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# Adiabatic shear bands in α-titanium tube under external explosive loading

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**Abstract** The radial pressure explosive experiment is successfully used to investigate the formation of adiabatic shear bands (ASBs) in α-titanium (α-Ti) tube under external explosive loading. The ASBs initiate at the inner surface of α-Ti tube, and most of the shear bands are in spiral form along the cross-section of the tube towards counterclockwise direction. Tip of a shear band propagates along the surface of the maximum shear stress. Four patterns of ASBs such as bifurcation, collection, crossing and N-shape are observed. The developed shear bands are the preferred sites for nucleation, growth and coalescence of microvoids. The nucleation of microvoid is caused by the local hot spots and stress concentration in the shear bands. The coalescence of microvoids forms the crack within ASBs, and when the critical crack length is reached catastrophic fracture occurs.

## Introduction

Adiabatic shear banding is a kind of deformation and failure mechanism observed in metal when processed at high strain rates, such as machining, metalworking, ballistic penetration and explosive fragmentation [1–4]. Hoggatt and Recht [5] had studied the shear damage in metal tube under internal explosive loading. However, studies on the failure of the tube under external explosive loading have been carried out in recent years. Tang et al. [6, 7] observed the recovered fragments of steel tube generated by external explosive loading and found that fracture had occurred along the maximum shear stress loading. Nesterenko et al. [8, 9], Meyers et al. [10] and Xue et al. [11, 12] investigated the initiation and propagation of shear bands in metals of thick-walled cylinder. For all metals, shear bands exhibit a clear self-organization with a characteristic spacing that is a function of a number of parameters.

In order to investigate the shear bands and the fracture in α-Ti tube under compression and shearing stresses, a radial pressure explosive experiment is proposed; the objectives of this paper are to observe the formation of ASBs in α-Ti tube under external explosive loading, and to understand the mechanism of shear failure and microvoids evolution within the shear bands.

## Experiment

Cold rolled pure titanium [TA2 (α-Ti)] tube was used in the present work. The size of α-Ti tube was 60 mm in length, 2 mm in thickness and 28 mm in inner radius. Thickness of the copper tube and the nylon barrel were 0.5 mm and 5 mm, respectively. The explosive with the detonation velocity of 2900–3200 m $s^{-1}$ and initial density of 0.95–1.0 g $cm^{-3}$ was used for the experiment.

Figure 1 shows the experimental configuration of the study; the explosive surrounds the specimen uniformly. The detonator was detonated in the center of the end cap. The nylon top cap was used to reduce the damage of the top of α-Ti tube by detonation wave. The nylon barrel covered the outside of α-Ti tube and the copper tube was kept inside the α-Ti tube to preserve the titanium tube from deformation.

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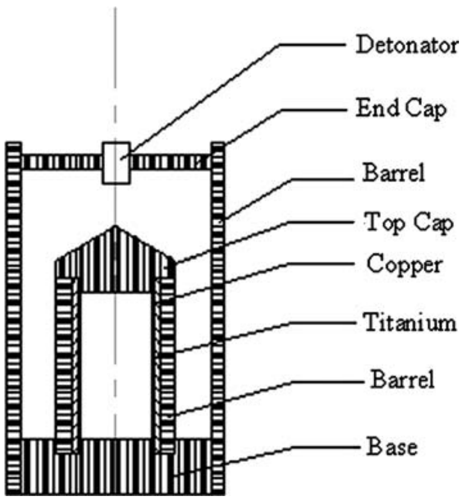



