Simulation of Adiabatic Shear Band Propagations

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Abstract

Constitutive modeling and numerical simulation of dynamic shear band propagation in an impact-loaded pre-notched plate has been carried out in both two and three dimensions.

It has been found that (1) There is strain rate concentration region in front of an adiabatic shear band tip with multiple dimensional character, which is believed to be induced by wave trapping mechanism (Wu and Freund (1984)). It implies that a possible singular strain rate field exists in front of the shear band tip, which is in contrast with the notion that adiabatic shear band tip is diffused in nature (Gioia and Ortiz (1996)). (2) There is a thermal-mechanical instability occurring inside fully grown adiabatic shear band in the post-bifurcation regime, which supports the recent experimental observation by Guduru et al Guduru et al. (2001b). The authors believed that this newly discovered thermal-mechanical instability suggests a second instability that might be used as the criterion for the onset condition of adiabatic strain localization.

1 Strain rate concentration

It has been found in the numerical simulation that there is high strain rate region ahead of the adiabatic shear band tip. This region appears to be locally

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self-similar in shape, and has extremely high strain rate concentration. In Fig. 1, the spatial distribution of effective strain rate observed in numerical computation is juxtaposed with temperature signature of the adiabatic shear band. It indicates that there exists an asymptotic strain rate tensor field moving with the adiabatic shear band tip. We postulated that this high concentrated strain rate field is induced by a pointwise "wave trapping" mechanism (see one-dimensional (1D) model by Wu and Freund (1984)). Based on Wu-Freund 1D linear (or logarithmic) rate sensitivity model, one may expect that the strain rate will become unbound at the shear band tip. To the authors' knowledge, the simulations shown here is the first numerical realization reported of wave trapping induced strain rate concentration in front of an adiabatic shear band tip in multiple dimensions. Most of previous studies on shear band tip processing zone failed to take into account the wave-trapping mechanism.

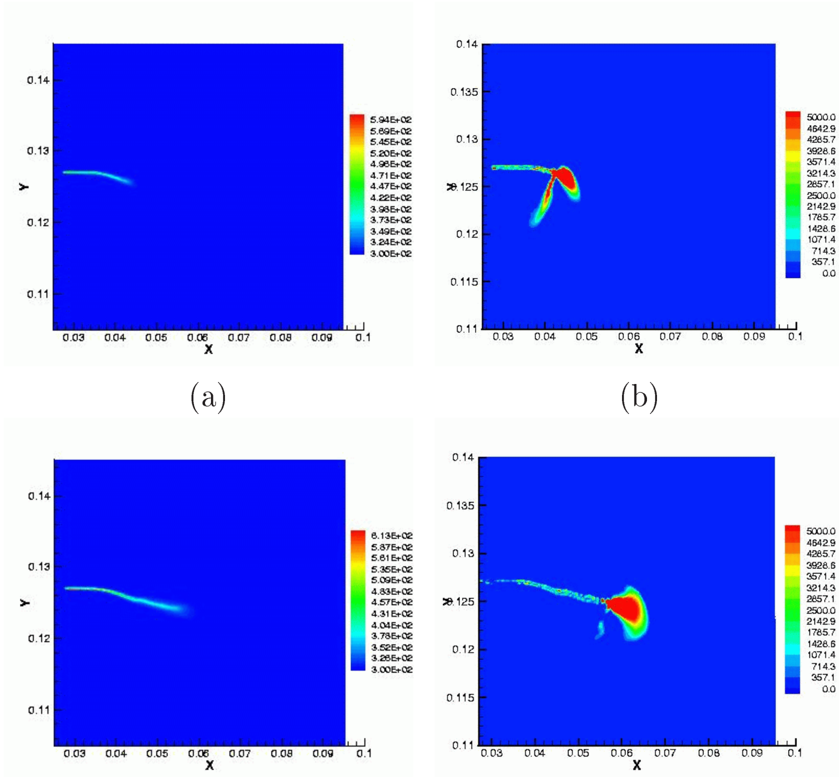
It is natural to draw a comparison between asymptotic strain rate tensor field in front of an adiabatic shear band with the asymptotic stress tensor field in front of a brittle crack. It is possible that there is a local, autonomous, self-similar, high strain rate concentration field at the adiabatic shear band tip, playing a similar role as the autonomous singular stress field at a propagating crack tip in moving crack tip (See Fig. 1).

