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Prediction of shear localization during large deformation of a continuous cast Al–Mg sheet

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Abstract

In this work, a novel continuum solid mechanics approach has been proposed to predict shear band formation in uniaxial tension, utilizing both plane stress and three-dimensional analyses. The approach postulates a heterogeneous distribution of mechanical properties through the starting material. This may be attributed to the second-phase particles, textural banding or grain size variability of the sheet material. The model is used to study the effect of such heterogeneity on the development of shear localization with increasing strain. We also consider how such a model depends on the constitutive equations that are used. It is found that the Voce equation offers realistic predictions of necking and shear localization whilst the Hollomon equation fails to do so over a realistic range of deformation. The location of necking in each structure is controlled by the largest zone of soft material. The influence of the distribution, size and geometry of soft zones have been extensively studied. The amount of inhomogeneity required to precipitate localization is determined and confirmed using the Marciniak–Kuczynski method. The predicted force–displacement curves, limit strains to failure and the shear band angles all agree well with experimental observations.

Keywords: Al–Mg alloy; Finite element method; Shear localization; Uniaxial tension

1. Introduction

Continuous cast (CC) aluminium alloys have attracted increasing commercial interest due to their low processing cost and reduced energy requirement compared with the conventional direct-chill (DC) cast alloys. One of the challenges with CC Al alloys is to understand and improve their formability in order to make this equivalent to or better than DC alloys. The formability of automotive materials is often limited by shear localization in the form of macroscopic bands through the thickness of the sheet. This phenomenon is regularly observed in Al–3% Mg alloys such as AA5754-O (in CC and DC variants) during sheet forming.

A considerable body of work now exists related to the prediction of shear localization using finite element method (FEM). Generally, this has been accomplished by: (1) introducing yield surface vertex effects such as J_2 corner theory [1] and (2) considering the explicit softening effect due to either adiabatic heating (especially in high strain rates) or microvoid nucleation and coalescence. Crystal plasticity models, for example, inherently involve vertex effects [2]. Such models are regarded as holding great promise for the prediction of shear localization and have been extensively used in recent years. However, such models demand extensive computing resources, especially when large scale heterogeneity is of interest.

The Gurson–Tvergaard–Needleman (GTN) model [3–4] is a classical void induced constitutive softening model. A scalar variable, the volume fraction ratio, is integrated into the yield function to produce a softening effect. Although the fracture surface shows dimples, detailed experimental observations for low Fe (0.08%) Al–3% Mg alloys have not revealed any convincing evidence to support the argument that shear localization is caused by intense microvoids nucleation,

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growth and coalesce, until very late in fracture process where macrovoids were found within the shear bands [5]. Moreover, this model is based on an erroneous criterion of microvoid coalescence [6]. Therefore, GTN model is not applicable to this alloy.

It is generally accepted that formability is closely related to the microstructure inherited from the upstream processing. The distribution of microstructure (such as textural components, grain size and orientation, and the second phase particles) is typically inhomogeneous. Raabe et al. [7] found that the existence of soft and hard inclusions stimulates strong heterogeneity of surface strains and results in ridging. Wittridge and Knutsen [8] found that, when the strong *R* texture component was embedded within the soft matrix of cube texture component, strain localization was produced through the specimen thickness. The cross-sectional area will naturally display small variations along the gauge section of a tensile specimen. Affected by surface defects (such as roughness and scratch), and to some extent the thickness of the received material is also not uniform. The work conducted by Yamaguchi et al. [9] indicated a close correlation of strain localization, strain hardening and surface roughness. In general, unavoidable variations exist in mechanical properties: some regions are hard and difficult to deform, whilst other regions are soft and undertake considerable deformation.

