain hysteresis loops in the cyclic zone. A noticeable difference in the shape of the initial-subsequent hysteresis loops' branches is observed for most metals, including aluminium 7075, as illustrated in Fig. 1.

In the constitutive modelling of metallic materials, it is typically assumed that the monotonic to cyclic transition is irreversible; therefore, a commonly adopted modelling solution is to utilise two sets of model parameters in order to simulate the monotonic and the subsequent cyclic behaviour [3,18,33]. Zhu et al. [38,39] and Zhu and Poh [40] have managed to simulate both the monotonic and cyclic zones without the need

* Corresponding author.
E-mail address: kyriakos.kourousis@ul.ie (K.I. Kourousis).

https://doi.org/10.1016/j.ijmecsci.2018.05.036
Received 8 December 2017; Received in revised form 16 April 2018; Accepted 17 May 2018
Available online 29 May 2018

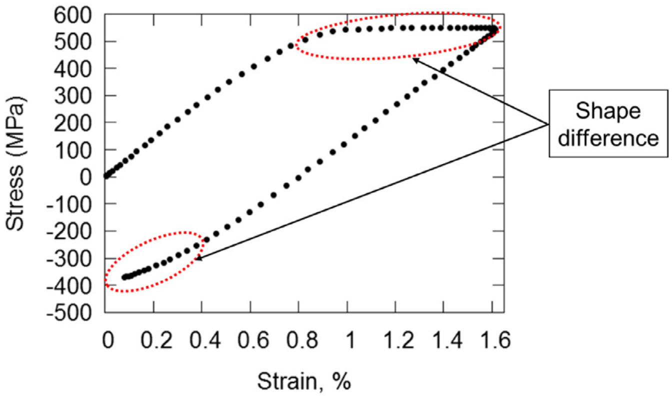

Fig. 1. Experimental stress-strain test data obtained for aluminium 7075 when loaded under an asymmetric strain controlled history (experimental data from Agius et al. [2]. The difference in the hysteresis loop branch shape between the initial (monotonic) and cyclic region is indicated by the red-dotted contour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of a parameter switch, by introducing a dynamic nonlinear kinematic hardening coefficient.

In an investigation conducted by Yu et al. [36], where a variable amplitude load case was applied to aluminium 7075, the monotonic behaviour was reactivated by an overload (a larger strain amplitude), with stress-strain evolution achieved being almost identical to the initial monotonic loading branch. The peculiarity of the results lies in the re-emergence of the monotonic deformation behaviour, even after the formation of a very different dislocation microstructure. These Yu et al. [36] findings are confirmed by examining the previously published work of Arcari and Dowling [7] where, although not specifically reported or discussed, the re-emergence of the monotonic behaviour is observable in the variable amplitude hysteresis loop data. These examples suggest that the monotonic to cyclic stress-strain evolution may be reversible and appear later in variable amplitude loading histories.

The difference observed in the backstress evolution between the initial (monotonic) and the cyclic loading could be explained by examining the micro-mechanisms occurring during each stage of loading. A change in the dislocation density between that occurring during the first few cycles and that at a later stage of loading, could result in a changing evolution of the backstress. Huang et al. [22] observed this change in dislocation density at different stages of loading and showed that the dislocation density eventually stabilised after a number of cycles. It has been previously identified that two types of effects give rise to backstresses in polycrystals, namely the intergranular and intragranular effects [32]:

- Intergranular effects are those which occur as a consequence of grain interaction (due to differing crystallographic orientations) or interactions between phases of alternate strength and/or stiffness [34].
- Intragranular effects refer to backstress formed as a result of dislocation interactions which exist as a consequence of the formation of a dislocation microstructure of regions of high and low dislocation densities, forming cell walls and cell interiors respectively [29].

Since the intragranular backstress is influenced by the dislocation density, before the onset of dislocation density stabilisation noticed by Huang et al. [22], it is possible that there is difference in the backstress evolution between the cyclic and monotonic zone.

Furthermore, one must also consider the micro-mechanism contribution to the re-emergence of the monotonic stress-strain evolution in a variable amplitude loading condition, noticed by Yu et al. [36]. An explanation to this re-emergence could be based on the influence of the dislocation structure formed during the benign cyclic loading. During the first few cycles of the benign load case, the material would have hardened as a consequence of dislocation interaction, particularly due to internal stresses formed from anchored dislocations within crystals [23]. Therefore, when the overload occurs, an increased stress is required to overcome these dislocation interactions to initiate the dislocation movement, as well as to nucleate dislocations, leading to the monotonic stress-strain evolution.

The re-emergence of the monotonic behaviour and the difference in stress-strain evolution between the monotonic and cyclic loading branches cannot be ignored in constitutive modelling of materials subjected to variable amplitude loading histories. This is due to the influence of the monotonic stress-strain evolution on post load conditions. Additionally, it has been previously shown that the mean stress relaxation is also dependent on the tensile plastic strain history [35]. Therefore, it is important to capture the re-emergence of the monotonic behaviour in order to obtain an accurate representation of the mean stress relaxation in variable amplitude loading histories.

Another feature of elastoplastic behaviour which affects stress-strain evolution, and requires consideration in the development of constitutive models, is the mean stress relaxation dependence on strain amplitude. For low strain amplitudes, the rate of mean stress relaxation has been identified to be considerably lower and for particular amplitudes experiencing saturation rather than complete relaxation. This phenomenon has been identified in various aluminium alloys, such as 7075 [2,6], 7475 [6], 7050 [20], 2124 [17] and 6060 [19], as well as steel alloys [26,35].

A number of different phenomenological constitutive models have been proposed over the last several decades, as comprehensively reviewed by Chaboche [12]. Although modifications to phenomenological models have primarily been focused on improving simulation accuracy of strain ratcheting, more recently, the need for improvements to the mean stress relaxation capabilities have drawn increased attention [7,9,10,35]. A few modifications to the constitutive models have been proposed to capture the phenomenological behaviour of aluminium alloys [7,25,33]. However, the modifications to these models do not take into account the aforementioned combination of elastoplastic behaviour experimentally observed and investigated by several researchers.

In light of the elastoplastic behaviours presented and the need for a constitutive model to simulate these features accurately, this study proposes a modification of the Multi-component Armstrong-Frederick (AF) [8] model with Multiplier (MAFM) [15]. This modification aims to improve the simulation accuracy of the backstress evolution in both the cyclic zone and the initial (monotonic) loading part. In particular, the modification of the MAFM model incorporates features that enable:

- The reversibility of the monotonic behaviour, allowing for capturing its re-emergence during variable amplitude loading;
- The mean stress relaxation dependence on strain amplitude.

This new modelling approach is shown to improve the simulation accuracy of mean stress relaxation and hysteresis loop development of two commonly used aerospace aluminium alloys (7075 and 7050), both in constant and variable amplitude loading.

2. Theory

2.1. Constitutive model development and mathematical formulation

The new constitutive model proposed employs:

- A kinematic hardening rule which contains dynamic coefficients capable of recognising the contribution of the monotonic micro-mechanisms, as well as the strain amplitude.
- A shrinking strain amplitude memory which allows for the reactivation of kinematic dynamic coefficients at strain amplitudes higher than previously encountered in the loading history.