Expansion Fracture Behavior of Metallic Cylindrical Shell Caused by Explosive Detonation

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Abstract. To investigate the dynamic behavior of expansion-induced fracture of a metal cylindrical shell driven by the detonation of condensed explosives, detonation driving tests were designed and implemented under two working conditions, namely, (i) the metal cylindrical shells made up of different metals were driven by the same explosive, and (ii) the cylindrical shells made up of the same metal were driven by different explosives. The entire expansion process was recorded using a high-speed scanning camera, and the curves of expansion displacement and velocity vs. time were plotted. The applicability of the parameters characterizing the detonation driving capability of explosive was also analyzed. The SEM images of the fragment fracture sections of the metal shells show that the metal fracture mode is related to the driving capability of explosive and the properties of metals. The shells made up of metals with a suitable ductility showed mainly the ductile tensile fracture with local brittle fractures, while the shells made up of metals with a poor ductility showed mainly the brittle shear fracture.

1. Introduction

Studies on the deformation, expansion, and fracture behaviors of metal cylindrical shells driven by detonation have important theoretical and practical engineering applications. Many dynamicists and material scientists have conducted extensive studies on this subject, mainly focusing on the fragment parameters and fracturing mechanisms of shells during detonation to satisfy the requirements of industry and military. Since the 1940s, Gurney [1], Mott [2], Taylor [3], et al., performed extensive theoretical and experimental studies on the fracture and crushing behavior of shells under the action of explosive loads. They derived the initial velocity and mass distributions of the metal fragments driven by detonation; moreover, they derived the expression of fracture radius by introducing material strength and yield criteria, thus initiating studies on detonation-driven metal fracture. By the 1960s and 1970s, the research focus shifted from simple macroscopic experiments to the analysis of fracture mechanisms. Slate [4], Hoggatt and Recht[5], and F. Olive[6] et al. conducted several experiments to analyze the fracture mechanism and modes of materials, carried out semi-empirical correction on the expansion velocity and fracture criterion, and investigated the strain rate effect of fractures. Kury[7] proposed cylinder tests that served as the general references for studies on the shells driven by explosive detonation. Recent studies mainly focused on the fracture mode and crushing behavior of materials [8–15]. Based on the development of experimental methods, they gained in-depth insights from the analysis of macroscopic tests into the micro-mechanisms, analyzed the detonation driving
processes and metal cracks by high-speed photography and micro-mechanism analysis by scanning electron microscopy (SEM), and investigated many fracture modes of metals driven by detonation.

The essential characteristic of the expansion and deformation of metals driven by explosive detonation is energy conversion. The energy transfer depends on the complex coupling interactions between the explosive detonation and metal shells. Because the detonation-driven tests generally have high costs and certain risks, most studies reported the experimental investigations on the detonation performance of explosives. In these tests, the detonation-driven capacity of explosives was generally characterized by Gurney energy or coefficient, obtained by driving copper shells in the standardized tests. As the characteristic parameters of condensed explosives, the generality of Gurney energy or coefficient for the shells made up of other metals still needs further studies. Under the detonation driving, the dynamic fracture of metals is a complex process, and the physical mechanisms are unclear. The analysis of the micro-mechanisms of the metal’s expansion-induced fracture under a high strain rate is an effective method to study the dynamic mechanical behavior of fractures under extreme conditions. In this study, based on the standard cylinder test, the condensed explosive detonation-driven tests were designed and implemented under two working conditions: (i) different metal shells were driven by the same explosive and (ii) the same metal shells were driven by different explosives. The applicability of the parameters that can characterize the explosive driving capability was evaluated, and the mechanical behavior of the expansion-induced fractures of copper, steel, and aluminum shells were analyzed, thus improving the research on the fracture mechanical behavior of metals under extreme conditions.

2. Design of test schemes

To investigate the detonation-driven entire process including the expansion, acceleration, and fracture of metal shells driven by explosive detonation, the tests were conducted under the following two working conditions: (1) the explosive detonation-driven tests were conducted on different shells made up of different metals when the same explosives were loaded, and it labeled as working condition I; (2) the explosive detonation-driven tests were conducted on the same shell when different explosives were loaded, and it labeled as working condition II.

The tests were conducted by following the standard Ф50 cylinder tests [7]. The test system comprised explosives, metal shells, electric probes, and an argon flash bomb for lighting, a reflection mirror, and a high-speed scanning camera in the bunker. For security, the expansion of the cylindrical shells on both the ends of slits reflected by the mirror was recorded using the high-speed scanning camera with a scanning velocity of 1.5 mm/μs. The slit was located at 295 mm away from the detonation point. The argon flash bomb was used as the background light source so that the negatives were recorded more clearly. The actual detonation velocity was measured using electric probes that were fixed at the two ends of the explosive column. The principle of the test system is shown in Figure 1.

