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Expansion and fracture of AISI 1045 steel explosive-filled cylinders

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Resume: Le comportement de p' expansion et de la fracture des cylindres-explosifs-remplis charges par trois explosifs a puissance differente est etudie. Les cylindres essayes sont faits enacier AISI 1045 traite par deux sortes de chaud-traitement. Une technique de la photographie encadrant a la source-lumineuse-fronte amelioree est utilisee et des parametres de la fracture dynamique sont obtenus. On discute la caracteristique de fracture et la distribution de dimension des fragments en combinant les microstructures des materiaux essayes avec la force chargee.

Abstract: By a improved front light-source framing photography technique and a simple fragments soft recovered method, the expansion and fracture behaviour of the AISI 1045 steel cylinders loaded by three different brisance explosives have been studied. Cylinders were heat treated-normalized and quenched and tempered. Experimental results show that the more intensive of the loading, the stronger capability of the metal's plastic deformation and the larger the expansion ratio of the cylinder before rupture. Fining and evening up the metal grains can increase the proportion of shear fracture and enlarge the fragment size.

1. INTRODUCTION

The high speed deformation and fragmentation of the explosive-filled cylinder had been payed much attention early because of its importance. As early as in 1947, Mott⁽¹⁾ considered the natural fragmentation of ductile metal ring and derived a well known relationship for cylindrical ring bodies between fragment size and certain material properties. Taylor⁽²⁾ studied the fracture of explosive-filled cylinder and deduced a failure criterion that when the internal pressure of the detonation products fall to the value of the material yield strength, the failure would be complete through the wall thickness. Both Mott and Taylor didn't consider the shear fracture. Hoggatt and Recht⁽³⁾ improved Taylor's work by developing a model which can explain the existence of shear lip.

Ivanov⁽⁴⁾ proposed another criterion for shell rupture from the viewpoint of energy. Recently Fong⁽⁵⁾ presented a damage-level criterion from the viewpoint of accumulated damage and this damage-level criterion can explain the experimental results in which there is a maximum value of rupture strain with strain rate around 10^4 s^{-1} . Since 1970s, fracture mechanism and numerical simulation of the explosive-filled cylinder have been studied greatly and had been made a great progress⁽⁶⁻⁸⁾.

In this paper we report a improved front-lighting framing technique used in our study. Some ex-

pansion and fracture behaviour of the AISI 1045 steel cylinders are reported. Combining with micro-structure of the shell material and the loading strength, the fracture characteristic and fragment size distribution are also discussed.

2. EXPERIMENTAL PROCEDURES

2.1 Material Details

The test cylinders were made from the normalized AISI 1045 steel bar (0.44C, 0.88Mn, 0.03Si) with a coarse and uneven pearlite /ferrite grains shown in Fig. 1(a). Some of the cylinders are quenched at 840°C and tempered at 400°C, Fig. 1(b) shows the microstructure for this heat treatment consisted mainly of finer and even sorbite. There are two kinds of cylinders, one is 220mm long and had an inside diameter of 32mm, its wall thickness are 3.6mm and 8.0mm, another is 240mm long and had an inside diameter of 100mm with a 11mm wall thickness.

Fig. 1 two kinds of microstructures of AISI 1045 steel

The explosives used in this investigation are PBX-9404, TNT/RDX(40/60) and RDX/PVB(55/45). Their explosion pressures are 36.9GPa, 27.0GPa and 4.8GPa, respectively, and their corresponding densities are 1.86g/cm³, 1.78g/cm³ and 0.83g/cm³. We call them as A, B, C explosive for brevity from now on.

