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A texture-based representative volume element crystal plasticity model for predicting Bauschinger effect during cyclic loading

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ABSTRACT

A texture-based representative volume element (TBRVE) crystal plasticity model is developed to predict the Bauschinger effect (BE) in rolled polycrystalline aluminium alloy 7075 under cyclic loading. The TBRVE is systematically created using the Voronoi tessellation method and discretisation of orientation distribution function, to more accurately represent both the grain morphology and crystallographic texture. Simulations of loading in the transverse and rolling directions are conducted using a backstress incorporated crystal elasto-viscoplastic model. The hysteresis loops are successfully predicted by the proposed model up to saturation, and the BEs in both the transverse and rolling directions are also captured. For the first time, the effects of backstress and residual stress, which induce the mechanical BE and microstructural BE respectively, are quantitatively determined through simulation. It is found that they have similar contributions to the total BE. This study indicates that TBRVE is important for crystal plasticity finite element method to effectively reproduce the anisotropy of the material, and more importantly, determine the components of BE during cyclic loading.

1. Introduction

The Bauschinger effect (BE) has been shown to play an important role in the spring back phenomenon during sheet metal forming [1–3]. It has been observed in most polycrystalline metals that the absolute value of the yield stress drops during reversal loading [4,5]. The magnitude of the BE is related to complex factors, such as the loading path, strain rate and temperature, as well as the texture of the material tested. Weng [6,7] reported that the BE of a single crystal was caused by the kinematic hardening behaviour which relates to dislocation pileups, while in a polycrystal it was caused by both the kinematic hardening and the residual stress. As a consequence, the BE is found to be closely connected to slip deformation at the micro-scale. Using the modern micro-scale experimental technology, Demir and Raabe [8] observed that the BE in a copper single crystal under micro-bending consisted of two sources, the internal backstress and the reversibility of the microstructure, and introduced the mechanical BE and the microstructural BE to describe these two contributions to the total BE. However, quantitative determination of the mechanical and microstructural BEs experimentally is still not available. We propose to evaluate them numerically through crystal plasticity finite element (CPFE) method.

The internal backstress has been widely used to explain the mechanical BE induced by dislocations. The term backstress was first introduced by Nowick and Machlin [9] as the inner stress field of the lattice of stuck dislocations. In the crystalline lattice, the backstress is always smaller than the applied stress and opposite to the direction of the shear stress. Kassner et al. [10] conducted synchrotron X-ray micro-beams diffraction experiments and confirmed the existence of the backstress in Cu single crystals with a cellular substructure. Various theories and methodologies have been developed [11–16] to model the evolution of backstress. Among these models, the Armstrong–Frederick nonlinear kinematic hardening rule for single crystals [17,18] is frequently employed to capture the recovery of backstress. Other theories were developed continuously. For instance, Bayley et al. [19] used the geometrically necessary dislocations model to consider the backstress which includes latent kinematic hardening from all the slip systems in single crystals. A simple backstress equation was proposed by Sauzay [20] with the assumption of having hard and soft phases in microstructure, and successfully predicted the intragranular backstress in single crystals.

Meanwhile, the CPFE method is widely employed to simulate the mechanical response and texture evolution of crystalline materials [21–27]. Efforts have been made to incorporate the

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backstress within the CPFE framework to model the BE in the past few decades. For instance, Yapici et al. [28] used a viscoplastic self-consistent polycrystal model where the backstress was incorporated to study the stress–strain asymmetry under various strain paths. They concluded that the asymmetry and anisotropy are not only induced by crystallographic texture but also related to the severe pre-straining history in different directions. Recently, the BE in dual-phase steels involving plastic incompatibility was investigated by Kim et al. [29] using a simplified dislocation density model combined with a representative volume element (RVE). They concluded that the strain hardening stagnation can be explained by the dislocation pileup induced backstress during reversal loading. Brahme et al. [13] imported electron back-scatter diffraction (EBSD) maps to the CP microstructure, and investigated the dependence of backstress evolution on strain paths and deformation boundaries. Hansen et al. [30] also utilised EBSD data combining with CPFE method to model the texture evolution of Cu/Nb layered nano-composites, and effectively simulated the experimental texture change. More recently, Li et al. [31] included the factors of elastic anisotropy, dislocation densities, grain sizes and crystallographic orientations along with the Armstrong–Frederick rule in their polycrystal plastic model, which successfully predicted the cyclic responses of 304L steel at different strain amplitudes.

