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Analytical formulation of a criterion for adiabatic shear failure

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ABSTRACT

Numerical modeling and prediction of adiabatic shear localization require a criterion that is both robust and simple enough so that it can be implemented into numerical codes. This criterion should have a minimum number of adjustable parameters, each of which being measurable, with sufficient generality to avoid adjustments for each new investigated case.

This paper presents a detailed analytical study of such a criterion formulated in terms of plastic strain energy density. The criterion contains 3 physical parameters: an exponent b and two energy parameters corresponding to the initiation of the shear band and its final failure. It describes both the initiation and the propagation of the damage (shear band) in the dynamically loaded solid, while b represents the damage tolerance characteristics of the material. We show that the general stress–strain relationship decays exponentially (or close to) with ongoing damage, which allows attainment of very large strains in the shear band. A detailed procedure is reported for the experimental identification of each of the above-mentioned parameters, for any value of the exponent b.

The criterion was previously used for dynamic shear localization simulations on empirical grounds [1], that are now firmly established for the first time through a rigorous analysis, including systematic parameters' identification.

1. Introduction

Adiabatic shear banding (ASB) had been studied in numerous works from mathematical, mechanical and metallurgical considerations, for over seven decades. This failure mode plays a major role in dynamic applications such as machining, high-rate metal forming, and particularly in ballistic impacts [2]. Instead of a homogeneous plastic deformation state, the strain gets localized into a narrow plane (band in two dimensions), which leads rapidly and abruptly to catastrophic structural failure. The bands are characterized by both very large shear strains (of the order of 10), and consequently very high local temperatures (several hundred degrees), as a result of thermomechanical coupling effects [3].

The classical explanation for the occurrence of this failure mode was proposed by Zener and Hollomon [4], who pointed out that localization occurs when the thermal softening effect overcomes strain hardening of the material. At this point, a material instability develops and the material loses abruptly its load bearing capability. Based on this premise, attainment of a critical strain is usually considered as a failure criterion [5]. However, earlier work by Dormeval and Ansart [6] examined this concept through a series of experiments involving static pre-loading, followed by dynamic loading. Those authors showed that a critical strain criterion is inadequate to predict the onset of adiabatic shear failure.

Based on similar two-stage experiments, Rittel et al. [7] reached a similar conclusion, but suggested to consider only the dynamic phase of the experiments. Those authors reported that irrespective of the level of quasi-static prestrain, the measured dynamic strain energy density remained quite constant. Those authors consequently proposed a new criterion for dynamic failure, with special emphasis on adiabatic shear bands (ASB). The criterion is based on the dynamic stored energy of cold work instead of the commonly accepted critical strain criterion. This criterion is based on part of the total strain energy density invested in the impacted material. Here, one should mention the work of Mazeau et al. [8] who ranked the susceptibility of various titanium alloys to adiabatic shear failure on the basis of the strain energy density absorbed by the material prior to failure.

Justifications for this criterion are based on the following:

a. The authors showed that the dynamic strain energy (density) to failure is constant for different values of pre-strain, thus a critical strain criterion is not suitable [7].

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b. In another work of Rittel and Wang [9], it was shown that the temperature rise prior to instability is of the order of a few tens of degrees. Such an increase is most likely insufficient to cause significant material softening, contrary to the claim of Zener and Hollomon [4].
c. An evaluation of the respective contribution of microstructural changes and thermal softening can be found in Osovski et al. [10]. This study investigates the joint operation of the two softening mechanisms, pointing out that for those materials that exhibit high strength levels and overall low ductility, microstructural softening is likely to kick in prior to any thermal softening, whereas for lower strength materials with a high ductility, provided microstructural evolutions have not occurred, thermal softening is likely to be the dominant factor leading to the instability. Those results are summarized graphically in Fig. 13 of this work [10].
d. Osovski et al. [11] showed that for a range of strain rates, the strain energy density at failure is constant. This stands at odds with the strain criterion which should be adapted for each strain rate in particular, as for example in Zhou et al. [12] and Medyanik et al. [13].

Finally, one should mention recent work, based on molecular dynamics, that added to the feasibility of an energy approach to dynamic shear localization [14].

The numerical implementation of the strain energy density as a failure criterion was carried out recently by Dolinski et al. [1], and by Noam et al. [15]. In the first work, four different laboratory experiments were modeled successfully, both qualitatively and quantitatively. The second work included simulations of scaling of plate response under explosive loading and ballistic perforation, problems which both involve ASB-related failure. However, the strain energy concept was used on a purely empirical basis in those works. Likewise, this approach was also implemented recently for non-metallic materials by Aranda-Ruiz and Loya [16], who successfully reproduced the failure mode transition experiments of polycarbonate performed by Ravi-Chandar et al. [17].

