The fragmentation of thin-walled Q235 steel shell under explosion

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Abstract. The fragmentation of a shell filled with explosive is quite valuable for evaluating the killing ability of improvised explosive device. A typical explosive device with Q235 steel shell and TNT explosive is chosen to study the fragmentation of thin-walled structure. With sand recovery method, experiments are conducted to get fragments with the mass above 0.1g. G-S formula shows a better agreement with experimental results when predicting average fragment mass than Mott formula. Further researches show that shell thickness and length-diameter aspect ratio have great effect on the fragmentation of shell. Average fragment mass increases exponentially and total fragment number decreases exponentially when shell thickness increases, while average fragment mass remains almost unchanged and fragment number grows linearly when length-diameter aspect ratio increases. These results are very helpful for whenever academic study or real application.

1. Introduction

If the explosive is detonated, the outer shell is subject to extremely high internal pressure from the gaseous products and then begins to move rapidly outwards. Radial expansion causes the shell to shatter into various sized “natural fragments” that fly in all directions. These fragments gain high scattering velocity and kinetic energy enough to defeat many targets. This kind of damage element has been widely applied in both military weapons and improvised explosive devices [1-3].

There are four parameters associated with fragment: number, mass, initial velocity and spatial distribution. Natural fragmentation yields a random distribution of fragment sizes (masses), while many researchers had done significant work to predict it for engineering application. Mott [4] recognized the need for scaling relations to allow designers to immediately assess the effects of parameter changes on fragmentation characteristics. Held [5] found that two-parameter Weibull distribution may give an excellent description of mass distribution for natural fragments. Arnold [6] carried out some experiments to compare the mass distribution of light and heavy steel casings after explosion. Zhang [7] designed a few shells with variable thickness and studied their fragmentation by experiments and theoretical methods. Based on the Mott formula, Gurney and Sarmousakis [8] gave another calculation method (G-S formula) for average fragment mass by considering the type and mass of explosive.

In the present paper, the fragmentation behavior of different shells containing high explosive has been studied. The shells are made from mild steel which is typical in common application. Two kinds of explosive devices are experimented to study their characteristics of fragments and then compared
with Mott formula and G-S formula. Moreover, the influence of shell thickness and length-diameter ratio on fragmentation is explored in depth in order to grasp their changing rule.

2. Fragment Mass Distribution Law

For a whole shell under explosion, the crack location is totally random. Not only fragment number but also fragment mass is uniform which leads to no simple and accurate theoretical calculation formula for number and mass distribution of fragments. Through lots of experiments, some empirical formulas were put forward to estimate the fragmentation, such as Russian Air Force Academy formula, Cook formula, Mott formula, etc. The first two formulas did not consider the influence of explosive charge, while Mott formula did. Mott formula and G-S formula are described in detail below.

2.1. Mott formula

The Mott formula proposed by Mott and Linfoot has been successfully used by numerous researchers over the past several decades to compare vast amounts of exploding munitions fragmentation data. Especially in many US military manuals, Mott formula has been cited as a standard method. The expression is:

$$N(m_f) = \frac{M}{\bar{m}_f} e^{-\left(m_f/\bar{m}_f\right)^{1/i}}$$

where $N(m_f)$ denotes the number of fragments with mass larger than $\bar{m}_f$; $M$ is the total mass of fragments, namely the mass of the case; $\bar{m}_f$ is the average mass of fragments; $i$ is the dimension (1, 2 and 3); $\mu_i$ is called Mott fragmentation parameter and related with $\bar{m}_f$, $\mu_i = \bar{m}_f/i!$.

When a fracture occurs at a point on the Mott cylinder, two Mott release waves are created and propagate away from the fracture. It means that the thin-walled shell is broken into fragments in two dimensions. Of course, this theory is based on that fracture in two principle direct ions are independent and governed by the conditions of the linear fragmentation theory. Hereby, the Mott fragment mass/number distribution can be expressed as:

$$N(m_f) = \frac{M}{2\mu} e^{-2(m_f/\mu)^{1/2}}$$

where $2\mu$ is the average fragment mass, $M/2\mu$ is the total number of fragments $N_0$. It can be seen that $N_0$ and $N(m_f)$ can be calculated as long as $\mu$ is known.

Following extensive and insightful analysis, Mott found the average fragment mass is a parameter depending on the inner diameter and thickness of the shell. Later he arrived at a scaling relation for the fragmentation of exploding cylindrical shells:

$$\mu^{1/2} = K \delta_0^{5/6} d_0^{1/3} \left(1 + \frac{\delta_0}{d_0}\right)$$

where $K$ is a constant depending on the explosive and the shell material, for TNT and steel material, $K$ is often chosen as 0.145; $\delta_0$ is the thickness of the shell, m; $d_0$ is the inner diameter of the shell, m.

2.2. G-S formula

Based on the Mott formula, Gurney and Sarmousakis considered the influence of the type and mass of explosive on fragmentation, and then gave another calculation method for $\mu$, which was suitable for the fragmentation mass analysis of thin-walled shells. It can be expressed as:

$$\mu^{1/2} = A \frac{\delta_0 (d_0 + \delta_0)^{1/2}}{d_0} \sqrt{1 + 0.5\left(\frac{C}{M}\right)}$$

where $C/M$ is the ratio of explosive charge mass to shell mass; $A$ is the coefficient associated with the charge. For TNT, $A$ is 0.4.
The average mass of the fragments can be obtained by the equation (4), and together with the equation (2), the total number and mass distribution of fragments would be determined.

3. Fragmentation experiments

3.1. Experimental design

The fragmentation test of the explosive device is carried out in an explosion chamber. Two samples are designed as Fig. 1. With the same outside diameters and shell thicknesses, they have different ratios of length to diameter.

