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Adiabatic shearing failure of explosively driven metallic cylinder shell, from experiments to simulation

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Abstract. The adiabatic shear bands (ASB) of the tubular metal specimens expanded explosively have been studied by many researchers in the recent years. The onset and evolutions of the multiple shear failure of metal cylinder under explosive loadings are affected by many factors such as the characteristics of the impulsive loadings, the dynamic behavior of the materials, etc. In this work, we investigate the failure and fragmentation of 45# steel cylinder shell driven by the JOB9003 explosive. Experimental and FEM numerical simulation investigations are made for cylinder modeled shell. The results show that for the perfect homogeneous FEM model, the failure mechanism of cylinder shell is differs from that of the experiments, in which the spalling originates is oriented by high intensity of rarefaction wave. Through numerical experiments, it was found that distributed geometrical defects of cylinder shell affect the fragmentation process and mechanism, in which the strain localization controlled by the defects and shear bands initiate on the inter-surface of the cylinder shell.

1. Introduction

The subject of fragmentation of explosively driven cylinder has long been of interest in the military field, which relate to the applications including the design of fragment and blast resistant structures and protective facilities [1,2]. It is a highly complex phenomenon in which the fragmenting material is plastically deformed by the passage of an intense shock (∼ 30 ms of GPa) followed by high-rate expansion deformation that ultimately leads to fracture. The previous works shown that several failure modes in the fragment cross-section could be occurs, including radial fracture, internal micro cracks, shear-lip fracture and spall fracture, which are related to the cylindrical geometry, materials behavior and loading characteristic of the experiment [2–5]. As one of the major failure mechanism in explosively driven metallic expansion cylinder, adiabatic shear bands (ASB) have receved increasing attention in recent years [6–8]. This phenomenon is characterized by a localization of the plastic deformation in narrow band. The onset of thermo-plastic instability has been examined, either through a maximum stress criterion (e.g., Zener and Hollomon [9]), through linear stability analyses (e.g., Bai [10]). However, the questions of how an ASB formation and develops after instability and how it interacts with the boundaries or neighboring localizations still require further understanding. Nesterenko, Xue et al. [11–14] proposed a controlled way to create multiple shear bands in collapsing thick-walled cylinder (TWC). Another approach of study of ASBs is to model it by numerical simulating via numerical computations and constitutive modeling [15–18], because a numerical simulation can easily include nonlinear effects or check the limits of a theoretical solution. One of the major issues or difficulties in the simulation of ASB propagation is the onset criterion for ASB growth and propagation [15,18].

In this work, we investigate the failure and fragmentation of medium carbon 45 steel cylinder shell driven by the JOB9003 explosive. The high-speed photography has been applied to observer the expanding fracture of the steel cylinder shell. The metallurgical analysis reveals adiabatic shear fracture mechanism. The FEM simulation was conducted to investigate the evolution process of strain localization. It was found that distributed geometrical defects of cylinder shell affect the fragmentation process and mechanism, in which the strain localization controlled by the defects and shear bands initiate on the inter-surface of the cylinder shell. The effects of the defect on the ductile fragmentation process were investigated.

2. Experiment

2.1. Dynamic expansion of cylinder shell

In order to study the initiation of failure and fragmentation of metal cylinder shell during dynamic loading, an axisymmetric cylindrical geometry driven by inner explosive is used in the current experiments. Figure 1 presents a schematic view of the experimental device. The cylinder has an internal diameter of 40 mm and wall-thickness of 5, all made from medium carbon 45# steel. The microstructure of the 45# steel contains dual phases of ferrite grains and pearlite colonies.The high explosive is bonded into the cylinder. A nominal cylinder length of 140 mm is used to achieve a plane-strain load path. A frustum shaped booster comprising a conventional high explosive, RHT-901, initiates the JOB9003 main charge at

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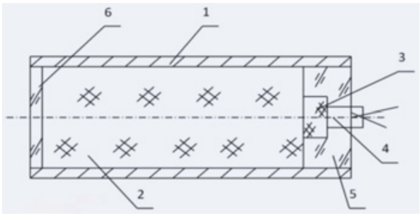


Figure 1. Schematic view of the experimental device.

