NUMERICAL SIMULATION OF ADIABATIC SHEAR BANDS IN Ti-6Al-4V ALLOY DUE TO FRAGMENT IMPACT

Müge Fermen-Coker
U.S. Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ABSTRACT

Current distributions of continuum mechanics codes used by the Army do not have the capability to model failure associated with plastic shear localizations in ballistic applications, such as plugging failure of targets due to ballistic impact by blunt-nosed projectiles. This paper discusses the development and validation of a computational capability to accurately model highly localized deformations in complex projectile-target interactions germane to survivability and lethality technologies for the Army's Future Combat Systems. Onset and propagation of adiabatic shear bands are investigated both experimentally and computationally by studying the ballistic impact of 20-mm steel fragments against Ti-6Al-4V plates. Numerical simulations are carried out using a three-dimensional localization model being developed for CTH, an Eulerian wave propagation code. A failure criterion that uses homogenous material response and scaling laws to estimate the plastic strain at which stress collapse due to adiabatic shear should occur, for rate dependent, work-hardening, thermally softening materials, has been implemented into CTH, and is used as a nucleation criterion. Numerical results provided good agreement with experimental observations.

1. INTRODUCTION

By Zener and Hollomon's widely accepted postulate, an adiabatic shear band (ASB) is a localized band-like narrow deformation zone of intense plastic shear strain that occurs when the strain rates are so high that there is not enough time for the heat due to plastic work to diffuse away from the deforming zone, causing a local thermal softening effect that exceeds the strain, or strain rate, hardening [Zener & Hollomon, 1944]. Under intense dynamic loading due to ballistic impact of a projectile against a target plate, the plate material is rapidly accelerated ahead of the projectile, creating a velocity discontinuity within the target, which gives rise to plastic localization under adiabatic conditions. Near ballistic limit velocities, shear bands propagate towards the back of the target to form a plug. The ballistic limit velocity (V_{50}) is a measure of armor effectiveness, and is defined as the velocity at which a projectile has 50 percent probability of perforating the target. Even though the impact speed (V_s) of the projectile may not be high enough to perforate the target, the armor plate still fails via plugging or discing, depending on the material properties of the plate. The ballistic performance, crater morphology, and the dominant failure mechanism for Ti-6Al-4V processed above and below β-transus temperature differ drastically [Burkins et. al, 1997]. However, shear bands were observed regardless of the annealing temperatures, influencing the dominant failure mechanism, and therefore the V_{50}. The capability to model failure associated with plastic shear localizations has long been desirable, but found to be difficult due to the complexity of the failure process. This paper focuses on simulating shear band nucleation and propagation using an Eulerian hydrocode, CTH, being developed by Sandia National Laboratories [McGlaun & Thompson, 1990].

2. COMPUTATIONAL MODEL

The first ASB model developed and implemented into CTH by Silling [Silling, 1993], was a two dimensional ad-hoc model. The improved ASB model that constitutes the numerical framework for this study is more recently developed by Silling and is three-dimensional (3D). Fermen-Coker implemented a failure criterion by Schoenfeld and Wright [Schoenfeld & Wright, 2003] based on earlier work by Wright [Wright, 1992, 1994], into Silling's ASB model in CTH [Fermen-Coker, 2004]. The criterion emphasizes homogenous behavior as defined by the material's constitutive response, and does not require experimental determination of any additional parameters. The failure strain is estimated by multiplying a scale factor with the perturbation in the velocity field:

$$\varepsilon_{cr} - \varepsilon_{max} = \sqrt{\left(-\frac{2m\sigma}{\pi\sigma_{,\varepsilon\varepsilon}}\right)_{max}} \; ln\left(\frac{1}{\beta}\right) \qquad (1)$$

where, ε_{cr} is effective failure strain, ε_{max} is effective strain that corresponds to peak stress in adiabatic response, subscript max indicates values at peak stress, σ is effective stress, $\sigma_{,\varepsilon\varepsilon}$ is the curvature at the peak, and m is strain rate sensitivity. Perturbation velocity is implemented as a variation in effective strain rate:

$$\beta = (\dot{\varepsilon} - \dot{\varepsilon}_{ave}) / \dot{\varepsilon}_{ave} . \qquad (2)$$

If a requirement for minimum distance to active and inactive shear bands is also satisfied, a shear band is allowed to nucleate by introducing a Lagrangian tracer particle at that location. Upon nucleation, the shear band is allowed to grow at points along its edge, conforming to the local planes of maximum shear, provided that the prescribed growth strain and strain rate criteria are satisfied. The yield stress of cells that contain the shear

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bands are significantly reduced. Shear band nodes are convected with the material according to the local cell face velocities.