2.2 Explosive Testing

1. Test cylinder, 2. water box, 3. light bombs, 4. Reflector, 5. To the frame camera

Fig. 2 Schematic diagram of experimental arrangement

The expansion and fracture behaviours of the cylinder are usually observed through the photos taken from the x-ray and framing camera. But many of them are not very clear and we can't observe the dynamic image in more detail. The measurement of the data is not so desirable. So we improved the traditional framing photography with front-light source in the respects of light source size and its position. Fig. 2 shows the experimental arrangement, in which the light sources consist of two argon bags and each with a piece of explosive ($\phi 220\text{mm} \times 10\text{mm}$, Composition-B) behind it. The size of the argon bag is about $500 \times 500 \times 300 (\text{mm}^3)$. Put one of the light bomb (argon bag with explosive) on the left of the cylinder, the other on the right.

The test cylinders were filled with explosives of the same length, detonated by a booster with a detonator at one end. The fragments were softly recovered by magnet and dried.

3. RESULTS AND DISCUSSION

3.1 The Expansion and fracture characters of the cylinder

From the framing photos we find the cylinder loaded by high explosive (A, B) almost immediately expand outwardly when the internal detonation wave arrives there. After several microseconds or more, the surface of the cylinder begin to appear cracks. With another several microseconds or more time's expansion, the detonation products appear on the cracks and this represents the time when failure is complete through the wall thickness, But for those cylinders loaded by explosive C, it will take a very long time (compared to explosive A and B) for them to begin expand after detonation wave passed there. Very few longitudinal cracks appear on the surface compared with the high explosive-filled cylinders.

Fig. 3 shows the expansion history of the outer surface (up to the first fracture) of the same kind of cylinders loaded by A, B, C explosives. All the data are measured from the same position, just near the middle of the cylinders. From Fig. 3 we can see the greater the brisance of the explosive, the bigger the radial acceleration of the shell and the bigger the plastic deformation before fracture.

Table 1 Comparison of experimental data when cylinders were broken

data \ No	0A1	1A1	0A2	1A2	0B2	0C2
C/M	0.44	0.44	0.18	0.18	0.16	0.08
$t_f (\mu\text{s})$	15.9	15.4	20.9	22.5	18.4	56.0
R_f/R_0	2.32	2.29	1.85	1.89	1.52	1.26
$\bar{\epsilon}_f (\%)$	131.1	129.0	84.7	88.7	52.3	26.4
$\dot{\bar{\epsilon}}_f (\times 10^5 \text{s}^{-1})$	0.83	0.84	0.41	0.38	0.28	0.05

Some experimental results are listed in Table 1, where t_f is the time after detonation wave arrived the measured position, R_f/R_0 is the ratio of initial outer radius R_0 with the fracture radius R_f . $\bar{\epsilon}_f = (R_f - R_0)/R_0$, $\dot{\bar{\epsilon}} = \bar{\epsilon}_f/t_f$, C/M is the weight ratio of explosive and cylinder. From Table 1 we find the expansion ratio of the cylinder (R_f/R_0) increase with the increase of strain rate. This result coincided with Clark's results⁽⁷⁾ of HF-1 steel and Bearcat steel cylinders loaded by PBX-9404, TNT and Baratol respectively.

3. 2 Application of Ivanov's criterion

Suppose the energy of propagation of a crack is given by the elastic energy liberated by the refraction waves travelling from the crack. If λ is the crack energy per unit surface area, and q is the specific elastic energy, for cylinders, $\int q dv = \lambda s$. Assuming a visco-elastic relation for the flow stress. $\sigma = \sigma_0 + \eta \dot{\epsilon}$, leads to

$$\mu^2 \dot{\epsilon}^2 \epsilon (\epsilon + 2)/2 + \dot{\epsilon} (2\mu\epsilon - \alpha) + \ln(\epsilon + 1) = 0$$

with $\mu = \frac{\eta}{\sigma_0}$, $\alpha = 4E\lambda/3C\sigma_0^2$, where C is the sound velocity and E is Young's modulus. For AISI 1045 steel, $\sigma_0 = 5.7 \times 10^8 \text{ Pa}$, $E = 2.1 \times 10^{11} \text{ Pa}$, $C = 4.6 \times 10^3 \text{ m/s}$. We obtained the experimental curve $\epsilon = f(\dot{\epsilon})$ shown in Fig. 4 by changing two parameters η and λ . When the theoretical curve fits the experimental results best, our choice for α and μ leads to $\eta = 2.1 \times 10^3 \text{ Pa} \cdot \text{s}$ and $\lambda = 10.4 \times 10^4 \text{ J/m}^2$. The values of η and λ are not far from those obtained by Ivanov⁽⁴⁾ and Olive⁽⁶⁾.

