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On what controls the spacing of spontaneous adiabatic shear bands in collapsing thick-walled cylinders

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Abstract. Shear bands formation in collapsing thick walled cylinders occurs in a spontaneous manner. The advantage of examining spontaneous, as opposed to forced shear localization, is that it highlights the *inherent susceptibility* of the material to adiabatic shear banding without prescribed geometrical constraints. The Thick-Walled Cylinder technique (TWC) provides a controllable and repeatable technique to create and study multiple adiabatic shear bands. The technique, reported in the literature uses an explosive cylinder to create the driving force, collapsing the cylindrical sample. Recently, we developed an electro-magnetic set-up using a pulsed current generator to provide the collapsing force, replacing the use of explosives. Using this platform we examined the shear band evolution at different stages of formation in 7 metallic alloys, spanning a wide range of strength and failure properties. We examined the number of shear bands and spacing between them for the different materials to try and figure out what controls these parameters. The examination of the different materials enabled us to better comprehend the mechanisms which control the spatial distribution of multiple shear bands in this geometry. The results of these tests are discussed and compared to explosively driven collapsing TWC results in the literature and to existing analytical models for spontaneous adiabatic shear localization.

1. Introduction

The initiation and growth of shear bands have been extensively studied since the pioneering work of Zener and Hollomon [1], using various experimental techniques with which the formation of a shear band is well defined. The Kolsky - bar technique is widely used for the study of shear localization with specially designed shear specimens, such as the "Hat" [2] and "Punch" [3] geometries, or the Shear Compression Specimen (SCS) [4,5]. The torsion bar is used to induce ASB in tubular specimens. This technique was used in the seminal work of Marchand and Duffy [6], who identified the successive stages in the evolution of the adiabatic shear bands. Other experiments used pre-notched plates with a symmetric double notched specimen, as in Kalthoff [7], or an eccentric single notched specimen, as in Mason [8] and Zhou [9]. The common basis for all of these well-used techniques is that they all refer to a state of *forced* shear localization. In such cases, shear bands are formed in *well-defined regions*, dictated by the specimen geometry, parallel to the direction of the maximum shearing load. A controlled shear band has many advantages, enabling one to study the evolution of the shear localization process. Yet, the process of shear initiation is in fact dictated geometrically, and therefore externally forced

In order to examine the initiation stage of shear localization, a different set-up is used, referring to *spontaneous* shear localization (as referred to by Chen et al. [10]). In this case, the loading characteristics do not constrain the specific locations or directions of shear banding and multiple shear bands can evolve in regions and in directions other than the direction of the prescribed load. The major advantage of examining spontaneous shear localization is that it highlights the inherent susceptibility of the material to adiabatic shear banding.

The evolution of shear bands in the collapse of a thick-walled cylinder is an excellent example for spontaneous shear localization. In this case, an external pressure induces an inward collapse of the cylinder. The cylindrical symmetry lacks a transverse boundary, and shear bands which evolve from the inner surface of the collapsing cylinder, do not form on a clear boundary or by stress concentration. Free of transverse boundary constraints, the initiation of the shear bands occurs spontaneously. Nesterenko et al. [11,12] introduced a well-controlled and repeatable technique to create multiple shear bands in collapsing thick walled cylinders driven by an explosive loading.

Stokes et al. [13] conducted several TWC experiments on the Pegasus-II facility using electro-magnetic forces as the driving collapsing force. A pronounced advantage of this loading technique is due to the more uniform collapse of the specimen, as compared with the explosively driven ones, which are also driven by an axial force due to the directional ignition of the explosive driver. More recently, we introduced an electromagnetically driven version of the TWC technique [14,15], using a pulsed current generator. This method has the advantage that it is highly controllable and somewhat simpler than the use of explosives or alternatively, the use of a large scale Mega-Joule energy facility. In a TWC experiment, one can measure the number, spacing and length of the spontaneously initiated

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ASBs, as in [11] and [14]. Consequently, the TWC techniques, either explosive or electromagnetic, offer an ideal experimental platform to validate existing models for ASB formation, and use the data to calibrate material models for shear band formation.