3. FRAGMENT IMPACT RESULTS

A three-dimensional rectangular mesh is used with 1 mm cubic cells, resulting in 20 cells across the diameter of the projectile. The Mie-Grüneisen equation-of-state, and Johnson-Cook constitutive model are used for both the projectile and the target materials. Earlier experiments indicated that the V_{50} for 0º obliquity is 1.016 km/s [Burkins et. al., 2001]. The dominant failure mode is not plugging but discing in this case, however shear bands still have an influence on the complex failure mechanism and the V_{50}. Without activating the ASB model, CTH predicts only a small bulge in the back of the target as shown in Figure 1.

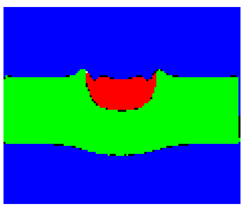
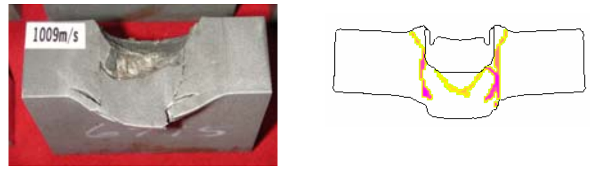


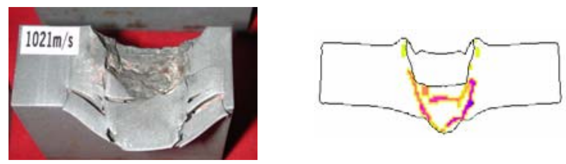
Figure 1. CTH result for V_s = 1100 m/s Vs at 0° obliquity, prior to the implementation of theASB model.

For an impact speed of 1009 m/s, i.e. just below V_{50}, the sectioned plate shown in Figure 2a reveals ASB's between the impact crater and the back surface of the target, along with the in-plane delaminations in the rolling direction. Rolling creates directionality of properties, since pre-existing impurities are elongated in the primary rolling direction. These become sites for localized deformation and eventual cracking. An accurate representation of microstructural effects and the mechanism that leads to in-plane cracking and delaminations do not currently exist in the computational model. However, as indicated by the corresponding computational result obtained using the ASB model (Figure 2b), the morphology of shear bands match the experiment qualitatively and the overall ballistic performance prediction is improved significantly. A time sequence of 3D images indicate a spiral pattern of growth, as also indicated by experiments [Fermen-Coker, 2004]. Lighter colors indicate earlier nucleation, whereas shear bands that nucleate later in time are assigned progressively darker colors. For an impact speed of 1021 m/s, i.e. just above V_{50}, both the experimental and computational result indicate that the shear bands reach the back of the target, as shown in Figure 3 (a) and (b), respectively. Cracks formed around the outer edge of the disc shaped delaminated layer nearest to the back surface, where a chip flied out from the back of the target, confirming that the V_{50} was exceeded. Additional numerical experiments indicated that, plugging failure becomes gradually more dominant as the shear band spacing is decreased, allowing more shear bands to nucleate in the armor material, which suggests a link between ease of ASB nucleation in a material due to its microstructure, and the dominant failure mode.



	(a)	(b)
Crater depth:	19 mm	18 mm
Bulge thickness:	12 mm	11 mm

Figure 2. Results for V_s = 1009 m/s. (a) Target cross section (b) Corresponding simulation using ASB model.



	(a)	(b)
Crater depth:	23 mm	20 mm
Bulge thickness:	13 mm	13 mm

Figure 3. Results for V_s =1021 m/s. (a) Target cross section (b) Corresponding simulation using ASB model.

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