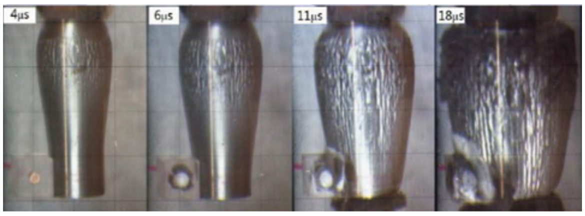


Figure 2. Typical framing records for an exploding 45# steel cylinder with fully charged JOB9003.

Figure 3. The recover samples show shear failure characteristics.

one end. The purpose of this booster is to provide a near-planar detonation to the main charge.

The high-speed photography (sampling time 0.67 ms) has been applied to observer the expanding fracture of the steel cylinder shell. The fiber Doppler velocimeter was used to measure the expanding velocity on outer surface of the metal cylinder.

2.2. Experimental results

Figure 2 shows typical high-speed photography records for a fully charged cylinder of 45# steel expanding symmetrically. A number of crack initiation and axial propagation are seen on the surface at 4 and 18 ms, these features were also seen in other cylinders of TC4 titanium alloy[7]. Typical fragments from an 45 steel cylinder areshown in Fig. 3. The fragment widths are typically a few mm. The processes of the appearance of initial shear fracture and their developments on inner surfaces were recorded. and the fractured surfaces of recovery specimen are analyzed, showing the longitude shear fracture cell characteristics typical for 45 steel, as shown in Fig. 3.

Shear failure running parallel to the fragment length define the fragment width. The fragment cross-sectioned perpendicular to its length, shows fracture surfaces that are inclined at about 45 or 135 degrees with the original inner and outer surfaces. Shear bands are also found within the fragment width, as shown in Fig. 4. Within the fragment interior many adiabatic shear bands are observed in parallel (see Fig. 4), which their separations are on

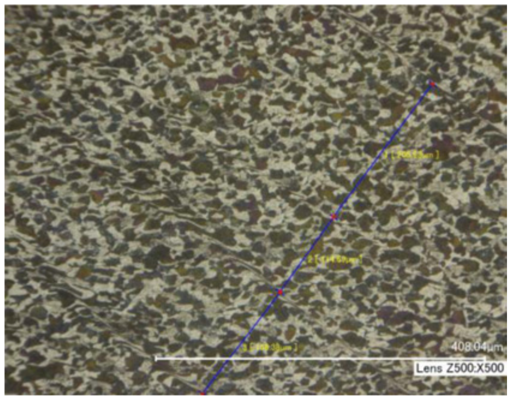


Figure 4. Cross-sectional micrograph of the fragment show shear bands patterns.

Figure 5. Schematic diagram of shear cracks and shear bands spacing.

the order of 110–210 mm. These ASBs do not associated with cracks and propagate the entire way through the shell thickness.

The fracture and metallurgical analysis reveals adiabatic shear fracture mechanism, i.e. the self-organized shear bands deform in inter-surface of cylinder and develop outwards either in the clockwise or anticlockwise direction, at an angle of about 45° or 135° with the radius, the crack propagate along the shear bands, as shown in Fig. 5.

3. Numerical simulation and discussion

3.1. FEM model

To understand the adiabatic shear fracture phenomena and fragmentation size of the cylinder shell, computer simulation for the initial stage of explosion was made using Abqus software, Fig. 6, the FEM element mesh size is 40 μm × 40 μm. The 2D numerical modeling of shock dynamic processes were carry out. Explosive behavior was described by the radial shock loading $P(t)$ applied on inner surface of the shell,

$$p = p_0 e^{-(t-t_d)/t_d} \tag{1}$$

here, P_0 is Chapman-Jouguet pressure 35 Gpa, t_d is decay time 1.25 μs.