In this work, we conducted on the EM platform tests on 7 mettalic alloys, examining the number of shear bands and spacing at different stages of collapse. For some of the materials we compared the results with those obtained in the explosively driven tests reported in the literature. We further compared the results with theoretical models in the literature for evaluating the spacing between shear bands.

2. Experimental work

2.1. Experimental set-up

We are using an Electro-Magnetic (EM) set-up to provide the collapsing force on the cylindrical specimen. The EM set up is based on a pulsed current generator (PCG) using a capacitor bank system. The capacitors are charged with voltages of ∼30 kV which are released using an array of low inductance rail spark-gaps, allowing a fast discharge into the conductor system. The currents created are of the order of 1 MA, with a rise-time of ∼1 μsec. The conductor system is made of two plates, each attached to an opposite pole, separated by an isolating layer. The specimen is an assembly of coaxial cylinders: an inner Cu cylinder, the metallic specimen, an outer Cu cylinder (attached to the upper conductor plate), an insulating plastic cylinder and an outer brass cylinder (attached to the lower conductor plate). When the voltage is discharged, a current flows on both sides of the plastic isolator: through the outer Brass cylinder and the outer Cu cylinder, but in *opposite* directions, creating repulsive magnetic forces between them. The controllable parameters in the set-up are the voltage to which we charge the capacitors, resulting in different magnetic pressures, and the specimen's geometry, controlling the extent of collapse and the stage of shear band evolution. The main diagnostics is post-mortem: the collapsing cylinders, which come to a stop at the end of the experiment, are cut and polished to reveal the spatial distribution of shear bands and the spacing and lengths of the bands are measured.

2.2. Experimental results

Using the EM set-up described above, we conducted tests on 7 different materials: Stainless Steel – ss304L, Titanium (CP grade2), Ti6Al4V – Wrought material, Ti6Al4V – LMD (Laser metal deposition – "printed" material) was chose to examine the influence of microstructure and grain size in comparison with the wrought material, cast aluminum Al-A356, cast Magnesium Mg-AM50 and OFHC Copper: heat treated copper to vary grain size and examine the effect of grain-size on shear band distribution. The studied effects of grain size on shear band evolution are not discussed here.

The polished and etched specimens reveal the multiple shear bands which evolved in the specimen at different stages of collapse. For each specimen we characterized: the final dimensions (these measurements determined the final effective strain which were reached at each experiment), the number of shear bands (counting all shear bands at all lengths) and the average spacing between shear bands. We found that the number of shear bands remained constant during the collapse, meaning no new shear bands initiate during the later stages of propagation. Thus, the numbers of shear bands in specimens at an early stage or late stage of evolution are comparable. The number of shear bands and spacing in all tested materials are summarized in Table 1.

Table 1. Results summary for all tested materials.

Material	**Avg. Spacing [mm]**	**Avg. Number of SB**	**Grain size [mm]**	**Compression failure strain**
CP-Ti	0.205	32	150	0.50
Ti6Al4V wrought	0.46	20	2	0.20
Ti6Al4V LMD	0.43	21	100	0.20
ss304L	0.14	52	100	0.45
Mg-AM50	0.24	35	10	0.30
Al-A356	–	No SB	100	>0.70
OFHC-Cu With different Grain sizes	–	No SB	20–300	>0.85

It can be seen that we reached with the different materials very different behaviors: materials with a large number of shear bands and small spacing (ss304L), materials with a small number of shear bands and large spacing (Ti6Al4V materials), an intermediate behavior for CP-Ti and Mg and materials which showed no shear band evolution up to plastic strains of 85% (Cu and Al).

3. Results and discussion

In this study we examined our experimental results to answer two questions:

(1) How do our results compare with the larger specimens tested in the explosively driven thick wall cylinder (ED-TWC) experiments in the literature?
(2) How do our results compare with the theoretical approaches predicting spacing, for different materials?

