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Study on dynamic fragmentation of multiple metal rings under high explosive loading

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Abstract. A new type of expanding ring experiment is employed to investigate the dynamic fragmentation of multiple metal rings. The experimental platform and layout of the multiple metal rings initiation system, and fundamental principle, are detailed, and are used to conduct the dynamic loading of pure aluminium and oxygen-free high conductivity (OFHC) copper materials. A review of the reassembled fragments indicates that this experimental platform can achieve simultaneous and stable loading of multiple metal rings. Finally, calculated strain at fracture is carried out and statistical distribution is carefully analyzed.

1. Introduction
Dynamic fragmentation of materials under high-speed shock loading is a very complex non-equilibrium dynamic process. The physical mechanism of the fragmentation process is not only influenced by the stress wave interactions associated with structural geometry, but is also related to microscopic defects, crack nucleation and growth in shocked materials. In spite of many factors affecting fragmentation process, numerous experimental results indicate that ultimate statistical behavior reveals universality [1–5].

The use of expanding ring experiments is an appropriate technique to investigate fragmentation under dynamic loading because of its simple loading and test controllability, which involves the electromagnetic loading techniques proposed by Gourdin \cite{6}, and the high explosive loading techniques developed by Hoggatt \cite{7}. Currently the two loading techniques have been widely used to study the flow stress and failure behavior at a strain rates of about $10^4$ s\(^{-1}\). The corresponding physical model and statistical principles are developed by Mott \cite{8} and Grady \cite{1}, who lay the foundation for a deeper understanding of dynamic fragmentation from statistical method and energy-conserving viewpoint, respectively. Nevertheless, the limited fragment number of expanding ring imposed by low strain rates, and the non-reproducible loading states of different experiments, leads to the difficult prediction of statistical distribution of fragments.

In this paper, in the context of the expanding ring experiments developed recently in \cite{10}, we extend the ideas of the fragmentation process of multiple rings stacked on a same driver. The experimental results of dynamic fragmentation of pure aluminium and OFHC copper are obtained and the corresponding statistical behavior is predicted.
2. Experimental technique

Because electromagnetic loading techniques generate a significant amount of heat \[2, 9\], we develop and explosively driven experimental platform to investigate an expanding ring test. In this experimental platform, wire explosion technique \[11, 12\] initiating the high explosives of cylindrical structure is employed to generate a radially symmetric cylindrical blast wave that uniformly loads the metal driver to achieve the radial expansion of a metal ring.

The experimental setup is illustrated schematically in figure 1, including initiation system of high explosives and driving system of metal ring. The circuit layout of the initiation system consists of two main components: charged system containing DC (direct current) high voltage source, current-limiting resistor and pulse capacitor bank, and discharge system composed of a pulse capacitor bank, spark gap switch and exploding wire. The key role in the initiation system is played with trigger control of rapid high-voltage switch, accomplished by high-pressure generator and trigger electrode. The triggering principle focuses on the high-pressure pulse generator that produces a negative high-pressure pulse to lower the voltage of trigger electrode, and then augments the voltage difference between positive pole of the spark gap switch and the trigger electrode. When this voltage difference exceeds the breakdown voltage, a voltage surge is produced across the spark gap. This voltage surge causes breakdown to occur, forcing the conduction discharge. In the tests described below, the pulsed capacitance is 12 \( \mu F \) and the DC high voltage is 40 kV.

The integral arrangement of the driving system includes a copper wire, powder explosive, metal driver, PMMA shell, insulated plug, cover board and test ring. The exploding copper wire synchronously initiates the cylindrical powder explosive along the axial direction, which generates the blast wave of cylindrical symmetry. Then the cylindrical diverging detonation wave uniformly imparts the metal driver and partly travels through the ring specimen. Once the release wave reflecting from outer surface of the expanding ring reaches the interface between test ring and metal driver, they immediately separate and the test ring flies radially outwards.

The choice of material for the driving system includes OFHC copper of 0.2 mm in diameter. The wire length can be estimated in light of the experimental demand; however, it influences the capability of explosion that decreases with a longer wire. Its initiation principle is described in the following. The large current pulse produced by the stored energy of the charged system flows through the fine exploding wire. Under the short-time action of high current, the exploding wire melts and vaporizes, forming a plasma that rapidly compresses the surrounding powder explosives, which results in a radially symmetric cylindrical blast wave.

A series of tests indicates that the choice of material for the driver is of significant importance to the experimental performance. It must meet with the following criteria: (i) its mechanical behavior of high strength and high toughness is considered to maintain the uniform deformation
Figure 2. Recovered fragments of test no. 1: (a) pure aluminium; (b) OFHC copper.

Figure 3. Statistical analysis of recovered fragments: (a) pure aluminium; (b) OFHC copper.

without the formation of numerous bulging and cracks during the expansion stage; (ii) acoustic impedance between the driver and the test ring is approximately matched: importantly, the driver impedance must be larger than the test ring impedance. Therefore, before assembling the driver and the ring, it is essential to estimate their acoustic impedances, which assesses the feasibility of test performance. In the experiments that follow, the carbon steel was chosen so that the driver’s acoustic impedance was about $3.6 \times 10^7$ Kg/m²s, and the aluminum and OFHC copper separately had acoustic impedances of $1.4 \times 10^7$ Kg/m²s and $3.6 \times 10^7$ Kg/m²s, respectively, which effectively meets the requirements listed earlier.