The GRUNEISEN state equation and Johnson–Cook constitutive equation are used to describe for the homogeneous behavior of 45# steel:

$$\sigma = (A + B\varepsilon^n)\left[1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_t}{T_t - T_m}\right)^m\right] \tag{2}$$

where A, B, n, m and C are the material parameters, $\dot{\varepsilon}_0$ is a reference strain rate, T_0 is the initial temperature

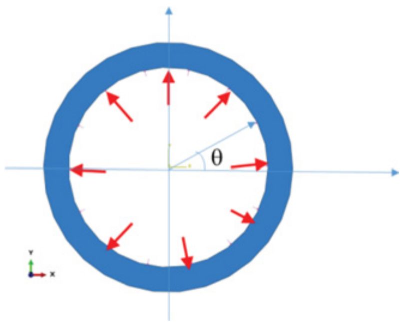


Figure 6. FEM model.

Table 1. Parameters of the 45# steel.

A MPa	B MPa	n	c	m	Melting Temp [K]	Transition Temp [K]	Reference Strain Rate
507	320	0.28	0.064	1.06	1793	293	1
state equation		C_0/m/s	S	$g\gamma_0$			
$u_s - u_p$		4600	1.49	2.17			

(room temperature in this case) and T_m the melting temperature. The parameters of the J-C model we used in the simulations are listed in Table 1.

Shear band formation is complicated and can involve failure of the material in the developing band. The thermal softening, obtained using the J-C model, is sufficient to correspond to the heating of the bulk material. However, in order to obtain localization of the ASB's, a more enhanced softening is essential–accomplished by the use of the shear-soften model. Briefly stated, shear band formation and failure can be seen as an cohesion instability failure of material which is characterized by the progressive deggradation of the material stiffness [],

$$D = \frac{\varepsilon - \varepsilon_{cr}}{\varepsilon_f - \varepsilon_{cr}} \qquad \varepsilon_{cr} < \varepsilon < \varepsilon_f. \tag{3}$$

Here, $\varepsilon_{cr} = 0.3$ adiabatic shear initiation plastic strain, $\varepsilon_f = 0.7$ as the adiabatic shear failure strain of the material. Once the initial of damage, the flow stress in the shear band is,

$$\sigma = \sigma_0 (1 - D) \tag{4}$$

which provides the positive feedback needed to cause adiabatic shear localization. Once $D = 0.9$, the material is no longer allowed to carry hydrostatic tension or deviatoric stresses.

3.2. Simulation results and discussion

3.2.1. Results of the perfect homogeneous shell model

Considering a perfect homogeneous shell model, i.e. the cylinder shell is without any geometric imperfections and strain loclization cause from the random difference of the elememt meshes. Figure 7 shows the results, where we can observe that the damages of micro cracks and voids were produced firstly in the middle area of metal shell. The failure mode of cylinder shell is differs from that of the experiments, in which the self-organized shear bands deform in inter-surface of cylinder and develop outwards either in the clockwise or anticlockwise direction, at an angle of about 45° or 135° with the radius, the crack propagate along the shear bands. The spall fracture originates on this case is oriented by high intensity of rarefaction wave, and propagates in the material inward and outward to surface of shell.

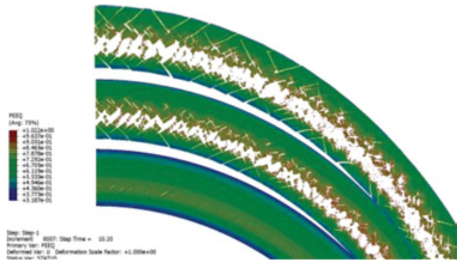


Figure 7. Configuration of the equivalentic plastic strain and damages evolution.