3.1. Comparison with ED-TWC experiments

The geometry of the specimens we tested in the research, using the EM platform, is scaled down by a factor of 4 in comparison with the geometry tested in the explosively driven experiments [16,17]. As we examined specimens at different stages of collapse, the spacing between shear bands change (become smaller) with the extent of collapse. Thus, we normalized the results in each specimen to the geometry upon initiation and used this definition for the ED-TWC specimens reported in the literature as well. The data in the literature enabled us to compare our results for ss304L, CP-Ti and Ti6Al4V. The comparison is given in Table 2.

Table 2. Comparison of shear bands' spacing between the EM and Explosively driven tests.

Material	Electro-magnetically driven TWC-tests (this work) [mm]	Explosively-driven TWC tests [mm]
Ti	0.21	0.24
Ti6Al4V	0.46	0.55
ss304	0.14	0.14

The comparison between the two cases shows an overall good agreement with differences of only 10%–20%, despite the large scale-factor. The slightly larger spacing in the explosively driven tests could be possibly explained by the smaller strain rate (strain rates in the explosively driven tests are $\sim 6\text{–}8 \cdot 10^4$ and in the EM driven tests are $\sim 2\text{–}3 \cdot 10^5$).

We concluded from this comparison that the spacing between shear bands does not depend on geometrical dimensions of the specimen (e.g radius, wall thickness) but rather on material properties.

3.2. Comparison with theoretical spacing models

There are several theoretical models in the literature for evaluating the spacing between shear bands in TWC tests. The two main models, referring to the spacing at the initiation stage, are those of Wright and Ockendon [18] and of Molinari [19]. The published experimental results are compared with these models. These models are developed following a perturbation analysis on the set of conservation equations including thermal conductivity and a constitutive equation. The basis for these analyses is the classical approach for shear band evolution by thermal softening overcoming strengthening effects of strain and strain rate. The spacing is calculated as the wavelength which shows the fastest growth-rate. The expressions derived by Wright & Ockendon [18] and Molinari [19] are:

$$L_{WO} = 2\pi \left[\frac{k \cdot C}{\dot{\gamma}_0^3 a^2 \tau_0}\right]^{1/4} \cdot m^{3/4},$$

$$L_{Mo} = 2\pi \left[\frac{k \cdot C}{\dot{\gamma}_0^3 a^2 \tau_0}\right]^{1/4} \times \left[\frac{m^3(1-aT_0)^2}{(1+m)}\right]^{1/4} \qquad (1)$$

$$\tau = \tau_0 \left[1 - a(T - T_0)\right] \left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)^m$$

where τ_0 is the static shear stress, a is the thermal sensitivity coefficient, $\dot{\gamma}$ is the strain-rate, m is the strain-rate sensitivity, $\dot{\gamma}_0$ is the reference strain-rate set to be 1e4 $\sec^{-1}$, k is thermal conductivity and C is the heat capacity. Strain rate in our tests were taken from the numerical simulations and we used here a value of $\dot{\gamma}$ =2–3 $\cdot 10^5 \sec^{-1}$. For the explosively driven tests, strain rate was $\dot{\gamma} = 6\text{–}8 \cdot 10^4 \sec^{-1}$. The calculated spacings suing Eq. (1) in comparisson with the measured ones are presented in Table 3.

Table 3. Calculated spacing using Eq. (1).

Material	Model Model	Calculated [mm]	Measured [mm]
CP-Ti	WO	0.075	0.205
	Molinari	0.07	
Ti6Al4V (Wrought)	WO	0.11	0.46
	Molinari	0.10	
Ti6Al4V (LMD)	WO	0.11	0.43
	Molinari	0.10	
ss304L	WO	0.24	0.14
	Molinari	0.22	
Mg-AM50	WO	0.31	0.24
	Molinari	0.29	
Al-A356	WO	0.21	—— (>0.70)
	Molinari	0.19	
OFHC- Cu	WO	0.42	—— (>0.85)
	Molinari	0.39	

From the comparison between the calculated and the experimental spacings, we drew the following conclusions:

(1) The theoretical expressions do not match the experimental results, as far as spacing is considered.
(2) The high strain rate in our tests has a very pronounced effect on the calculated spacing values. While for the explosively driven tests, the spacing values for CP-Ti and ss304L showed a limited match, the higher strain rate (by a factor of 5) result in much smaller spacing values for which the matching is lost. The effect of the strain rate overrides all other differences in the coefficients, according to a variety of values reported in the literature.
(3) The models predict small differences in the spacing of CP-Ti and Ti6Al4V, indicated also in the work of Xue et al. [17]. Yet, the experimental results show **a factor of 2–3** between the two materials.
(4) The models predict small spacing values for Aluminum and Copper which do not agree with our experimental results, in which no shear bands evolved.