Besides the commonly used RVE, other volume elements were developed for crystal plasticity simulations. The statistical volume element (SVE), which is smaller than a RVE but large enough to represent the microstructural response at a particular location, was developed to study parameters of interest at the grain level [32,33]. Usually the SVE only reflects the crystalline features of the particular grain aggregate that is sampled. Thus it cannot represent the macro-scale material response like a RVE, but it can be extended to statistically reveal the global response through the assembly of several individual SVEs. Shenoy et al. [34] used the SVE to simulate the effects of microstructure attributes and properties on driving forces for fatigue crack initiation and microstructurally small crack growth in a polycrystalline Ni-base superalloy. Qidwai et al. [35] developed a weighted statistical volume element (WSVE) that can estimate the response of large grain aggregates with reasonable accuracy and requires less computing power as compared with the traditional RVE. Very recently, Zhang et al. [36] constructed a statistical representative volume element (SRVE) which consists of 100 grains, and used it to predict the low-cycle fatigue life of pure copper. However, none of these volume element representations completely describes the grain texture and morphology of the macro-scale polycrystals, and the applications of these representations are mainly limited to equiaxial grains. Although simulations using the SVE and WSVE run faster than that using the RVE, multiple simulating sets are necessary because of the intrinsic statistical characteristic.

As discussed by Demir and Raabe [8], the microstructural BE, which is caused by freely mobile dislocations in a single crystal, will be much weaker in polycrystals than in a single crystal. Referring the conclusion of Weng [7] that the BE is induced by kinematic hardening and residual stress in a polycrystal, a presumption is made that the microstructural BE will be no longer dominated by the reversibility of microstructure but by the residual stresses in polycrystals, although it is still called microstructural BE. Those results motivated the present study for the development of a CPFE model that not only represents the material texture and morphology, but also accounts for the mechanical BE and the microstructural BE of polycrystals simultaneously.

In the present work, an approach is proposed to improve the prediction of the BE of aluminium alloy 7075 (AA7075). It takes the grain texture and morphology into account and provides localised responses of individual grains. An Armstrong–Frederick nonlinear kinematic hardening rule is implemented into the CP framework to consider the backstress evolution, and a texture-based representative volume element (TBRVE) is developed to accurately represent the grain texture and morphology for better predicting the microstructural BE.

The remaining sections of the paper are arranged as follows. The properties of AA7075 and the cyclic loading experiments are introduced in Section 2. The modification of the backstress incorporated CP formulation along with the definition of residual stress range are presented in Section 3. The TBRVE is introduced and the parameters are calibrated in Section 4. The CPFE simulation results are validated with experimental data in Section 5, and the factors influencing the BE are discussed in this section as well. The conclusions are given in Section 6.

2. Material and uniaxial cyclic loading experiments of AA7075

The specimens of AA7075-T651 are all taken from a large plate of a commercial product (see Fig. 1). The chemical composition of the material is listed in Table 1. The cyclic loading tests are conducted according to the American Society for Testing and Materials standard ASTM E606-04. To reflect the anisotropy of the material, specimens are cut along 0° and 90° with respect to the rolling direction. The specimens are subjected to constant amplitude uniaxial cyclic loading with a strain limit of $\pm$ 1.5% and a strain rate of 0.0004 s^{-1} in a servo-hydraulic testing machine MTS-810. The cyclic loading is applied until the stress–strain loops reach saturation.

Table 1
Chemical compositions of AA7075-T651.

Composition	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	other	Al
Content (wt%)	0.11	0.21	1.6	0.02	2.4	0.2	5.8	0.03	0.07	Bal.

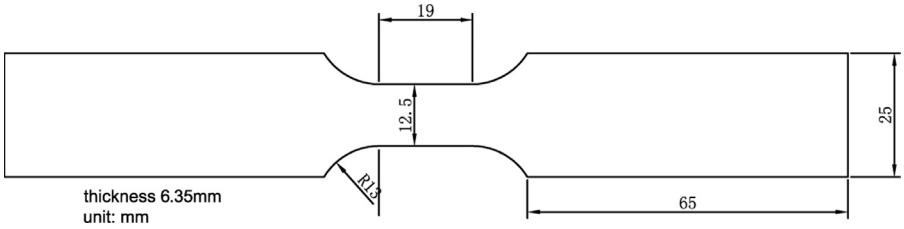

Fig. 1. Dimensions of the AA7075 specimens subjected to cyclic loading.