**Fig. 1** Experimental configuration for external explosive loading

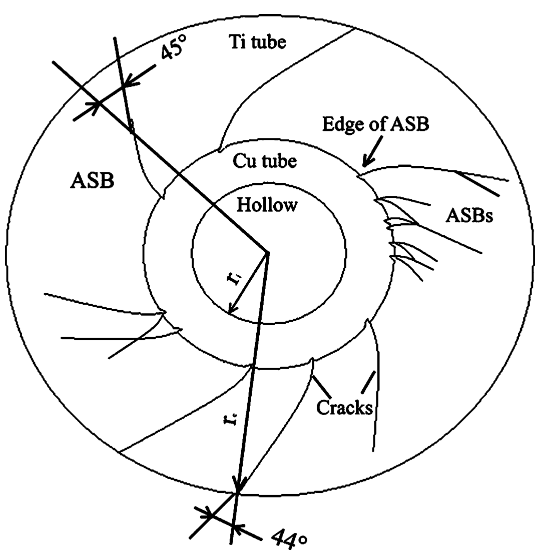



**Fig. 2** Schematic plan of the cross-section of the collapsed configurations of α-Ti tube

Specimens for analyses were cut normal to the axis of the collapsed tube. The etchant used to reveal the microstructure of α-Ti was 4 mL $HNO_3$+6 mL HCL+5 mL HF+100 mL $H_2O$. Fracture and microstructure were observed in optical microscope POLYVAR-MET. Scanning electron microscope (SEM) observations were carried out in KYKY-2800, operated at 20 kV.

## Results

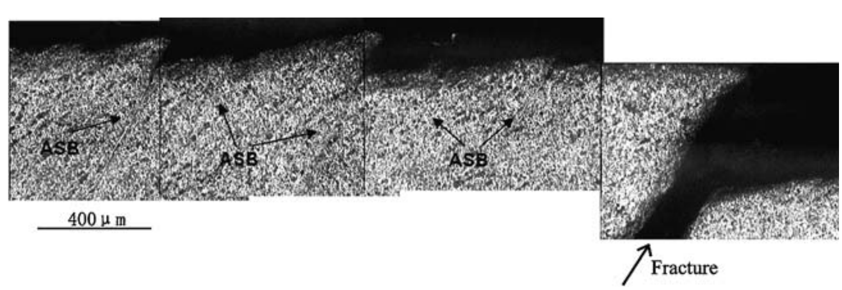
The specimen configuration in cross-sectional view is shown in Fig. 2. The cracks and most of the ASBs are in spiral form along the cross-section of the tube towards counterclockwise direction. The shear bands form at an angle of about 45° with the radius. The copper tube protects the deformation of the inner surface of α-Ti tube.

Mostly ASBs are initiated at the inner surface of α-Ti tube, as shown in Fig. 3. Several special patterns of ASBs such as bifurcation, collection, crossing and N-shape are observed along the radial direction of the tube, as shown in Fig. 4. The microvoid forms at the bifurcation point of the shear bands as shown in Fig. 4a.

The nucleation of microvoids is considered as a result of the tensile stress within the shear band. The nucleation, growth and coalescence of microvoids in ASBs are observed as shown in Fig. 5. The elliptical microvoids form within the shear band and the long axis of them is at certain angle with the shear band. The axes of the microvoids start to rotate at the early stage of the growth, as shown in Fig. 5a. In addition, microvoids dispersed along a line is observed in several locations (Fig. 5a).

The crack in α-Ti tube is along a shear band, as shown in Fig. 6. The macrostructure of collapsed α-Ti tube fragment is like the shape of strip shown in Fig. 7a. The fracture is along the maximum shear stress direction, as shown in Fig. 7a and b. At higher magnification shear dimples are observed (Fig. 7c). Thus, it can be concluded that microvoid coalescence within the shear band induce cracks in the tube. The initiated cracks at different locations propagate to fracture the α-Ti tube.