Two kinds of local instabilities, Piobert–Lüders (PL) and Portevin–Le Chatelier (PLC) instabilities, are regularly observed in the macroscopic stress–strain curve for Al–Mg alloys. The PL phenomenon is a strain softening type instability and is characterised by the presence of a plateau of almost constant stress after the onset of yielding. The PLC effect is a strain rate softening type instability and manifests itself as serrations in the stress–strain curve during the work hardening stage of deformation. A generally accepted mechanism for the PL phenomenon is attributed to dislocation locking by interstitial atoms in solid solution under ageing [10]. The PLC phenomenon, on the other hand, is understood as a consequence of dynamic strain ageing of dislocations by diffusing solute atoms [11]. These two instabilities make the prediction of microstructural influence on formability a great challenge. Recently, several studies have been carried out to study the PLC phenomenon by the use of finite element method (FEM) [12–14]. A simple approach was also reported to simulate the PL effect [15].

In this paper, instabilities in the form of diffuse and localized necking are predicted using FEM, with emphasis on the effect of microstructural inhomogeneity on strain-hardening behaviour. We have also studied the effect of mesh size sensitivity, influence of constitutive relationships used (the Hollomon and the Voce equations), the distribution, size and geometry of heterogeneous regions in the material and distribution of mechanical properties through the thickness. The required amount of inhomogeneity is finally determined and confirmed by the use of Marciniak–Kuczynski method.

2. Experimental procedures

Uniaxial tension tests were performed according to ASTM standard B 557M-94 to obtain the basic mechanical properties of CC AA5754-O in different orientations, i.e. tensile axis parallel to the rolling direction (RD) and transverse direction (TD). All the tests were done at a strain rate of $6 \times 10^{-4}\,s^{-1}$. Load and displacement values were continuously recorded during the tests. Tensile tests for *R*-value measurements were conducted according to ASTM standard E517-92 along RD, TD and at 45° orientations with respect to RD. The *R*-values were evaluated in the engineering strain range of 0.09–0.11 and 0.15. The *R*-values measured were 0.6, 0.75, and 0.65 along RD, TD and at 45°, respectively, indicating that the material had a rather weak texture. This is further confirmed by the measured yield stresses along RD, 45° and TD of 107, 103 and 106 MPa, respectively. A decorating technique developed by Lloyd et al. [16] was used to show the shear band formation. Some typical optical micrographs from surface region within the neck are shown in Fig. 1.

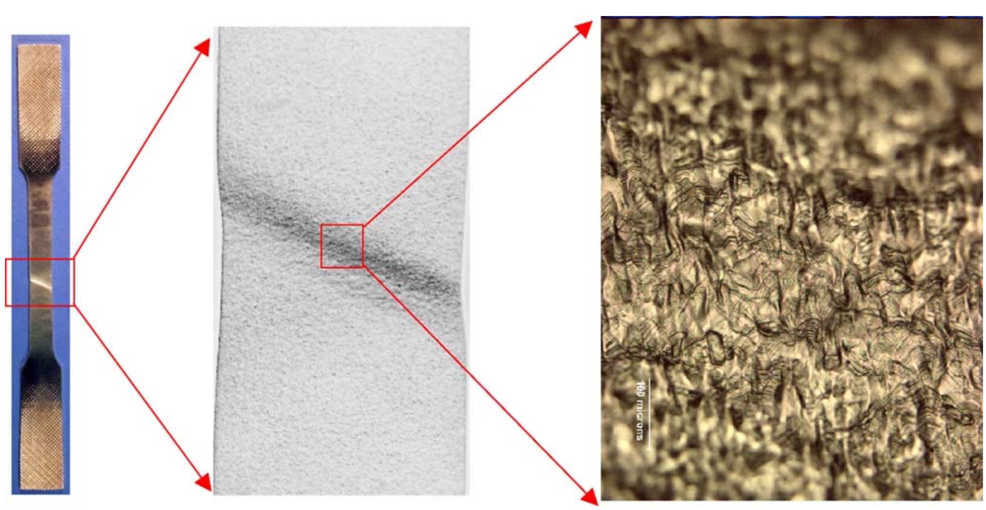

Fig. 1. Experimental observations of shear band.