TNT, JH16, and CL20-based aluminized explosives were used in the tests. The explosive column with a size of Ф 50×495 mm² was seamlessly spliced by multiple small explosive columns with the
same density and size. The surface of the explosive column had no cracks, and the edges had no defects. During the tests, the detonation was initiated using an electric detonator at one end. Table 1 lists the specific parameters of the explosives. The metal cylindrical shells were made up of three common elastic materials: oxygen-free copper, 45# steel, and 6061 aluminum alloy, in which the oxygen-free copper and 6061 aluminum alloy were manufactured without any heat treatment, whereas the 45# steel was manufactured by a normalizing treatment at 850 °C, then through heat preservation at 840 °C for 20 min, and finally by oil quenching. Table 2 lists the specific parameters of the metal cylindrical shells.

| Table 1. Parameters of the explosives |
|--------------------------------------|
| **Explosive** | **Density (g/cm³)** | **Detonation velocity D (m/s)** |
| TNT | 1.58 | 6836 |
| JH16 | 1.67 | 8279 |
| CL20-based aluminized explosive | 1.97 | 8540 |

| Table 2. Parameters of the metal cylindrical shells |
|--------------------------------------|
| **Materials** | **Inner diameter (mm)** | **Outer diameter (mm)** | **Density (g/cm³)** | **Yield strength (MPa)** | **Tensile strength (MPa)** |
| Oxygen-free copper | 50.10 | 60.34 | 8.9 | 200 | 380 |
| 45# steel | 50.05 | 60.00 | 7.85 | 355 | 600 |
| 6061 aluminum alloy | 50.02 | 60.00 | 2.9 | 276 | 310 |

In the tests, under working condition I, the most common TNT explosive was used for driving the cylindrical shells made up of three metals; under working condition II, the cylindrical shells made up of oxygen-free copper for standard cylinder tests were used, in which three different explosives were tested. To guarantee the accuracy, each group of tests was repeated once, and the mean values were selected as the test result. After each group of the tests was completed, the negatives were scanned (Figure 3), in which the expansion trajectories of the outer walls of metal cylindrical shells were recorded.

| Table 3. Scanned negatives under different working conditions |
|--------------------------------------|
| **Working condition** | **Scanned negatives** |
| I | (a) Copper shells |
| II | (b) Steel shells |
| | (c) Aluminum shells |
| | (d) Copper shell charged with TNT |
| | (e) Copper shell charged with JH16 |
| | (f) Copper shell charged with CL20-based aluminized explosive |

### 3. Analysis of the expansion of shells driven by detonation

#### 3.1 Expansion velocity of the shell driven by detonation

After conducting boundary treatments on these negatives, the expansion trajectories and interface coordinates of the outer walls of shells were obtained. Then, the expansion displacement of the outer interfaces of shells and time data were calculated based on the magnification and scanning velocity of images. The curves of the expansion displacements of shells vs. time were plotted as shown in Figure 2.
The analysis of the mechanical essence of the detonation-driven metal shells indicates that the combined action of explosive shock wave and the driving force generated during the expansion of gas detonation products results in the expansion of cylindrical shells. The shock wave action is so rapid and transient that it increased the expansion velocity of shell rapidly during the early stage, whereas the driving force generated during the expansion of gas detonation products has a lower peak magnitude, but a relatively longer duration. The relationship between the expansion displacement of shell \((R - R_0)\) and expansion time \((t)\) can be expressed as follows [16]:

\[
R - R_0 = V_s \left( t - \tau_s \left( 1 - \exp \left( -\frac{t}{\tau_s} \right) \right) \right) + I_{\text{gas}} \left( \tau_2^2 \exp \left( -\frac{t}{\tau_2} \right) - \tau_1^2 \exp \left( -\frac{t}{\tau_1} \right) + (\tau_2 - \tau_1) t + (\tau_1^2 - \tau_2^2) \right) \tag{1}
\]

where \(R\) and \(R_0\) are the expanded radius of cylindrical shell at \(t\) and initial radius, respectively; \(V_s\) is the expansion velocity of cylindrical shell driven by shock wave; \(\tau_s\) is the acceleration period of cylindrical shell due to the action of shock wave; \(I_{\text{gas}}\) is the amplitude of the expansive fluctuation induced by gas detonation products; and \(\tau_1\) and \(\tau_2\) are the increase and decrease in the time constants of the expansive fluctuation induced by gas detonation products.

Using the Origin software, nonlinear fitting was conducted on the acquired cylindrical shell’s expansion displacement and time data under different explosive charging conditions using Eq. (1). After the initial values of parameters were set, the iteration was performed until the convergence was achieved, i.e., the fitted curves almost coincided with the experimental curves. Table 4 lists the fitting parameters.

