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Adiabatic shear banding assisted dynamic failure: Some modeling issues

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ABSTRACT

Adiabatic shear banding (ASB) is a precursor of failure of high strength metals and alloys when submitted to impact and other high strain rate loading. As a mechanism of plastic flow localization triggered by a thermo-mechanical instability in the context of dynamic plasticity, ASB causes a discontinuity of the strain/strain rate field. In the present paper, some models available in literature are assessed regarding their ability to reproduce ASB features and further consequences. Some tracks for further developments in the field are also given.

1. Introduction

Adiabatic shear banding (ASB) is a process of localized deformation which occurs at low stress triaxiality under dynamic loading involving quasi adiabatic conditions. It results from a thermomechanical instability and, though developing in very narrow bands, i.e. at a mesoscale, it may lead to a premature failure of the structural material, i.e at the macroscale. Shown as causing a loss of ballistic performance of protection (armor) plate made of high strength steels and alloys, adiabatic shear banding has been widely studied for military applications, mostly from a material viewpoint with the aim of reducing possibly material ASB-sensitivity. On the other hand, it is possible to take advantage of this fracture-favoring mechanism, in particular in cutting processes, including notably high speed machining (of e.g. titanium alloys), for it facilitates the chip serration and further reduces the cutting force. Condition for ASB initiation has during a long time been considered as failure criterion in the design of protection structures submitted to impact and other high strain rate loading. However, this approach generally leads to over-conservative sizing. It has thus become indispensable to deal explicitly with this progressive, irreversible, softening mechanism of localized deformation in the same manner as it has become necessary to account for damage-induced softening in another but not so far field of application. The purpose of the present contribution is to consider a selection of ASB-oriented modelling approaches available in literature (while not pretending to be exhaustive) in view of guiding researchers and engineers in their aim of dealing with adiabatic shear banding and further consequences in structural metals and alloys.

For decades, adiabatic shear banding has been experimentally evidenced as pre-failure mechanism for a wide range of metals and alloys used as structural materials, including but not restricted to

- steels: Martensitic steel, Zener and Hollomon (1944); HY100, Marchand and Duffy (1988); Maraging C300, Zhou et al. (1996-I); 4340VAR, Minnaar and Zhou (1998); ARMOX500T, Roux et al. (2015); etc
- titanium alloys: various titanium alloys, Mazeau et al. (1997); Ti-6Al-4 V, Liao and Duffy (1998); β-CEZ, Sukumar et al. (2013); UFG pure Ti, Wang et al. (2014); etc
- aluminum alloys: AA25XX, Liang et al. (2012); AA50XX, Yan et al. (2014); AA60XX, Adesola et al. (2013); AA70XX, Mondal et al. (2011); etc

On post-mortem structures, the bandwidth which generally covers several grains is mostly seen to have well-defined borders allowing for measuring its mean value along its length, leading to dimensions typically ranging from some micrometers to some hundreds of micrometers. Moreover, the presence of distinct borders reinforces the admitted statement according to which adiabatic shear banding involves a discontinuity, namely a weak discontinuity (i.e. of the displacement/velocity gradient). It must also be noted that the distinction between transformation/transformed and deformation/deformed bands seems to be less and less pertinent in the sense that some microstructure transformation always takes place even in very small proportion and that large deformation features adiabatic shear bands.

In the modeling process, the choice of the state variables is conditioned by the size of the representative volume element (RVE),

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Nomenclature

Physical quantities

ρ	mass density (kg.m^{-3})
c	specific heat (J.kg^{-1}.K^{-1})
t	time (s)

Geometrical quantities

w	width of the strongly heterogeneous deformation (ASB) zone (m)
W	width of the weakly heterogeneous deformation zone (m)
h	RVE/FE characteristic length (m)
Ω	whole domain
Ω_G	global domain
$\Omega_{\tilde{G}}$	fictitious domain
Ω_L	local domain
Ω_S	domain covered by the structure

Kinematics related quantities

$\mathbf{e^e}$	elastic strain 2nd order tensor (-)
$\mathbf{d^p}$	plastic strain rate 2nd order tensor (s^{-1})
u_i	ith component of the displacement field (m)
v_i	ith component of the velocity field (m.s^{-1})

Stress related quantities

$\boldsymbol{\sigma}$	Cauchy stress 2nd order tensor (Pa)
s	deviator of the Cauchy stress 2nd order tensor (Pa)
$\sigma_{\mathrm{m}} = \frac{1}{3}\boldsymbol{\sigma} : \mathbf{I}$	mean stress (Pa)
$\sigma_{eq} = \sqrt{\frac{3}{2}\mathrm{s} : \mathrm{s}}$	equivalent stress (Pa)
r	isotropic hardening force (Pa)
σ_y	yield stress (Pa)

