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A unified model for coupling constitutive behavior and micro-defects evolution of aluminum alloys under high-strain-rate deformation

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ABSTRACT

High strain rate forming (HSRF) is promising to break through the conventional forming limit of materials and thus to form hard-to-deform components. During HSRF process, long-lasting micro-defects before fracture, i.e. adiabatic shear bands (ASBs) in compression and voids in tension, are significant characteristics existing in a large strain range. These defects bring about the non-destructive softening of stress and continuous exertion of ductility, in return, the stress responses affect the evolution of micro-defects. However, the interaction between stress responses and defects evolution has not yet been reflected in the existing models, resulting in a limited prediction accuracy. Aiming at this issue, the competition between hardening caused by thermal activated dislocation movements and the flow softening brought by micro-defects evolution was well modeled in this work. During the modeling, the relation between the normal strain and effect zone of ASBs was established via the modification of Bai–Dodd model by considering the geometric features of ASBs. Moreover, by introducing a rate-dependent ASB trace angle, the half width of ASBs was expressed as a function of maximum shear strain and critical instability strain. The effect of strain and strain rate to the evolution of voids under tensile conditions was taken into account by combining Hollomon hardening law with Johnson–Mehl–Avrami–Kolmogorov (JMAK) equation. Then, the interactions between micro-defects and structure-related athermal stress were characterized by connecting volume fraction of voids and effective bearing area in tension and the intensity of flow localization with ASBs width in compression. As a consequence, a unified model of constitutive behaviors coupled with micro-defects evolution was established with considering rate-dependent hardening and softening. Applied to aluminum alloys, this model predicts the stress responses, evolution of ASBs and voids, and low or negative strain rate sensitivity with high precision in large ranges of strain (0–0.6) and strain rate (0.001–5000 s^{-1}). The proposed model is thus believed to be with a successful application in precise prediction and optimization of HSRF processes.

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1. Introduction

High strain rate forming (HSRF) techniques, e.g. electromagnetic forming (EMF), electrohydraulic forming and explosive forming, are with great potentials to break through conventional forming limit and manufacture hard-to-deform components (Neugebauer et al., 2011; Psyk et al., 2011). Therefore, they attract more and more attentions in the manufacture of light-weight components from sheet metals during recent decades (e.g. widely used aluminum alloys) (Khan and Liu, 2012a, b; Pandey et al., 2015). During HSRF process, sheet metal undergoes high strain rate (HSR) deformation (with the peak strain rate higher than 1000 s^{-1}) under impaction body/surface force and thus shows distinctive deformation behaviors (Shojaei et al., 2013; Yanilkin et al., 2014; Hunter and Preston, 2015; Khan et al., 2015; Morrow et al., 2016). Precisely characterizing these constitutive behaviors of materials is crucial for the simulation and process optimization of HSRF and so with great importance.

According to the state-of-art technology, the HSR constitutive modeling in certain ranges of strain and strain rate is already a solved problem (Chaboche, 2008; Voyiadjis and Almasri, 2008; Colvin et al., 2009; Austin and McDowell, 2011; dos Santos et al., 2006). However, multi-fields coupling, time-varying force loading and multi-parameters affecting non-uniform deformation of materials during the HSRF process, for example the EMF, leads to wide ranges of strain (e.g., 0–0.6) and strain rate (e.g., 0.001–10^4 s^{-1}) which distribute non-uniformly within a HSRFed component. In addition, inhomogeneous distribution of micro-defects such as adiabatic shear bands (ASBs) in compression and voids in tension is also induced, which makes stress responses even more complicated (Djapic Oosterkamp et al., 2000; Ulacia et al., 2011; Cerreta et al., 2013; Shojaei et al., 2013; Roth and Mohr, 2014). In detail, the long-lasting ASBs and voids bring about the non-destructive softening of flow stress and continuous exertion of ductility (Smerd et al., 2005; Yan et al., 2014a). Longer duration and more homogeneous distribution of these defects before macroscale failure occurs are beneficial to the improvement of forming limit. These features bring about key problems on in-depth understanding and precise prediction of the interaction of micro-defects evolution and strain–strain rate-varying constitutive behaviors, the perfect solution of which will be beneficial for process design of HSRF.

