International Journal of Impact Engineering 95 (2016) 35–39

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Dynamic shear fracture of an explosively-driven metal cylindrical shell

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ARTICLE INFO

Article history:
Received 13 September 2015
Received in revised form 15 March 2016
Accepted 25 April 2016
Available online 28 April 2016

Keywords:
Cylindrical shell
PDV array
Velocity profile
Shear fracture
Sliding velocity

ABSTRACT

This work investigates shear fracture behavior occurring in a titanium alloy cylinder internally filled with high explosives through the use of photonic Doppler velocimetry(PDV) array, high-speed framing camera and soft capture tank. The real-time velocity profiles diagnosed by PDV array display from overlapping to scattering, corresponding to the cylinder from uniform expansion to onset of fracture. In addition to the general findings obtained from individual diagnostics, combined analysis from the experimental measurements determines sliding velocity between sheared cracks and the overall adiabatic shear failure process of the metal cylinder is discussed.

1. Introduction

Dynamic response of metal cylindrical shells at high strain rates receives considerable attention in the industrial and military applications, which includes expanding deformation, crack initiation and propagation, and final rupture. Physical mechanisms of crack formation, fracture criteria and fragmentation behavior are most focused on by experimental measurement, model development and numerical simulation. Earlier in 1943, Gurney [1] had proposed an empirical expression to estimate the ultimate velocity of fragments generated from the metal cylinder internally filled with high explosives. Taylor [2] suggested a theory about failure process of the cylinder related to stress states; however, it is only applicable to radial fracture. Hoggatt and Recht [3] further extended to shear fracture mode by perfecting Taylor's model. Mott [4] and Grady [5,6] separately investigated dynamic fragmentation behavior from statistics-based and energy-based perspectives, predicting the relationship between fragment number and loading strain rates and building a systematic theoretical model for fragmentation, which lays the foundation for conducting numerical simulations [7–11].

Compared to the comprehensive understanding of fragment formation and its statistic distribution, quantitative investigation on dynamic process for the metal cylindrical shell is still sparse, particularly for dominated shear fracture, which originates from adiabatic shear localization. Up to date, available experimental methods [12–20] for characterizing shear fracture failure mainly have: 1) high-speed framing camera, which determines the fracture mode from the photographed images of shell surface; 2) metallurgical characterization, which observes micrograph of the recovered fragments, e.g. large strain localization represents adiabatic shear band. However, these findings only provide qualitative information on the shear fracture for the rupture of the metal cylinder, which is insufficient to unravel the failure mechanism, build shear fracture model and perform numerical simulations. Therefore, it is of considerable importance to gain some quantitative data on shear fracture by improving the diagnostic technique and analytical capability.

In this paper, a combination of PDV array, high-speed framing camera and soft-recovery technique is utilized to investigate dynamic shear fracture response of the titanium alloy (Ti6Al4V) cylindrical shell internally filled with high explosives. The photographed frames offer the circumferential strain of crack initiation and rupture. The collected fragments are used for obtaining the average fragment length and metallurgical examination. Moreover, comparative analysis from real-time results obtains the sliding velocity between sheared cracks as well as elucidates failure character of the metal cylinder.

2. Experimental layout and diagnostics

The whole fielding layout is illustrated in Fig. 1, including experimental setup and diagnostics. The former is composed of a metal cylinder, a high explosive and a detonator, and the latter consists of high-speed framing camera, PDV array and capture tank. The metal

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http://dx.doi.org/10.1016/j.ijimpeng.2016.04.012
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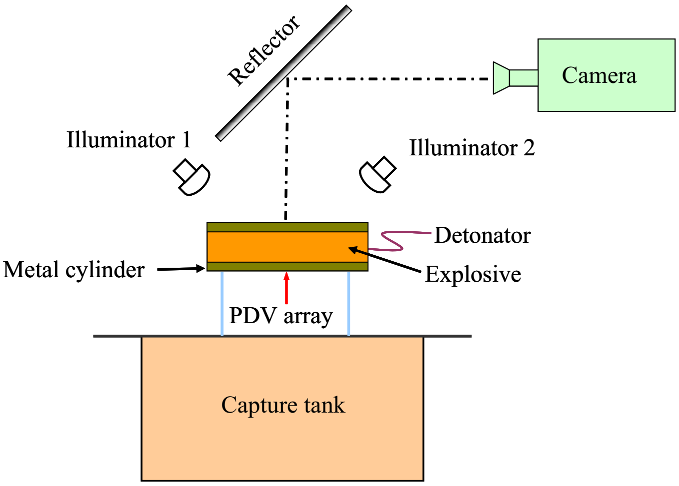


Fig. 1. Experimental layout of explosively-loaded metal cylinder and diagnostic tools.

cylindrical shell is machined from Ti6Al4V alloy, which has a mass density of $\rho = 4.43$ g/cm^3 and is prone to adiabatic shear band formation. The metal cylinder has an outer radius of 52 mm, a wall thickness of 6 mm and a length of 140 mm. The filled high explosives are JOB-9003 (87 wt.%HMX crystals) [21], which geometry has a diameter of 40 mm and a length of 120 mm. The JOB-9003 has a mass density of $\rho = 1.849$ g/cm^3, a detonation velocity of D = 8.7 km/s and a Chapman–Jouguet (CJ) pressure of $P_{CJ} = 35.2$ GPa.