Based on this analogy, an adiabatic shear band toughness may be obtained from the intensity factors of the strain rate field, just as stress intensity factors used as the measure of fracture toughness. It is speculated that adiabatic shear localization may be controlled by the intensity of strain rate tensor field ahead of the adiabatic shear band tip. After effective strain rate reaches a certain level, it causes damage as well as stress collapse in the newly formed material instability zone, i.e. shear band tip front. It then significantly reduces the flow stress carrying capacity at the tip, which leads to shear stress concentration in the undamaged region and drastic narrowing of the band width, i.e. strain localization and advance of the strain localization zone.

Since in the adiabatic shear localization, there is a gap between softening-instability and strain localization. Stress collapse inside instability zone signals the onset of the localization Wright and Walter (1987); Wright (1990). An invariant criterion to measure the onset of adiabatic strain localization is still missing.

2 Thermal-mechanical instability inside shear band

In most previous studies of adiabatic shear bands, the field variables, such as temperature, shear strain, or effective stress distributions are found smoothly varying along the shear band width Oilellio and Olmstead (1997a,b); Wright



(a) (b) (c) (d)

Fig. 1. Temperature contours (a,c) and strain rate contours ($V = 37m/s$) (b,d) ahead at the tip of the shear band : (a), (b) $t = 12\mu s$; (c), (d) $t = 24\mu s$;

and Ockendon (1992); Wright and Ravichandran (1997); Dinzart and Molinari (1998), i.e. there is basically no "life" within the narrow region inside the shear band.

The numerical simulations reveals that there is periodic oscillation in the temperature distribution within the adiabatic shear band both in space and time (Fig. 2). The numerical results support the recent experimental measurement done by Guduru et al. (2001a), in which it was found that the temperature inside the adiabatic shear band is not uniform, nor quiescent, but has a periodic fluctuation and oscillatory pattern. We compare the optical measurement with numerical computations. The experimental results (Fig. 2a,b,c) are juxtaposed with numerical results (Fig. 2d,e,f). As shown in Fig. (2), there is a strong qualitative agreement between experimental data and numerical results.

In the experiment conducted by Guduru et al. (2001b,a), the adiabatic shear band has an initial width about 100 μm (Fig. 2 a). As the localized high temperature starts to diffuse (yellow or green background in Fig. 2 a, b, c), the shear band width gradually increase to about 300 μm or more. Because of the absence of heat conduction in numerical simulation, the shear band width remain the same throughout the course of simulation, at approximately

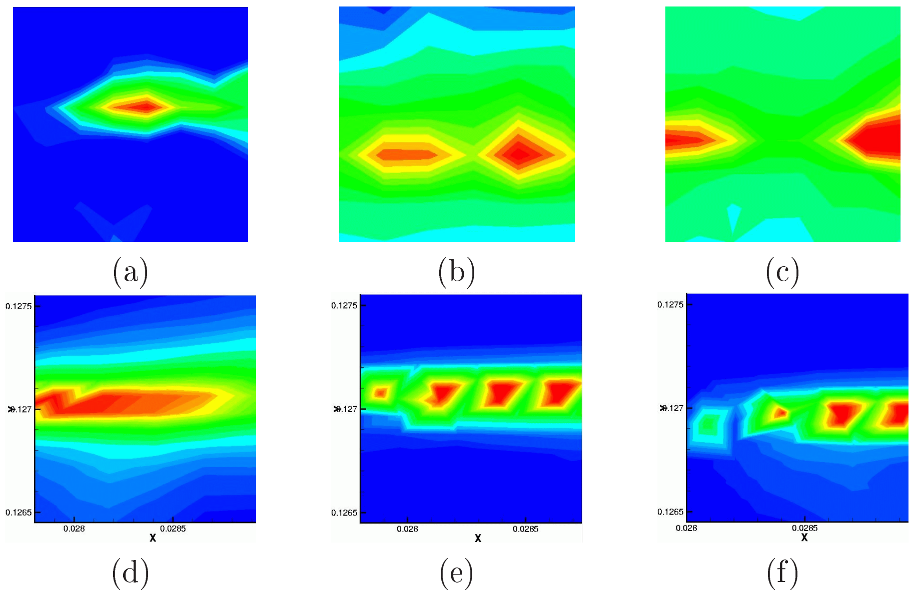


Fig. 2. Qualitative comparisons between experimental data and numerical computation on temperature distribution within the shear band ($V = 37m/s$): (a),(d) $t = 12\mu s$; (b),(e) $t = 36\mu s$; (c), (f) $t = 72\mu s$; (Experimental results : (a,b,c); Numerical results :(d,e,f)).

$200\mu m$ to $300\mu m$. The width actually depends somewhat on the discretization, or particle density in the Y-direction. In the computation shown in Fig. 2, there are about 10 particles distributed in the Y-direction.