**Fig. 3** Montage of optical micrographs of the collapsed α-Ti tube



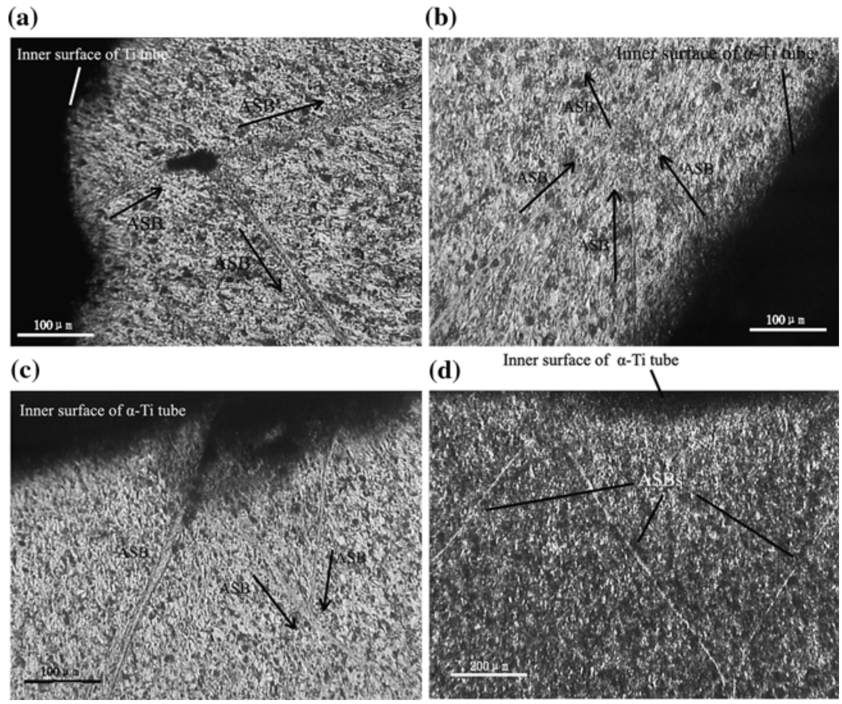



**Fig. 4** Special patterns of ASBs in α-Ti tube: (**a**) bifurcation; (**b**) collection; (**c**) crossing; (**d**) N-shape

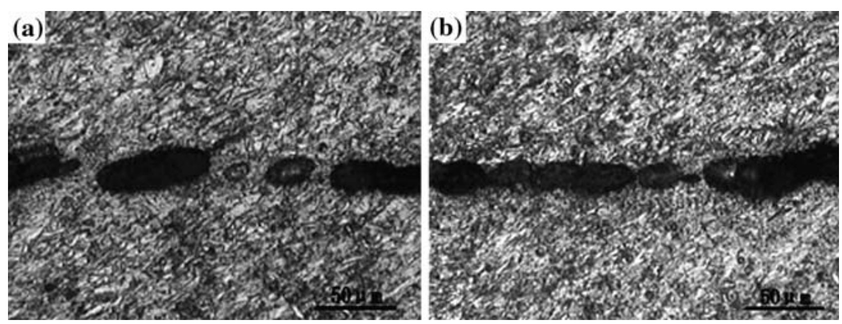



**Fig. 5** Microvoids nucleation, growth and coalescence within a shear band in α-Ti: (**a**) nucleation and growth of microvoids within the shear band; (**b**) coalescence of microvoids within the shear band


**Fig. 6** Montage of optical micrographs of the crack along a shear band

## Discussion

### Patterns of the shear bands

In general, shear bands should nucleate homogeneously at the inner surface of α-Ti tube under explosive loading. Only parts of shear bands nucleate and develop successfully because of the interaction between shear bands and the heterogeneous microstructure of the materials such as the presence of grain boundary, dislocation and other defects, which is also observed by Nesterenko et al. [8, 9], Meyers et al. [10] and Xue et al. [11, 12] in the thick-walled cylinder. Shear band's bifurcation was found at the late stage of shear banding in the collapsed stainless steel cylinder specimen and the long bands had a greater tendency to bifurcate than the shorter ones [12].

The stress state of α-Ti tube under the external explosive loading is shown in Fig. 8a. The radial stress, the tangential stress and the maximum shear stress for α-Ti tube were given by [7]:

$$\sigma_{\mathrm{r}} = \frac{-r_{\mathrm{e}}^2}{r_{\mathrm{e}}^2 - r_{\mathrm{i}}^2}\left(1 - \frac{r_{\mathrm{i}}^2}{r^2}\right)p \tag{1}$$

$$\sigma_{\theta} = \frac{-r_{\mathrm{e}}^2}{r_{\mathrm{e}}^2 - r_{\mathrm{i}}^2}\left(1 + \frac{r_{\mathrm{i}}^2}{r^2}\right)p \tag{2}$$