4. Summary and conclusions

In this work, we examined the shear band evolution in TWC tests on 7 metallic alloys, using an EM platform for driving the collapsing cylinders. We measured and compared the shear band spacing in the different materials and compared them with results obtained in larger scaled, explosively driven tests reported in the literature and to theoreical predictive models for spacing.

From the examination of the results obtained on the EM platform using scaled down geometry in comparison with the explosively driven specimens reported in the literature, we found that spacing is not characterized by a geometrical scale of the specimen size (e.g radius, wall thickness) but rather by material properties. The examination of the different materials enabled us to better comprehend the mechanisms which control the spatial distribution of multiple shear bands in this geometry. The incompatibility of the 1D models (W&O, Molinari) to predict spacing in the experiments strengthens the thesis that the thermal softening approach does not capture the full physics of shear localization. Further examination of these conclusions is currently examined through numerical simulations using energy based failure criteria which are indicating that plasticity mechanisms of the material are dominating the spatial evolution of shear bands in this geometry.

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References

[1] C. Zener, J. H. Hollomon, J. of Appl. Phys, pp. 22–32 (1943).
[2] L.W. Meyer and S. Manwaring, *Metallurgical Applications of Shock-Wave and High Strain Rate Phenomena* (Marcel Dekker, NY, 1986).
[3] W. Dabboussi, J.A. Nemes, Int J. Mech. Sci., Vol **47**, pp. 1282–1299 (2005).
[4] A. Dorogoy and D. Rittel, Exp. Mech., Vol. **45** (2), 167–177 (2005).
[5] A. Dorogoy and D. Rittel, Exp. Mech., Vol. **45** (2), pp. 178–185 (2005).
[6] A. Marchand, J. Duffy, J. Mech. Phys. Solids Vol. **36** No. 3 (1988).
[7] J.F. Kalthoff, S. Wrinkler, *Impact Loading and Dynamic Behavior of Materials* (EDS), Vol. **1**, pp. 185–195 (1987).
[8] J.J. Mason, A.J. Rosakis, G. Ravichandran, J. Mech. Phys. Solids **42**, 1679–1697 (1994).
[9] M. Zhou et al., J. Mech. Phys. Solids Vol **44**, No. 6, pp. 981–1006 (1996).
[10] Y.J. Chen et al., Mat. Sci. and Engineering A **286**, pp. 70–82 (1999).
[11] V.F. Nesterenko, M.P. Bondar, Expl. and Shock Waves, Vol **30** (1994).
[12] V.F. Nesterenko et al., Fizika Goreniya i Vzryva, vol. **25**, no. 4, pp. 154–155 (in Russian) (1989).
[13] J.L. Stokes et al., *Proceedings of International Conference on Fundamental Issues and Applications of Shock-Wave and High-Strain-Rate Phenomena* (Elsevier, 2001).
[14] Z. Lovinger et al., IJIE, Vol. **38**, 918–929 (2011).
[15] Z. Lovinger et al., JMPS (to be published) (2015).
[16] Q. Xue et al., Mat. Sci. and Engineering A **384**: 35–46 (2004).
[17] Q. Xue et al., Acta Materialia **50**, pp. 576–596 (2002).
[18] T.W. Wright, H. Okendon, Int. J. of Placticity, Vol. **12**, No. 7 pp. 927–934 (1996).
[19] A. Molinari, J. of the Mech. Phys. of Solids, Vol. **45**, No. 9 pp. 1551–1575 (1997).