![Figure 1. Two samples.](image)

The main parameters of the test samples are shown in Table 1.

| No  | Outside diameter (mm) | Length (mm) | Shell thickness (mm) | Mass of shell (g) | Mass of charge (g) |
|-----|-----------------------|-------------|----------------------|-------------------|-------------------|
| #1  | 60                    | 70          | 3                    | 269.3             | 213.5             |
| #2  | 60                    | 86          | 3                    | 337.2             | 275.5             |

The shell and two end lids of samples are all made of Q235 carbon structural steel, whose density is 7.85 g/cm³. Both upper and lower lids are 3 mm, which are screwed tightly with two sides of shell to form a sealed chamber. On the upper lid, a through-opening is made to install the detonator. TNT explosive is cast into the chamber from the through-opening. After that, the detonator will be installed in the through-opening just before the experiments begin.

3.2. Experimental method and layout

The fragmentation experiments are carried out with sand recovery method, and the steps are as follows:

- A steel plate is laid on the ground to allow explosive device to place on it. The ground would be protected from blasting.
- Lots of woven bags, filled with sand as buffer medium, are arranged in a circular shape around explosive device to collect upcoming fragments.
- A big sand bag is placed on the top and supported by side woven bags, thus an enclosed space is formed enough to do experiments.
- When the explosive device is initiated by a detonator, the shell of explosive device will shatter into pieces to fly into the woven bags.
- Several minutes later, the fragments are all collected by hands and needed tools for further analysis.

The Schematic diagram and layout of test site are shown in Fig. 2.
3.3. Experimental results and analysis

The recovered fragments are cleaned, dried and weighed, thus the total number and mass are obtained. Collected fragments of two experiments are shown in Fig.4. After the statistics, the fragment number and total mass of explosive device #1 are 263 and 174.5g respectively, while those of explosive device #2 are 307 and 220.6g respectively. In comparison with original mass of shell, the total mass of recovered fragments is up to 65%. It should be noted that the mass of each recovered fragment is basically above 0.1g in order to easy to collect and count, nevertheless too small fragments are not considered.

Next, Mott formula and G-S formula are used to calculate the mass distribution of fragments, which are compared with above mentioned experimental results, as shown in Fig.4. The two calculated curves fit the experimental data well when fragment mass is 0.5g or above. Due to ignoring tiny fragments, it is obvious that two curves differ from experimental data when fragment mass is less than 0.2g or below. Still, two formulae are enough to predict the effective fragments of explosive devices for damage ability is mainly determined by larger fragments. Of course, G-S empirical formula equation (4) is more accurate than equation (3) for average fragment mass prediction of thin-walled shell. That means the equation (4) and equation (2) are good enough to estimate the fragmentation characteristics for this kind of shell.
4. Influence on fragmentation

4.1. Influence of shell thickness on fragmentation

First of all, the influence of shell thickness on fragmentation is studied here. The outer diameter of shell and total height of explosive device are all set to 60 mm. The thickness of shell \( t \) is changed from 1 mm to 5 mm. From G-S formula, the average fragment mass can be calculated as 0.037g, 0.11g, 0.23g, 0.39g and 0.6g, respectively. That is to say, the average fragment mass shows an exponential increasing trend with the increase of shell thickness.

Moreover, the influence of on total number of fragments is obtained, as shown in Fig.5 a). It can be seen that the number of fragments is close to exponential decrease with increasing of shell thickness. Fig.5 b) shows that the number of smaller mass fragments reduces when the shell thickness increases, while larger mass fragments have opposite results. In view of real damage ability, larger fragments are definitely more lethal.

4.2. Influence of length-diameter aspect ratio on fragmentation

Here, the outer diameter remains 60mm and the thickness of shell is set to 3 mm. Besides, the thickness of each end is still the same as that of the shell. If the length is changed, the ratio of length to diameter \( \frac{l}{d} \) will also be changed. The total height of explosive device is supposed to 0.8 times, 1.0 times, 1.2 times, 1.5 times and 2.0 times of outer diameter, respectively.

According to G-S formula, the corresponding average fragment mass is 0.22g, 0.23g, 0.23g, 0.24g and 0.24g. It can be seen that the difference among these five length-diameter aspect ratios is very small. With the help of equation (2), the fragment number is obtained. It indicates that total fragment number increases approximately linearly with the increase of aspect ratio, as shown in Fig.6 a). Furthermore, the fragment mass distributions of five cases are acquired. The results show that the area enclosed by the fragment distribution curve and the coordinate axis increases with increase of aspect ratio, which means the quantity of fragment for larger aspect ratio structure is bigger. Meantime, more large fragments are found in structures with larger aspect ratio.

![Figure 5. The influence of shell thickness on fragment number and mass distribution.](image)

![Figure 6. The influence of aspect ratio on fragment number and fragment mass distribution.](image)
5. Conclusions

The fragmentation of non-controlled shell under explosion has been intrigued by experts in both academic research and real application. A kind of typical improvised explosive device is chosen to study the influence of shell thickness and length-diameter aspect ratio on fragmentation of thin-walled shell. Experiments are conducted to get recovered fragments with sand recovery method. The fragment mass distribution of experiment is compared with classical empirical Mott formula and G-S formula. It shows that G-S formula is more accurate than Mott formula to predict average fragment mass for this kind of thin-walled shell structure.

The shell thickness and length-diameter aspect ratio have greatly affected the fragmentation of shell. With the increase of shell thickness, average fragment mass increases exponentially while total fragment number decreases exponentially. With the increase of length-diameter aspect ratio, average fragment mass remains substantially unchanged for shell with the same diameter and thickness. The number of fragment grows linearly with the increase of aspect ratio. The structures with larger shell thickness or larger length-diameter aspect ratio have more large fragments, which can bring about more huge killing ability.

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