The idea of energy as a failure criterion is not entirely new and has been applied to several cases, including fracture mechanics [18]. The notion of a limited strain energy (density) has been mentioned earlier in works of Farren and Taylor [19] and Taylor and Quinney [20]. However, to our knowledge, no failure criterion based on this exact notion was further developed. There are nevertheless two models for failure in the literature. However they should not be confused with our plastic strain energy density model for the initiation and propagation of adiabatic shear bands.

The first model – a very common failure criterion (C–L) was introduced by Cockcroft and Latham [21]. The C–L criterion: $\int_0^{\varepsilon_{eq}} \sigma_1 \mathrm{d}\varepsilon_{eq} \le W_{cr}$ with σ_1 being the maximal principal stress, to be compared with the previous plastic strain energy density criterion [1]: $\int_0^{\varepsilon^P_{eq}} \sigma_M \mathrm{d}\varepsilon^P_{eq}$ with σ_M standing for equivalent Mises stress.

Cockcroft and Latham [21] defined their criterion for *fracture*, based on the maximum principal stress component. When this criterion is met, the material loses *instantaneously* its load bearing capability. By contrast, the criterion discussed in the present work considers the equivalent stress together with a *gradual loss* of load-bearing capability, all in the dynamic regime, specifically for adiabatic shear failure. Last but not least is the fact that the plastic strain energy density is based so far on physical evidence only, showing the role of the stored energy of cold work in adiabatic shear failure [7]. The reader is referred to the comprehensive work of Wierzbicki et al. [22] in which the C–L criterion was compared to other six fracture models. The C–L criterion was implemented in various numerical works specifically focused on fracture even though there was also ductility. For example, Álvarez et al. [23] used the C–L criterion to model chip formation during machining, and Børvik et al. [24] used it to model fragmentation and other fracture modes during ballistic penetration.

The second model, which also invokes energy concepts for the *onset* of flow localization in thermal viscoplastic materials, was postulated by Shawki [25], and [26]. This criterion is based on a *kinetic* energy density for the onset of localization (as opposed to *total* energy as in our work). In two later works [27,28] this criterion was used to qualitatively characterize the onset and propagation of shear bands. Unfortunately, no quantitative comparison is available for this criterion with experimental observations.

It is once again worth mentioning that the strain density energy failure criterion used in the earlier numerical works (Dolinski et al. [1] and Noam et al. [15]) describes *both* the critical condition for failure initiation and the *path to total fracture*. In another words, failure is not instantaneous. Rather it is characterized by a gradual decrease in the stress–strain relationship, resulting from damage evolution.

In this paper:

i. We present the algebraic formulation of the energy failure criterion. We compare it with the "classical" critical strain failure criterion, and show that the local stress–strain curve of the former decays in an approximately exponential manner, while that of the latter can be simply proved to decay linearly.
ii. For a particular case of the energy failure criterion ($b = 1$ and elastic-ideally plastic material), we show that the local decay is exactly exponential. Later on we discuss more general cases and show that the exponential decay criterion can still be applied partially.
iii. We show that this exponentially decaying local stress–strain relationship is supported by limited previous experimental as well as numerical results.
iv. Finally we show how to evaluate the required parameters from the local and macroscopic curves.

2. Formulation of failure criteria

2.1. Plastic strain energy density criterion

In both Dolinski et al. [1] and Noam et al. [15], the stress was assumed to evolve according to the amount of accumulated damage, D, as shown in Eq. (1)

$$\sigma_{eq} = \sigma^*_{eq} \cdot \left(1 - D^b\right) \tag{1}$$

where σ_{eq} is the current flow stress at a given equivalent strain (ε_{eq}), and σ^*_{eq} is the flow stress of the undamaged material for the current ε_{eq}. b is a constant.

The damage (D) evolution is given by Eqs. (2) and (3):

$$D = \left\{ \begin{array}{cc} 0 & W \le W_{cr} \\ \dfrac{W - W_{cr}}{W_f - W_{cr}} & W > W_{cr} \end{array} \right\} \tag{2}$$

W is the plastic strain energy density for a strain level α:

$$W = \int_0^{\alpha} S_{ij} \mathrm{d}\varepsilon^P_{ij} = \int_0^{\alpha} \sigma_{eq} \mathrm{d}\varepsilon^P_{eq} \tag{3}$$

where S_{ij} is the deviatoric stress tensor and ε^P_{eq} is the plastic equivalent strain. W_{cr} is the critical value at which the material