Temperature related quantities

T	absolute temperature (K)
T_0	initial temperature (K)
T_m	melting point (K)
$g(T)$	thermal softening function (-)
β	inelastic heat fraction Taylor-Quinney coefficient (-)
k	thermal conductivity (W.m^{-1}.K^{-1})

Elasticity related quantities

$\mathbf{C}$	elastic stiffness 4th order tensor (Pa)
E	Young's modulus (Pa)
ν	Poisson ratio (-)
μ	shear modulus (Pa)

Plasticity related quantities

κ	isotropic hardening variable, equivalent/cumulated plastic strain (-)
$\dot{\kappa}$	equivalent plastic strain rate (s^{-1})
$h(\kappa)$	athermal stored energy (J.m^{-3})
$h'(\kappa)$	plastic strain hardening function (Pa)
$k(\dot{\kappa})$	plastic strain rate function (/)

Damage related quantities

f	void volume fraction (-)
D	damage intensity (-)
$\mathbf{D}$	damage-like 2nd order tensor (-)
$q(\mathbf{D})$	damage-induced softening function (-)
$\mathbf{P}(\mathbf{D})$	damage-related 4th order tensor (-)

Thermodynamics related quantities

$\varpi(T, \mathbf{e^e}, \kappa) = \varpi^r(T, \mathbf{e^e}) + \varpi^s(T, \kappa)$	Helmholtz free energy (state potential) (J.m-3)
$\varpi^r(T, \mathbf{e^e})$	recoverable part of the free energy (J.m^{-3})
$\varpi^s(T, \kappa)$	stored part of the free energy (J.m^{-3})
F	yield function (rate dependent) (/)

Miscellaneous

$\mathbf{I}$	identity 2nd order tensor (-)

$$\begin{cases} \hat{x} = x + \frac{1}{2}\ell^2\nabla^2 x \\ \bar{x} = \frac{x}{(1-\hat{D})} \\ \hat{D} = \sqrt{\hat{\mathbf{D}} : \hat{\mathbf{D}}} \end{cases}$$

$$a_{i,j} = \frac{\partial a_i}{\partial x_j} (/)$$

Model constants

$A, B, n, q, C, \dot{\kappa}_0$	Johnson-Cook model constants in models {1} and {5}
$K, \kappa_0, n, q, \dot{\kappa}_0, m, \dot{\kappa}_c$	constants in model {2}
$q_1, q_2, K, \kappa_0, n, \alpha, \dot{\kappa}_0, m$	constants in model {3}
$K, \kappa_0, n, \delta, q, \dot{\kappa}_0, m, \gamma, \alpha, \kappa_1, \kappa_2, \dot{\kappa}_r$	constants in model {4}
b, W_c	constant in model {5} in complement to Johnson-Cook model constants above
$\ell, A, B, b, q, \eta, m$	constants in model {6}
h_0, H, λ, C	constants in model {7} in complement to the constitutive model constants
H	constant in model {8} in complement to the constitutive model constants
h_0, H	constants in model {9} in complement to the constitutive model constants
$A, B, b, \gamma, a_1, a_2, \eta, m$	constants in model {10}

an explicit and frequently tacit choice. We are here considering ultimately a RVE size which is compatible with engineering applications, i.e. of the order of the millimeter and above, involving the use of commercial finite element (FE) computation code for the design of large structures. Formally, the RVE material point corresponds to the FE integration point. As a FE may have several integration points (this is actually often the case), there is generally no straightforward link between the RVE size and the FE size. However, for simplifying the following discussion on the scale postulates, let consider that this link is satisfied as for a FE with reduced integration, i.e. a single Gauss point. The size postulate evoked above, which implies for the models to phenomenologically describe the consequences of the underlying physics and not the physics itself, requires simplifications which may be sometimes strong. This is particularly true when it is attempted to model the very behavior of the band material during the shear banding process. ASB lasting only a few microseconds or tens of microseconds, the behavior in question is indeed generally unknown, or at least ill-known, due to a lack of accurate space- and time-resolved measurements. The common hypothesis about the adiabaticity condition between the shear band and the bulk material is also debatable – as is the adiabaticity condition between the bulk material and its environment. It however allows for solving the mechanical problem only, and not both the mechanical and thermal problems, by considering the plastic dissipation as heat source. When dealing with adiabatic shear banding, and other softening mechanisms, using standard FE computation codes, the loss of mesh objectivity of the numerical results and the large distortion of the finite elements are the main computational issues. There exist some regularization techniques aiming at attenuating the mesh dependence

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