A global picture of "hot spot" temperature pattern is displayed in Fig. 3 in a three level zooming process. From Fig. 3, one can observe how such thermal-mechanical instability, i.e. periodic "hot spots", move towards downstream, and interact with each other. In fact, a similar oscillation pattern in stress components as well as strain components have also been observed in numerical simulations. The preliminary results have been reported in Li et al. (2001b,a). A further study of such thermal-mechanical instability inside the adiabatic shear band in the post-bifurcation phase is under way.

The cause of this thermal-mechanical instability may be viewed as a thermal plastic flow under either viscous heating, or hydrostatic pressure driven temperature convection, which is characterized by the following constitutive equation in the damaged stress collapsing zone,

$$\frac{\partial v_i}{\partial t} + v_j \frac{\partial v_i}{\partial x_j} = \frac{\alpha K^*}{\rho(T)} \frac{\partial (T - T_0)}{\partial x_i} + \frac{\mu^*(T)}{\rho(T)} \nabla^2 v_i \tag{1}$$

$$v_{i,i} = 0 \tag{2}$$

$$\frac{\partial T}{\partial t} + v_j \frac{\partial T}{\partial x_j} = \frac{\chi}{2\rho(T) C_p} \sigma_{ij} \Big(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \Big) \tag{3}$$

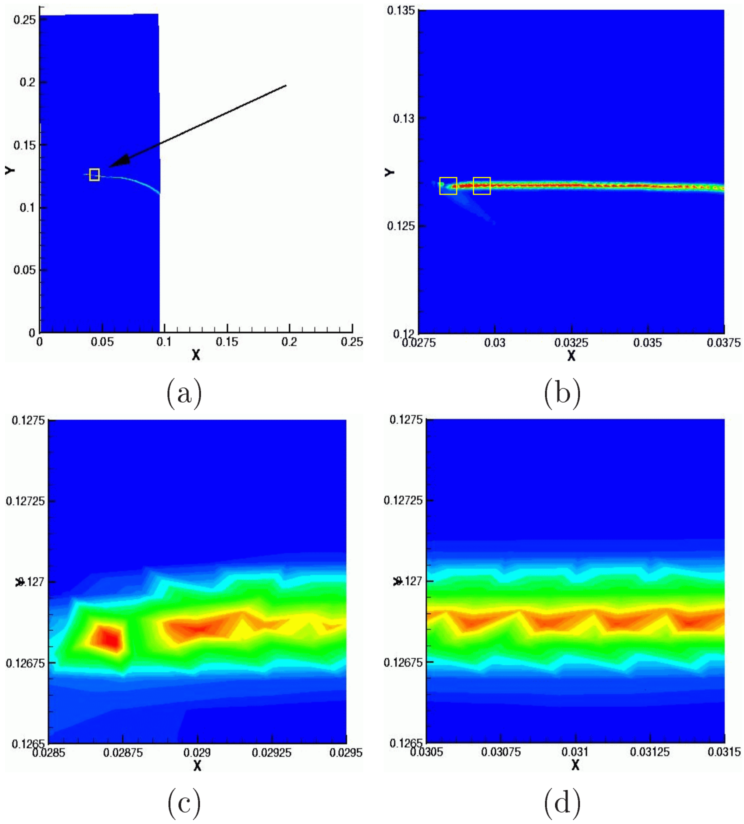


Fig. 3. The micro-structure (temperature profile) of adiabatic shear band: (a) level one; (b) level two; (c) level three (1); (d) level three (2)

where T is the temperature, v_i is the velocity field, density $\rho = \rho_0(1 - \alpha(T - T_0))$, α is the linear thermal expansion coefficient, and K^* is the damaged bulk modulus. The viscosity dependence on temperature is described by the Arrhenius law, i.e.

$$\mu^*(T) = \mu_0 \exp\Big(-\beta \frac{T - T_0}{T_0}\Big) \tag{4}$$

Based on the simulation results, we postulated that the onset localization of adiabatic shear deformation may be marked by the onset condition of a second thermal-mechanical instability of a shear band in the intermediate stage. This second instability is different from the initial material instability caused by thermal-softening. The second thermal-mechanical instability occurs in the post-bifurcation regime as observed in this simulation as well as the experiment by Guduru et al. (2001a). The critical condition of the second instability marks the onset of strain localization. This definition may lead an invariant basis for the susceptibility of a material to the adiabatic shear band. The rationale for this speculation is that if the damage due to microvoids or microcracks do occur in a shear band, it will provide a further softening mechanism which will accelerates the localization process. The subsequent softening may leads to a self-sustained instability path, which should be able to quantified by a second instability.

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