Fig. 3 The expansion histories of the cylinders loaded by A, B, C explosives, respectively.

Fig. 4 Application of the rupture criterion of Ivanov to our results for AISI 1045 steel

(a) Tensile fracture area

(b) Shear fracture area

Fig. 5 The fractography of the fragments

3. 3 The fracture characters of fragments

We just describe the longitudinal fracture surfaces of the fragments. Macro-examination of fracture surfaces of all the fragments shows there are two basic kinds of fracture. When the radial expansion rate (strain rate $\dot{\epsilon}$) increases from 10^3 s^{-1} to 10^6 s^{-1} , the fracture modes change from tensile to shear correspondingly, or the proportion of shear fracture within one fragment increases and the amount of fragments formed by shear fracture also increases with the decreasing of the number of tensile frac-

ture fragments.

When the grains of the steel changes from coarse and uneven pearlite/ferrite to finer and even sorbite, the same trend also occurred.

The tensile fracture surface looks grey and fibred, while the shear fracture surface looks light and smooth. Under the scope of SEM, the micro-morpholgy of the tesile fracture surface is shown in Fig. 5 (a) which is of cleavage and quasi-cleavage characters. Fig. 5(b) is the micro-characters of shear fracture surface which consist of ductile dimples.

3.4 Fragment Size Distribution

Modified Payman distribution⁽⁹⁾ was used to compare the fragmentation behaviour of testing cylinders because of its validity and simplicity. The logarithm of cumulative mass percentage of fragments ($\lg p$) above a certain mass (m) is plotted against the normalized value m/M_R , where M_R is the total recovered mass of fragments. The slope of the straight line of best fit is named as fragmentation parameter (k). The smaller the k value, the more serious the fragmentation (the finer the fragments).

Fig. 6(a) shows the effects of micro-structures on fragmentation of two groups of cylinders. We found the fragments became coarser after being heat treated as finer and even sorbite grains. This result lies in the strengthening of plasticity and toughness. Gourdin⁽¹⁰⁾ and Affouard⁽¹¹⁾ also gained the similar results with OFHC-Cu and martensite steel, respectively.

(a) Effects of the heat treatment

(b) Effects of the brisance

Fig. 6 The modified Payman distributions of the fragments

The effect of the brisance is shown in Fig. 6(b). It is apparent that the more intensive of the loading, the smaller the k value. This means the fragmentation of the cylinder is finer and the number of the fragments is greater. This is because the shell material has absorbed more energy from the loading. As Grady⁽¹²⁾ pointed out that the number of fragments was controlled by the energy transmitted into the medium from loading.

4 CONCLUSION

From the above results and discussions we draw some conclusions as follows:

- (1) The framing photography technique with front-light source used in this study has recorded a very clear photos of the expansion cylinders. This method can be used in other high strain rate experiments, such as expansion ring.
- (2) The fragmentation of explosive-filled cylinder is a very complicated procedure. The main factors in determining the fracture mode of the cylinder are still the strain rate and the

micro-structure of the loading. (3) At explosive strain rates (10^3 - 10^5 s⁻¹), the more intensive of the loading, the stronger capability of the metal's plastic deformation and the larger expansion ratio before rupture. At the same time, the fragmentation is more serious owing to the larger energy density in the medium. (4) Under the same experimental condition, fining and evening up the grains can result in larger fragments, and the proportion of shear fracture also increase.

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