**Table 4. Fitting parameters for the displacement curves of the cylindrical shells made up of different metals**

| Working condition     | Detonation velocity \(D\) (mm/μs) | \(V_s\) (mm/μs) | \(\tau_s\) (μs) | \(I_{\text{gas}}\) (mm/μs) | \(\tau_1\) (μs) | \(\tau_2\) (μs) |
|-----------------------|------------------------------------|----------------|----------------|----------------------------|---------------|---------------|
| I TNT-Copper          | 6.836                              | 0.68466        | 0.37031        | 0.10267                    | 1.35037       | 7.77272       |
| I TNT-Steel           | 6.809                              | 0.75221        | 0.48186        | 0.14429                    | 1.27525       | 6.22192       |
| I TNT-Aluminum        | 6.795                              | 1.07305        | 0.55085        | 0.16475                    | 1.01048       | 7.14790       |
| II JH16-Copper        | 8.279                              | 0.86895        | 0.11826        | 0.11826                    | 0.83937       | 7.61043       |
| II CL20-based aluminum explosive-Copper | 8.540                              | 0.86476        | 0.11723        | 0.1214                     | 0.6994        | 9.61401       |

After taking the time derivative of Eq. (1), the equation for the expansion velocity of cylindrical shell, \(u\), was acquired and can be expressed as follows:

\[
u = V_s \left[ 1 - \exp \left( -\frac{t}{\tau_s} \right) \right] + I_{\text{gas}} \left[ \tau_1 \exp \left( -\frac{t}{\tau_1} \right) - \tau_2 \exp \left( -\frac{t}{\tau_2} \right) + (\tau_2 - \tau_1) \right] \tag{2}\]
By substituting the parameters in Table 4 into Eq. (2), the expansion velocity curves of cylindrical shell vs. time under different explosive charging conditions were acquired as shown in Figure 3. During the initial stage of detonation driving, the shock wave first acted on the cylindrical shells, and thus the shell’s expansion velocity increased rapidly. The acceleration completed within the driving period of 1 μs, whereas the increasing amplitude of velocity depends on the coupling action between the detonation wave and metal. Compared to the transient action of shock wave, the high-temperature and high-pressure detonation gas imposed a more lasting and smoother action on accelerating the cylindrical shell until the metal cylindrical shell fractured and reached the maximum expansion velocity.

![Figure 3. Expansion displacement curves of cylindrical shells vs. time](image)

(a) Working condition I  
(b) Working condition II  

3.2 Gurney energy and coefficient

The physical essence for the acceleration of metal shell driven by explosive is the energy conversion. In an explosive-metal system, the chemical energy of the explosives is converted to the internal and kinetic energies of the detonation products and the kinetic energy of metal shell. The energy with effective work is the kinetic energy of metal that reflects the explosive’s capability of performing work on the metal and is also an intrinsic physical parameter of the explosive itself, characterized by Gurney energy or coefficient [1]. Based on the Gurney energy of explosive calibrated by the standard cylinder tests for copper shells driven by detonation, many scholars derived several empirical formulas for simple calculations. Table 5 lists and compares the Gurney coefficients when the copper shells were driven by different explosives under working condition II; for the same type of explosive, the Gurney coefficients calculated by different empirical formulas are close to the test values with the maximum error <5%.

| Explosive                    | Gurney coefficient (m/s) | Test value | (1)  | (2)  | (3)  | (4)  |
|------------------------------|--------------------------|-----------|------|------|------|------|
| TNT                          | 2330                     | 2434      | 2219 | 2334 | 2392 |
| JH-16                        | 2800                     | 2838      | 2688 | 2819 | 2768 |
| CL20-base aluminized         | 2902                     | 2911      | 2773 | —    | —    |

Note: empirical formula (1) in Ref. [1]: \( \sqrt{2E} = 0.52 + 0.28D \); empirical formula (2) in Ref. [17]: \( \sqrt{2E} = D^{0.5}/3.08 \); empirical formula (3) in Ref. [18]: \( \sqrt{2E} = 0.887\phi^{0.5}\rho_0^{0.4} \); empirical formula (4) in Ref. [19]: \( \sqrt{2E} = 0.6 + 0.54(1.44\rho_0\phi)^{1/3} \). The latter two empirical formulas are suitable for...
nitro-hydrocarbons (CHNO) explosive; therefore, no calculation results were obtained for the aluminized explosives.

Then another question is raised, i.e., whether the Gurney coefficient calibrated by the detonation-driven copper shells can also be applied to the shells made up of other materials. Therefore, the Gurney coefficients of TNT for driving the shells made up of different metals, i.e., under working condition I, were analyzed. The results show that the Gurney coefficients of TNT for driving the steel and aluminum shells were 2349 and 2235 m/s, respectively, close to the value of TNT for driving the copper shells. This indicates that the Gurney coefficient of explosive calibrated by the standard copper shell tests can be directly used for calculating the initial velocity of the fragments of other metal shells.