In order to predict material behaviors during HSRF, phenomenological models were usually used for describing various phenomenological features of materials. Among these models, the Fields–Bachofen typed model (the F–B model) (Klopp et al., 1985; Zhang, 2003) and Johnson–Cook typed model (the J–C model) (Ulacia et al., 2011; Chen et al., 2009; El-Magd and Abouridouane, 2006) are two kinds of extensively used ones which consider strain hardening, strain rate hardening/softening and thermal softening separately by using multipliers. The F–B model is with simple expression and able to predict well in thermal effect. However, it is not suitable for predicting complex deformation process and thus the satisfactory prediction can only be achieved at 0.1–0.3 strain and a temperature of 423–573 K (Cheng et al., 2008; Lin and Chen, 2011). Moreover, the J–C models have constant material parameters within small ranges of strain, strain rate and temperature (Psyk et al., 2011) and thus still have limitations in wide-range prediction. With consideration of the rate-dependent strain hardening of body centered crystal (B.C.C.) alloys, Khan and Liang (1999) established an accurate Khan–Huang–Liang (K–H–L) model which successfully predicted the high-strain-rate softening of Armet 100 steel and tungsten alloy. Moreover, the K–H–L model also described the effect of loading path to the deformation behaviors (Khan and Liang, 2000). With the development of phenomenological model, microstructure-related parameters, such as grain size, effective structural scale δ, were also integrated into the constitutive models (Khan et al., 2006; Farrokh and Khan, 2009; Molinari and Ravichandran, 2005). Many characteristic deformation behaviors including the change in hardening behaviors caused by grain refinement (Khan et al., 2006), the variation of deformation/temperature histories (Molinari and Ravichandran, 2005), the variation of strain rate sensitivity from negative to positive value (Khan and Liu, 2012a, b; Kabirian et al., 2014) and the effect of temperature on hardening behaviors (Farrokh and Khan, 2009), were also expressed to a certain extent. However, the evolution of these microstructure-related parameters were not coupled into these constitutive models and the meaning of these parameters are still not clear. That is to say that phenomenological models are still lack of the capability of precisely predicting macro–micro behaviors of materials (Lin and Chen, 2011).

Physically-based constitutive models are based on the internal mechanisms of plastic deformation including dislocation dynamics, thermal activation theories and thus are intrinsically capable of capturing the essence of these physical processes. Hence, with their aid, the deformation behaviors of materials can be predicted more comprehensively within wider ranges of strain and strain rate. Follansbee and Kocks (1988) put forward a concept of mechanical threshold stress (the MTS model) and accurately predicted the thermal activation characteristics of dislocation movements of copper during HSRF. By taking other microstructure-related deformation mechanisms into consideration and employing corresponding modifications, the MTS model gained more and more extensive applications (Durrenberger and Molinari, 2009; Zerilli and Armstrong, 1987; Voyiadjis and Abed, 2005a; Voyiadjis and Almasri, 2008; Nemat-Nasser and Li, 1998). Apart from the above mentioned mechanism of thermal-activated dislocation movement, viscous drag/phonon drag (Hoge and Mukherjee, 1977; Rusinek and Klepaczko, 2001, 2009; Gao and Zhang, 2012), overdriven shocks (Preston et al., 2003) were also considered in corresponding models.

Taking different hardening characteristics of different crystal structures into account, Zerilli and Armstrong (1987) derived a rate and temperature-dependent constitutive expression on the basis of dislocation dynamics (the Z–A model). Following the Z–A framework, Voyiadjis and Abed (2005a) and Voyiadjis and Almasri (2008) established the V–A model to describe rate and temperature-dependent flow stress of Oxygen-free high conductivity (OFHC) copper with a consideration of the evolution and interaction of dislocations. In Nemat Nasser and Li's work (1998) (the NNL model), dislocation spacing rather