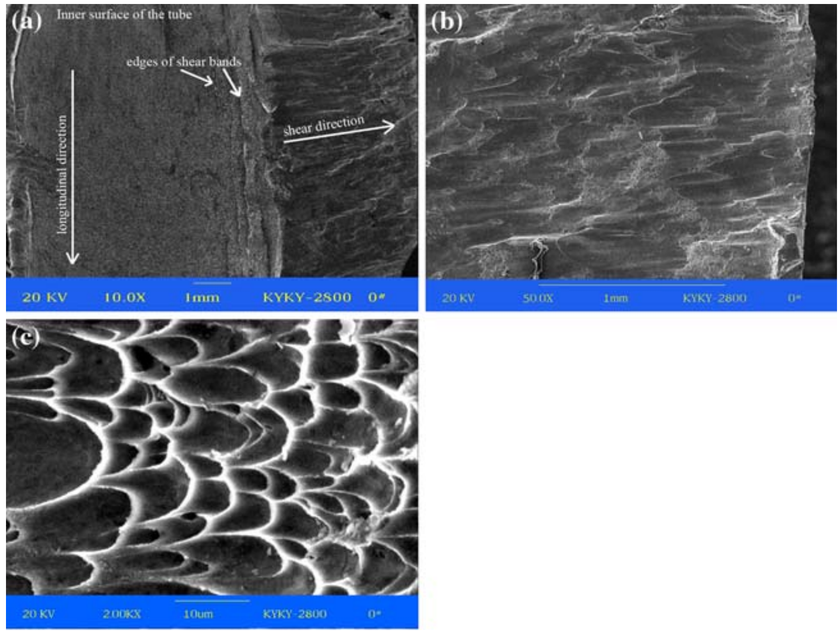



**Fig. 7** SEM morphology of the collapsed $\alpha$-Ti tube: (**a**) collapsed $\alpha$-Ti tube specimen; (**b**) pattern of fracture surface; (**c**) parabolic dimples on the fracture surface

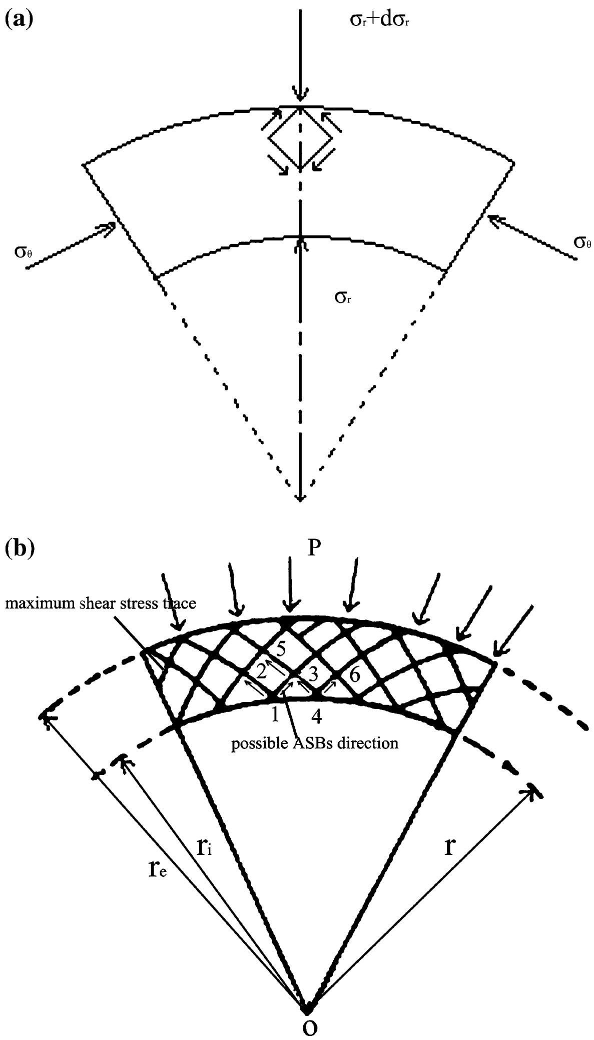



**Fig. 8** (**a**) Stress analysis of the tube; (**b**) Maximum shears stress trajectories in the tube

$$\tau_{\max} = \frac{1}{2}(\sigma_{\mathrm{r}} - \sigma_{\theta}) = \frac{r_{\mathrm{e}}^2}{r_{\mathrm{e}}^2 - r_{\mathrm{i}}^2}\frac{r_{\mathrm{i}}^2}{r^2}p \tag{3}$$

where $p$ is the pressure, $r_{\mathrm{e}}$, $r_{\mathrm{i}}$ and $r$ are external radius, inner radius and the radius, respectively.

In the present study, the values of $r_{\mathrm{e}}$ and $r_{\mathrm{i}}$ are 20.5 mm and 11.5 mm, respectively. The ratio of $\left(\frac{\tau_{\max}^{\mathrm{e}}}{\tau_{\max}^{\mathrm{i}}}\right)$ is 0.31. The maximum shear stress ($\tau_{\max}^{\mathrm{i}}$) in the inner surface is much larger than the shear stress ($\tau_{\max}^{\mathrm{e}}$) in the external surface. Thus, the shear bands should be initiated at the inner surface of $\alpha$-Ti tube.