3.3 Analysis of the fracture modes of metal cylindrical shells
The metal cylindrical shells would expand under the combined action of shock wave and detonation products. The shell first underwent an acceleration stage and then entered a high-strain-rate expansion stage, finally causing the penetrating fracture after a very transient period. It is generally considered that under the action of detonation, the following two factors mainly affected the fracture mode of shells, the microstructural properties of material, and the applied strain rate, reflecting the intrinsic physical characteristics of material and external loading conditions, respectively. In the tests, the fragments of the metal shells driven by detonation were recollected. The fragments with arbitrary sizes were randomly selected, and the fractures were scanned and analyzed using an electron microscope to observe the morphology of fractures and estimate the modes of fracture. The results are shown in Tables 6 and 7.

Figure 5 shows the macro-pictures of the fracture of fragment; the copper fragment is thin and exhibits clear traces of stretch, while the necking effect occurs at the fracture section. The microscopic SEM pictures of various fractures of fragment show that a large number of dimples exist at the fracture sections of the copper fragments detonated by JH16 and CL20-based aluminized explosives. Clearly, plastic deformation characteristics were observed, whereas the sizes and arrangements of the plastic deformation were irregular. The directionality on the fragment surface (the bright white lines) indicates some traces of a brittle stretch. It can be concluded that for the ductile materials with favorable malleability such as oxygen-free copper, the cylindrical shell can be fully expanded under the driving action of internal explosive loads because of its good ductility, generating some thin fragments. The fracture mode is primarily the ductile tensile fracture with some local brittle fracture traces.

Table 6. SEM observations of the fracture sections of the oxygen-free copper shells driven by different explosives

| Explosive Charging by TNT explosive | Charging by JH16 explosive | Charging by CL20-based aluminized explosive |
|-------------------------------------|---------------------------|---------------------------------------------|
| Recycled fragments                  | JH16                      | CL20--Al                                    |
| SEM observations of fragment surfaces | Cu                        | Cu                                          |
Unlike the ductile tensile fracture of the copper shells with favorable ductility, brittle materials with poor ductility have different fracture modes. As shown in Table 7, the fragments of steel and aluminum shells were relatively thicker and exhibited relative slip surfaces on both the sides of the fragments, with certain angles with the fracture surface. The microscopic SEM pictures showed that the flowing lines rather than dimples exist in the fractures of steel and aluminum fragments. The shear fissures were observed, i.e., the brittle shear fracture appeared after the combined action of high temperature and high pressure.

Table 7. SEM observations of the surface of the fragment fracture sections of the cylindrical shells made up of three metals driven by TNT detonation

| Forming materials | Copper shell | Steel shell | Aluminum shell |
|-------------------|-------------|-------------|----------------|
| Recycled fragments | ![SEM image] | ![SEM image] | ![SEM image] |

| SEM observations of the fragment surface | ![SEM image] | ![SEM image] | ![SEM image] |

4. Conclusions
We investigated the mechanical behavior of the expansion-induced fracture of metal cylindrical shells driven by the detonation of condensed explosives by performing tests and characterized the expansion velocity and detonation energy under different detonation driving conditions. By analyzing the microscopic properties of the fracture sections of the metal fragments, the dynamic fracture modes of shells made of different metals under detonation driving conditions were investigated. The main conclusions are listed below.

1) The metal cylindrical shells driven by the detonation of condensed explosives are a complex problem in explosion mechanics. The coupling action between the detonation of explosive and metal cylindrical shells determines this transient dynamic variation process. The experimental results indicate that the secondary reaction energy of the C-20-based aluminized explosive has a small driving effect, and the explosive shock wave driving the shell made of the same metal mainly depends on the detonation velocity.

2) The parameters characterizing the driving capability of explosive (i.e., Gurney coefficient) were also investigated. By comparing the test values with those calculated using empirical formulas, the maximum difference between the calculated and empirical values was 5% at the most. The Gurney coefficient calibrated through the tests for copper shells can be directly applied to the calculation of the initial fragment velocity of the cylindrical shells made up of other materials, i.e., the empirical formulas have general applicability to different condensed explosives.

3) According to the microscopic observations on the fragments of metal shells, for the cylindrical shells made up of the materials with favorable ductility, the shells can be fully expanded under the driving action of internal detonation loads, forming thinner fragments. The fracture mode was mainly the ductile tensile fracture and partly local brittle fracture. For the cylindrical shells made up of brittle
materials with poor ductility, the formed fragments are relatively thicker, and the fracture mode is mainly characterized by brittle shear fracture.

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