The high-speed framing camera is used for recording 40 images of the metal cylinder surface at a rate of 2 frames per μs. To avoid high-speed metal fragments directly impacting the camera, a reflecting mirror is oriented at an angle of 45° with respect to the axis of metal cylinder. An argon gas in a large plastic bag as a illuminator is explosively shocked to frontally light the cylinder with the background of a white gauze. To clearly photograph the cylinder surface, two illuminators are placed separately along the ± 45° direction. The capture tank filled with watered sawdust is positioned below the experimental setting at a distance of about 200 mm and only collects a fraction of metal fragments. Since we do not take into account the statistical distribution of fragments, these recovered fragments are adequate for metallurgical examination and length measurement. Scanning electron microscopy (SEM) is used for characterizing the fracture surface and microstructure for the metal fragments.

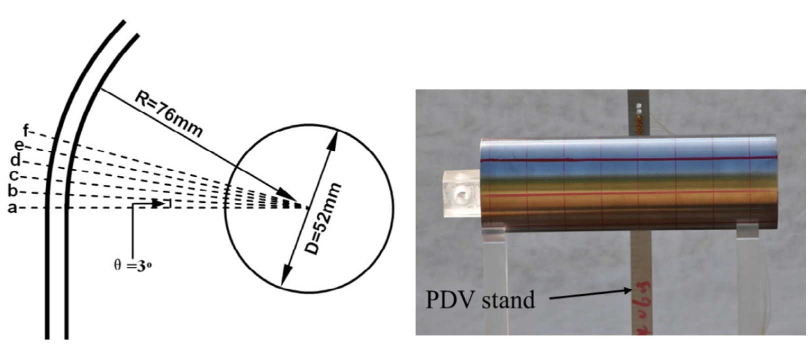
PDV technique is able to accurately measure high velocity profile of a moving body and has been widely employed for explosively loaded metal cylinders; however, to date it only restricts to individual measured point. Actually, theoretical formula concerned about the relationship between average fragment length and loading strain rate derived by Grady [5] could be appropriate for individual fragment, implying the dependence of fragment spacing on the fragment velocity, as will be illustrated in great detail in Section 3.2. Therefore, we contrive a PDV array arranged on a local position of shell surface along the circumferential direction, which ensures PDV probes to span multiple microscopic cracks. According to previous experimental results about average fragment width and PDV measured depth for Ti6Al4V alloy, designed PDV array is depicted in Fig. 2(a), which is an arc stand with a radius of 76 mm. This arc, made from aluminium alloy, includes six PDV probes normal to the shell surface and angle between probes is 3°. In the case of probe layout, distance between them on the shell surface is 1.36 mm, which is larger than the focal spot, preventing the probe from overlapping of light route. Fig. 2(b) illustrates the practical situation of PDV array placed in the middle of the metal cylinder.

3. Experimental results

3.1. Framing images

As a traditional approach for diagnosing dynamic response of the metal cylinder, high-speed framing camera photographs multiple images of shell surface at short time and enables us to obtain a visible observation, such as necking, crack initiation or detonation product leakage. Estimate from these images roughly acquires the circumferential strain of crack initiation and complete rupture of cylinder at different moments. Fig. 3(a) and (b) separately display the framing pictures of t = 17.0 μs and t = 22.5 μs. By defining the circumferential strain $\epsilon_c = (D - D_0)/D_0$, where D_0 is an initial diameter and D is a deformed diameter. Calculated from these two images, $\epsilon_c = 0.19$ denotes crack initiation and $\epsilon_c = 1.00$ is for detonation product leakage. In light of circumferential strain at the same location of the cylinder, such as $\epsilon_c = 0.40$ at t = 17.0 μs in Fig. 3(a) and $\epsilon_c = 0.77$ at t = 22.5 μs in Fig. 3(b), average expanding velocity is evaluated to be 1.90 km/s, close to the limiting Gurney velocity of 1.99 km/s. The exact ultimate velocity measured by PDV is 1.85 km/s, as seen in the next section. Observed from surface morphology of the cylinder shell, it can be determined that fracture characteristic is shear mode and short crack along the longitudinal direction, completely differing from the radial fracture proposed by Taylor [2].

It is also noted from Fig. 3(b) that bright region represents the sliding crack surface and the dark is for crack surface. Compared to Fig. 3(a), the former becomes wider but the latter keeps nearly unchanged; therefore, we are able to evaluate the relatively sliding velocity between shear cracks and fragment width along the transverse direction. For the sake of conveniently calculating these values,



(a) (b)

Fig. 2. (a) Schematic illustration of designed PDV array with six probes denoted by a–f. (b)Practical arrangement of PDV array on the metal cylinder surface.