Shear bands always try to propagate along the surface of the maximum shear stress. The trajectory of ASB can be obtained by describing the trace of the tip of the shear localization. The direction of the maximum shear stress is given by $\vec{\tau} = \vec{\sigma_{\theta}} - \vec{\sigma_{\mathrm{r}}}$. The maximum shear stress trajectories in the cross-section of the metal tube are illustrated by Fig. 8b. Large deformation induced by the external explosive loading leads to the rotation of the bands by around the central axis of the tube. Therefore, the shear bands occur in counterclockwise spirals form. Perhaps, after initiating from the inner surface of the tube, the shear bands meet the strong barriers such as grain boundaries, defects and impurities, at the points '1' and '4'. They cannot overcome these strong barriers and propagate along the another path of maximum shear stress, for example, '1–2', '1–3' and '4–3', '4–6'. Most of developed shear bands rotate in the same direction to the central axis of the tube under symmetrical compress-shear stress. Thus, the bifurcated shear bands on the lines '1–3' and '4–3' collect at the point '3' and propagate towards the counterclockwise direction (line '3–5'). The patterns of ASBs shown in

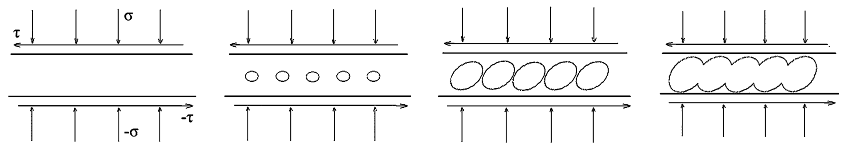



**Fig. 9** Schematic plan of the microvoids nucleation, growth and coalescence in α-Ti tube

Fig. 4 form at the places near to inner surface of the titanium tube because more severe deformation generates near the inner surface of the tube. The voids are easily form at the bifurcation point because of the stress concentration (Fig. 4a).

Microvoids evolution within the shear bands

The microvoids evolution within ASBs is composed of nucleation, growth and coalescence (Fig. 6). Timothy and Hutchings [13] and Timothy [14] proposed a simple T-H model to describe the microvoids evolution within the shear band generated by the ballistic impact, a good agreement with the most of the observations were noticed. The microvoids evolution within ASBs in α-Ti tube under external explosive loading can be described as follows.

Guduru et al. [15], Li et al. [16] and Yang et al. [17] studied the temperature and stress distribution within ASB by experimentation and computer simulation. The results indicated that the temperature and stress within ASB was decreased from the center to the boundary, and the hot spots were located within the center of the shear band. On the other hand, the defects in microstructure can easily cause stress concentration around them. Thus, the nucleation of microvoids occurs at the center of the shear band when the compressive stress is not great enough to close the cavity inside shear band caused by the tension stress, as shown in Figs. 9 and 5a.

The nucleated microvoids grow along major axis and minor axis under applied compressing ($\sigma$) and shear stresses ($\tau$). At the same time, microvoids gradually rotate around the axis normal to the shear band under the applied forces. As soon as the boundaries of microvoids reach the neighbor, they coalesce and form crack within ASBs. The schematic description is shown in Fig. 9.

The coalesced cracks decrease the strength of α-Ti tube. The α-Ti tube fracture when the cracks reach the critical length. Thus the fracture is along the shear band and the fracture surface is composed of parabolic dimples, as shown in Figs. 6 and 7.

## Conclusion

Adiabatic shear banding is the main damage feature of α-Ti tube under the external explosive loading. The shear bands initiated at the inner surface of α-Ti tube are in counter-clockwise spiral form with respect to radius of the tube. The shear bands form at an angle of about 45° with the radius. Some special patterns of ASBs, such as bifurcation, collection, crossing and N-shape are observed. Cracks in the cross-section are along the shear bands. The tips of the shear bands propagate along the surfaces of the maximum shear stress. The microvoids evolution within ASBs is composed of nucleation, growth and coalescence. The formation and growth of the microvoids are caused by local hot spots and stress concentration in the shear bands. The coalesce of microvoids leads to crack within ASBs. The fractures along the ASBs are formed as soon as the crack reaches a critical length.

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