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# A fragments mass distribution scaling relations for fragmenting shells with variable thickness subjected to internal explosive loading

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ABSTRACT

This paper presents scaling relations of the fragments mass distribution for fragmenting shell with variable thickness subjected to internal explosive loading. Available formulas usually predict the fragmentation law of shell with constant thickness, and there are few sources that describe the fragment mass distribution of shells with variable thickness, which are usually used in the Earth Penetration Warhead (EPW). In the study, shells with variable thickness fragmentation were investigated experimentally, and the fragment mass distribution was obtained by statistical analysis. Furthermore, the semi-empirical scaling relations between the fragments' mass statistical characteristic value of shells with variable thickness and the physical parameters based on the Mott statistical distribution and Grady formula is proposed by the theoretical analysis and data analysis. The position of the initiation end and the taper of the variable thickness shell are considered in the scaling relations which has wider applicability in the study of the fragments mass distribution of shells with variable thickness subjected to internal explosive loading.

## 1. Introduction

### 1.1. General background

Fragmentation is very important process for ammunition warheads subjected to explosion loading of cased explosive charges. The expansion and fracture of the warhead ultimately leads to its fragmentation. As is well known, fragments are the most lethal elements in most ammunition warheads.

In order to destroy strong underground targets effectively, the penetration velocity of earth penetration warheads (EPW) must increase continuously. Structural deformation and ballistic instability of a projectile are prone to occur when a projectile is subjected to huge overload in the process of penetration, which then seriously reduces the combat effectiveness of the warhead. In order to solve this problem, projectiles of cone and grooved cone shapes are used (for example Fig. 1). Those perform better in penetration and then result in a fairly straight penetration channel [1,2]. After entering the interior of a bunker, the EPW mainly effectively destroys the target by the high-speed fragments and shock waves produced by the fragmentation of the shell. So, the effect of fragments is very important. To be detailed, the fragmentation mechanism and the fragment mass statistics distribution for metal shells with variable thickness under internal explosive loading are the basis for the structural design and damage assessment. As to the present, many studies have been performed on constant thickness metal shells, but there are a few reports for shells with variable thickness.

### 1.2. Available theories for fragmentation of cylindrical metal shells

There are a lot of researches on the terminal velocity of the fragments subjected to the explosive loading which is very important to the study of fragmentation. Gurney [3] studied the terminal velocity of fragments, which could be approximated by a function of the ratio $M/C$, where $M$ and $C$ represent the shell mass and the charge mass of unit length respectively.

Hutchinson [4] studied the blast impulse from fragmenting shells, using as a basis the physical assumptions of R.W. Gurney. According to his study, a sound analytical formula can be derived and applied to the common situation where the fragments before it reaches a high expansion radius, thus allowing more blast impulse to escape. In his subsequent articles [5–7], an equation for blast impulse from fragmenting shells could be derived directly from Gurney's formula. The

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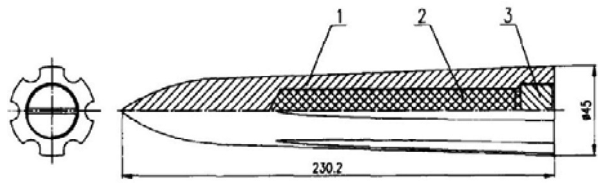


**Fig. 1.** A certain projectile of grooved cone (1-projectile; 2- filler; 3-seal cover) [2].

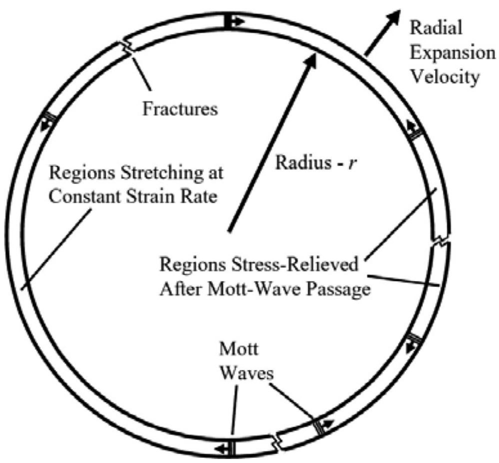


**Fig. 2.** The one-dimensional Mott wave schematic diagram by Ref. [12].

finite fracture strain and the yield stress of real shell metal can be taken into account. He also studied the effects of yield stress and shell thickness on blast impulse and fragment velocity [8].

At present, the methods for studying the dynamic fragmentation of shells is based on a large number of experimental results. In these methods, some mathematical techniques are adopted to study the fracture process of the shell and the fragmentation mechanism. A series of studies have been published since World War II.

