International Journal of Solids and Structures 000 (2016) 1–19

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Modeling spontaneous shear bands evolution in thick-walled cylinders subjected to external High-strain-rate loading

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ARTICLE INFO

Article history:
Received 29 December 2015
Revised 30 June 2016
Available online xxx

Keywords:
Adiabatic shear band
Thick-walled cylinder
Self-organization
Work-hardened layer
Single direction spiral pattern

ABSTRACT

The evolution of spontaneous shear bands in a 304 L stainless steel (304LSS) cylinder subjected to external explosive loading was numerically studied. As an instability process, the initiation of a shear band is strongly dependent on the non-uniformities of the material. A probability factor satisfied the Gaussian distribution was introduced into the macroscopic constitutive relationship to describe the nonuniform distribution of the local yield stress in material. On the basis of that the material inside the shear band undergoes a dynamic recrystallization process (DRX), the traditional J-C model was modified. The item melting temperature, T_m, was replaced by the temperature for DRX, T_{DRX}. Specifically, the T_{DRX} was set to be $0.4T_m$ at high strain rates ($>10^3 s^{-1}$) for 304LSS. Using the probability factor and the modified J-C model, we successfully simulated the initiation and propagation of spontaneous shear bands in the collapsing 304LSS cylinder. The pattern of the shear bands agrees well with the experimental observations, at both early stage and late stage. The perturbation amplitude was found to have a slight influence on the shear band spacing and the initiating time of shear bands. Some morphological characteristics of shear bands (such as bifurcation, intersection and countercheck), which are familiar in experiments, were also observed in our simulation. The formation mechanisms of these phenomena were analyzed on the basis of their evolvements.

The shear bands in TWC show a single direction spiral pattern, in other words, almost all the shear bands simultaneously propagate along a given direction, clockwise or counterclockwise. The single direction spiral pattern is closely related to the work-hardened layer in the internal surface of the 304LSS cylinder. The microstructures in the work-hardened layer (about 30 µm) are significantly different from those in the base material. The grains have been rotated and elongated along the cutting direction during the machining. In the simulation, periodic single direction spiral perturbations were applied to describe the grain orientation in the work-hardened layer, and the single direction spiral pattern of shear bands in 304LSS TWC was successfully replicated. While the spacing of the single direction spiral perturbations exceeds a certain value, the shear bands switch back to the bidirectional spiral pattern. The critical spacing for the pattern transition was found to be close to the spacing of well-developed shear bands.

1. Introduction

Adiabatic shear banding (ASB) is one of the most important failure mode in metals subjected to high strain rates deformation (Bai, 1990, Meyers, 1994, Wright, 2002, Børvik et al., 2001). The material inside ASB loses its shear-bearing capacity and sustains a weak continuity. ASB often acts as a precursor to catastrophic failure, so it has been paid increasing attention and been extensively studied in the past decades. The dynamicists tried to clarify the relationship between the formation of an ASB and the strength evolution of a material and/or a structure (Zener and Hollomon, 1944, Marchand and Duffy, 1988, Bai et al., 1994, Xu et al., 2008b). They pointed out that an ASB occurs while thermal softening effect prevails the strain and strain-rate hardening effects in materials. The peak of the stress-strain curve is the initial point of deformation localization. For idealized models of simple shearing deformations, Molinari and Clifton, (1987,1983) developed the critical conditions for shear localization in thermoviscoplastic materials. The metallurgists carefully tracked the evolution of microstructures in ASBs (Nesterenko et al., 1997, Meyers et al., 2001, Meyers et al., 2003, Xue and Gray, 2006a,b, Xue et al., 2007, Guduru et al., 2001). The substructures at an early stage of shear band was discovered to strongly depend upon existing defects. These defects provided

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http://dx.doi.org/10.1016/j.ijsolstr.2016.07.014
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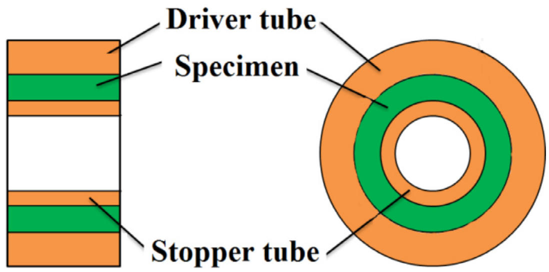

Fig. 1. The core of thick-walled cylinder configuration.

perturbations, which play key roles in the formation of an ASB (Xue et al., 2007). The material inside an ASB was found to behave like fluid (Guduru et al., 2001). Within the ASB, the microstructures consist of fine recrystallized grains, with the finer grains located closer to the center of the band. The process of grain refinement in ASB is considered to be controlled by dynamic recrystallization (DRX) (Xue et al., 2007).

According to the geometry of the specimen and the loading condition. ASB initiation can be divided into two groups: forced shear localization and spontaneous shear localization (Chen et al., 1999, Lovinger et al., 2011, Liu et al., 2014).

- Forced shear localization. It is usually observed in high speed machining, penetration and perforation. This kind of shear band does not result from material instability. Its initiation region and developing direction are determined by the geometry of the specimen and the direction of the maximum shear stress. Hat-shaped specimen or pre-notched specimen are widely-used to investigate this kind of shear localization (Xue and Gray, 2006a,b). The ASB evolution in such specimens is controllable, so they are very suitable to study the microstructure evolution in the ASB (Xue and Gray, 2006b).
- Spontaneous shear localization (Chen et al., 1999, Lovinger et al., 2011). This kind of shear localization emerges while symmetrical structures are driven by symmetrical strong loading. In general, multiple shear bands will appear under this kind of symmetrical conditions. The locations initiating shear bands are unknown before testing. Every position has the same chance to evolve into a shear band. Compared to forced shear localization, this kind of shear localization forms in a spontaneous way, so it can better reveal the interaction between multiple shear bands and the susceptibility of material to ASBs.