3.2.2. Results of the shell with geometric imperfections

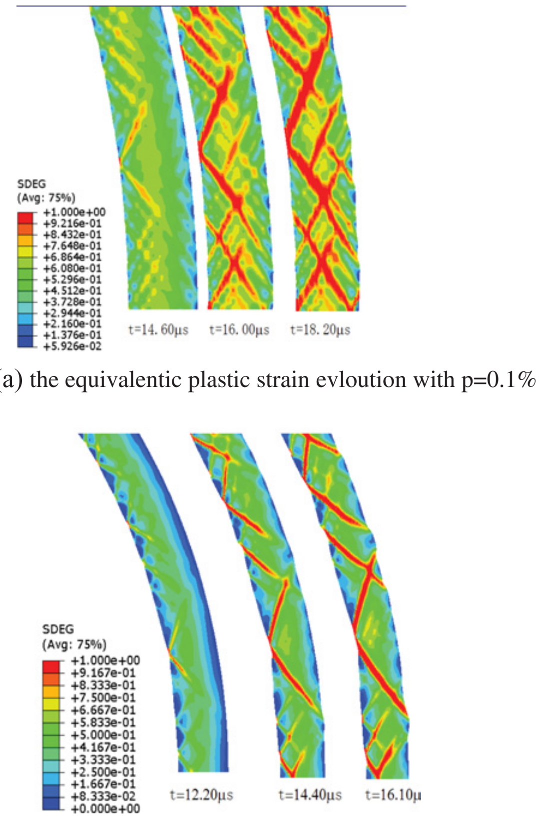
Actually during the fabrication and the machining process, metallic components are inevitably brought with defects or inhomogeneities. Generally such defects or inhomogeneities have an geometric distributions. In this paper, the cylinder shell is prescribed with random geometrical defects, i.e. inner radius of cylinder shell $r = r_0 + P\ rand(1)$, which *rand(1)* is random function and $P = \Delta r / r_o$ are 0.1% and 0.5% respectively.

Through numerical experiments, it was found that failure mechanism of the shell with the initial defects usually distingish from the shell without defects (see Fig. 8 and Fig. 7). The simulation results show that the equivalent plastic strain localization occure in the inner surface of metal tuber. All ASBs randomly propagate outwards either in the clockwise or anticlockwise direction, at an angle of about 45° or 135° with the radius. The lengths of those shear bands vary greatly, and a shielding effect is noticed that areas adjacent to the well developed shear bands are characterized by smaller shear bands as they enter stress-relieved regions. The FEM numerical results are consistent trend with the expermental phenomenon.

Futhermore, the size of the defect also affect the failure process. It was found that the shell with larger the initial defects usually broke into pieces earlier than that of relatively small defects. It show that numbers of shear band decrease with increasing defect size (see Fig. 8(a) and (b)).

4. Summary

In this work, we investigate the failure and fragmentation of metal cylinder shell driven by the JOB9003 explosive. Experimental and FEM numerical simulation investigations are made for cylinder modeled shell with external diameter of 50 mm and internal diameter 40 mm, all made from medium carbon 45 steel. The high-speed photography (sampling time 0.67 ms) has been applied to observer the expanding fracture of the steel cylinder



(a) the equivalentic plastic strain evloution with p=0.1%

(b) the equivalentic plastic strain evloution with p =0.5%

Figure 8. Configuration of calculation area at different times.

shell. The metallurgical analysis reveals adiabatic shear fracture mechanism, i.e. the self-organized shear bands deform in inter-surface of cylinder and develop outwards either in the clockwise or anticlockwise direction, at an angle of about 45° or 135° with the radius, the crack propagate along the shear bands. The FEM simulation was conducted to investigate the evolution process of strain localization. For the perfect homogeneous model, the failure mode of cylinder shell is differs from that of the experiments, in which the spalling originates is oriented by detonation wave, fracture initiates on the case and propagates in the material inward and outward to surface of shell. Through numerical experiments, it was found that distributed geometrical defects of cylinder shell affect the fragmentation process and mechanism, in which the strain localization controlled by the defects and shear bands initiate on the inter-surface of the cylinder shell. The effects of the defect on the ductile fragmentation process were investigated.

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