For example, Lloyd [9] divides the expansion and fragmentation of the shell under internal explosive loading into four main stages: 1. The shell expands outwardly with extremely high internal explosion pressure. 2. After expansion, the stress or strain of shell reaches a certain critical value, and then cracks began to be produced and spread. 3. When cracks run through the shell, the detonation products begin to flow out through the cracks. 4. Fragmentation of shell is completed and then fragments are produced.

Hu et al. [10] studied the propagation behavior of longitudinal cracks in the self-organized shear fracture model of metal cylindrical shells under internal slip detonation loading. According to their study, up-stream shear initiations may dominate the sites of shear instability growth on the neighboring section of the shell down-stream in extreme cases. In addition, the states of the shell before and after shear fracture are described. Also, the shell fracture process has been basically completed when surface cracking occurs.

Mott's study of the fragmentation behavior of shells suggests that there exist large or small weakening points such as defects or inclusions even if the shell is made from a homogeneous material [11]. These weakening points determine the size of fragments produced by the shell subjected to internal explosive loading.

When shells begin to crack even in a tiny area, the stress around that area unloads. Meanwhile, unloading waves are generated on both sides of the fracture surface, so that the unloaded area is impossible to crack again. In the area before the unloading wave arrives, the strain is still increasing, which leads to the probability of fracture increasing rapidly. After the entire ring is completely unloaded, the fragmentation is completed. At that moment, the average size of the fragments is related to the unloading wave velocity on both sides of the fracture surface or the size of the adjacent unloading area.

In Mott's study, he believed that kinetic energy provides the fracture energy required to produce fragments when the shell expands outward [13]. Furthermore, the scaling relations between the physical parameters and the mass distribution of cylindrical shells under internal explosive loading are addressed.

Grady also presented a series of studies of dynamic fragmentation of shell in multiple fields. Basing his theory on unloading waves, he established the dynamic fragmentation theory on the basis of energy [12,14,15], where the shell is considered as a rigid plastic body and thus the unloading waves propagating on both sides of the newly generated fracture surface are rigid plastic unloading waves. According to the energy conservation principle, the circumferential width of fragments for cylindrical shells can be calculated. Furthermore, the scaling relations of fragments produced by cylindrical shells under internal explosive loading are derived [12] and the following two complex characteristic mass expressions of fragments are presented.

$$N(>m) = N_0 \exp\left[-\left(\frac{m}{\mu}\right)^{\Lambda}\right] \tag{1}$$

$$\frac{\mu}{\rho t^3} = a\left(\frac{r}{t}\right)^{2n/\alpha}\left(\frac{Gt^{2-\alpha}}{\rho v^2}\right)^{n/\alpha} \tag{2}$$

To here Eq. (1) is the statistical fragment size Weibull distribution with two-parameter, $N(>m)$, $N_0$, $\mu$, and $\Lambda$ are the cumulative number of fragments with masses greater than Mass $m$, the total number of fragments, the distribution scale parameter which characterizes the mean fragment size and the shape parameter which reasonably constrains the distribution. Eq. (2) provides the relation between the distribution scale parameter $\mu$ and the geometric and kinematic properties of the fragmenting shells. Parameter $a$ is the aspect ratio of a fragment, $r$ and $t$ are the shell's radius and thickness, $G$ is the fracture resistance characteristics of the shell, and $v$ is the expansion velocity of the shell under internal explosive loading. Parameters $n$ and $\alpha$ are physical constants.

Zhou studied the one-dimensional fragmentation problems for ductile and brittle expansion rings [16–18]. The most rapid unloading characteristics of the fragmentation process for brittle solids are presented [18].

### 1.3. Experiments

Experiment is of great significance in the study of shell fragmentation. It mainly consists of two methods: recovery of fragments from static explosion and high-speed photography observations.

Hiroe et al. [19] adopted the static explosion recovery fragments method, by means of macroscopic and microscopic analyses, to study the fragments' fracture modes and morphological characteristics of various metal shells under explosive loading using PETN. Goto et al. and Lambert et al. also used this method to study the fracture and fragmentation mechanism of metal expansion rings and cylindrical shells, as well as the mass distribution characteristics of fragments [20–22]. High speed photography techniques can supply images of shell fragmentation processes including surface crack generation and propagation. Many researchers have studied the fragmentation of shells using high-speed photography techniques [20–23].

Duan et al. [24] observed the velocity of each point on the outer surface of a tube with variable thickness by using a rotating mirror high-speed camera, and the inconstant growth history of velocity was obtained and analyzed. However, there have been only a few researches of the fragmentation process, mechanism, and statistical characteristics of fragments from shells or tubes with variable wall thickness in addition to the work of Duan et al.

In this paper, the analysis of fragmentation for shell with variable thickness were studied by experiments and theoretical methods. It

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