These two kinds of shear localizations initiate in different ways, but the microstructure evolution and mechanical behavior of the material in ASBs are the same.

A thick-walled cylinder (TWC) method was proposed to study spontaneous shear localization by Nesterenko et al. (Nesterenko et al., 1989, Nesterenko and Bondar, 1994). The core of TWC configuration consists of three tubes, which is illustrated in Fig. 1. A cylindrical specimen is sandwiched between an outer driver tube and an inner stopper tube. Traditionally, explosive is axisymmetrically filled outside of the driver copper tube and detonated on its top to drive the TWC to collapse inwardly. Xue et al., (2003, 2004) evaluated the influences of several engineering factors on the spacing and length of ASBs in TWC, and then systematically investigate the formation and evolution of ASBs in 304 L stainless steel (304LSS). Recently, Lovinger et al., (2011, 2015) employed an electromagnetic technique to create the driving force. Using this technique, the TWC experiments are allowed to carry out in standard laboratory environments without specific experimental set-up, such as proving ground or explosive vessel. Using the electromagnetic set-up, Lovinger et al., (2015) examined the evolution of multiple shear bands in several metallic alloys.

In the TWC experiments, an effective strain is defined to quantitatively describe the deformation of the specimen, which is (Xue et al., 2004)

$$\varepsilon_{ef} = \frac{2}{\sqrt{3}}\varepsilon_{rr} = \frac{2}{\sqrt{3}}\ln\left(\frac{R_0}{R_f}\right) \tag{1}$$

where R_0 and R_f are the initial and final radii of the inner surface of the specimen.

In the collapse process, multiple shear bands initiate at the inner surface of the specimen and then propagate outwardly. The evolution of multiple shear bands in TWC exhibits self-organization character, which mainly consists of two aspects:

(1)The first one is that the multiple shear bands have a characteristic periodic spacing (see Fig. 2). In the TWC experiments, the spacing of shear bands is obtained by

$$L = \frac{2\pi R^*}{\sqrt{2}N_{SB}} \tag{2}$$

where R^* is the inner radius of the specimen upon shear band initiation, N_{SB} is the number of all shear bands. At present, the effects of several factors (Xue et al., 2004, Yang et al., 2008a, Yang et al., 2011b, Yang et al., 2011a, Yang et al., 2010), such as grain size, orientation of grains, phase composition and pre-notches on the shear band spacing have been researched in multiple materials, including tantalum (Meyers et al., 2001), stainless steel (Xue et al., 2003, Xue et al., 2004), 7075Al (Yang et al., 2008a, Yang et al., 2011a), CP Ti (Xue et al., 2002), granular material (Nesterenko et al., 1996, Shih et al., 1998) and so on. Recently, Chiu et al., (2013) and Oley et al., (2014a,b), Olney et al., 2015) used the TWC method to study the collapsing behavior of laminate cylinders. They found that the type of instability in TWC cylinders is closely related to the mesoscale properties of the specimen. The type of instability in Ni-Al laminate cylinders is buckling, which is dramatically different from that observed in solid ductile and brittle homogeneous materials.

There are many theoretical models (Xue et al., 2002, Mott, 1947, Grady and Kipp, 1987, Wright and Ockendon, 1996, Molinari, 1997, Zhou et al., 2006b) which are developed to predict the shear band spacing. Inheriting Mott's pioneering idea (Mott, 1947), Grady and Kipp, (1987) believed that the momentum diffusion dominates the shear band spacing. A shear band unloads the areas nearby. The shear band spacing is determined by the characteristic dimension of the unloaded region. Grady and Kipp used a simple constitutive relationship without work hardening and strain-rate sensitivity, the deduced shear band spacing is,

$$L_{GK} = 2\left[\frac{9kC}{\dot{\gamma}^3\alpha^2\tau_0}\right]^{1/4} \tag{3}$$

where k is the thermal conductivity, C is the specific heat capacity, $\dot{\gamma}$ is the strain rate, α is the thermal softening coefficient and τ_0 is the flow stress. The Grady and Kipp's model (GK model) is suitable to predict the spacing of well-developed ASB according to its principle.

Small perturbation is another theoretical method to predict the shear band spacing. It is assumed that the wavelength of the fastest growing perturbation corresponds to the shear band spacing. Using a constitutive relationship without work hardening, Wright and Ockendon, (1996) deduced the shear band spacing (WO model):

$$L_{WO} = 2\pi\left[\frac{m^3kC}{\dot{\gamma}_0^3\alpha^2\tau_0}\right]^{1/4} \tag{4}$$

where m is the strain-rate sensitivity.

Molinari, (1997), by using a perturbation analysis, developed a more general formula to predict the shear band spacing for materials with any types of strain hardening and thermal softening. For

Please cite this article as: M. Liu et al., Modeling spontaneous shear bands evolution in thick-walled cylinders subjected to external High-strain-rate loading, International Journal of Solids and Structures (2016), http://dx.doi.org/10.1016/j.ijsolstr.2016.07.014