The experimental assembly of the driver and multiple metal rings is shown in figure 1(b). The assembly included five aluminum rings in the upper half of the driver and five copper rings in the lower half. All of the driver rings had an inner diameter of 40 mm, a wall thickness of 1 mm, a height of 1 mm and were separated by 1 mm. To reduce the likelihood of release waves influencing the experimental results, the rings must be placed in the middle plane a suitable distance from the end of the driver.

Prior to the tests, the rings are uniquely marked to facilitate reassembly of the collected fragments. By fielding a steel chamber filled with the white foam for soft-recovery experiment, all the exploded fragments can be captured.
### Table 1. Fragmentation data of test no. 1 with ten metal rings.

| Ring no. | Mat. | Fragment number | Total mass (mg) | Length (mm) | Fractured strain $\varepsilon_f$ |
|----------|------|-----------------|----------------|-------------|------------------|
| R-1      | Al   | 1               | 347            | 156         | 0.18             |
| R-2      | Al   | 1               | 368            | 157         | 0.19             |
| R-3      | Al   | 1               | 363            | 156         | 0.18             |
| R-4      | Al   | 2               | 357            | 156         | 0.18             |
| R-5      | Al   | 2               | 347            | 160         | 0.21             |
| R-6      | Cu   | 5               | 1165           | 152         | 0.15             |
| R-7      | Cu   | 4               | 1150           | 151         | 0.14             |
| R-8      | Cu   | 3               | 1138           | 151         | 0.14             |
| R-9      | Cu   | 3               | 1133           | 150         | 0.14             |
| R-10     | Cu   | 4               | 1162           | 149         | 0.13             |

### 3. Experimental results and discussion

We conducted three sets of dynamic fragmentation experiments with the same height and diameter of the insulated PMMA shell. The total weight of filled powder explosive, which was PETN, was 6.3 g, 6.2 g and 5.9 g, respectively.

Figure 2 presents the fragments collected from the first experiment (no. 1), where subplots (a) and (b) relate to either the aluminium or the OFHC copper fragments.

The cylindrical expansion velocity was diagnosed with standard heterodyne laser Doppler velocimetry techniques (LDV) [13, 14, 16, 17], which determined the maximum expansion velocity was 110 m/s for the aluminium and 82 m/s for the OFHC copper, observations consistent with the different mass densities of aluminum versus copper. As a consequence, the corresponding loading strain rates are expressed as the expansion velocity divided by the initial radius, calculated as $5.2 \times 10^3$/s and $3.9 \times 10^3$/s. Taking into account the unique color marks at the ring surface, all the recovered fragments were sorted and reassembled. We found that the pure aluminium exhibits better ductility than the OFHC copper, and has the visibly local plastic deformation with several necked zones.

The fragment numbers, total mass and fractured strain of each metal ring in test no. 1 are detailed in table 1, where the fractured strain is defined as $\varepsilon_f = (L - L_0)/L_0$, where $L$ is the circumferential length of the reassembled ring, $L_0$ is the initial length of 131.95 mm.

The collection for each reassembled metal ring indicates a good consistency of fragmentation process by counting the fragment number, and by measuring the final length and mass of the reassembled rings. Therefore, the experimental results of test no. 1 suggests that multiple rings

### Table 2. Fragmentation data of three tests.

| Test no. | Expansion Velocity (m/s) | Strain rate ($s^{-1}$) | Fragment number | Total mass (mg) | Average fractured strain |
|----------|--------------------------|-------------------------|-----------------|----------------|-------------------------|
| Al-1     | 110                      | $5.24 \times 10^3$      | 7               | 1640           | 0.19                    |
| Al-2     | 112                      | $5.33 \times 10^3$      | 10              | 1728           | 0.20                    |
| Al-3     | 110                      | $5.24 \times 10^3$      | 6               | 1735           | 0.17                    |
| Cu-1     | 82                       | $3.90 \times 10^3$      | 19              | 5748           | 0.14                    |
| Cu-2     | 82                       | $3.90 \times 10^3$      | 24              | 5763           | 0.15                    |
| Cu-3     | 80                       | $3.81 \times 10^3$      | 19              | 5745           | 0.15                    |
Table 3. Fitting parameters of statistical fragments for OFHC copper.

| Test no. | \(m_0\) | \(m_{\text{min}}\) | \(m_{\text{ave}}\) | \(\chi = m_0/m_{\text{ave}}\) |
|----------|---------|-----------------|-----------------|------------------|
| Cu-1     | 250.39  | 105.50          | 302.53          | 0.83             |
| Cu-2     | 190.22  | 81.28           | 240.13          | 0.79             |
| Cu-3     | 290.20  | 87.77           | 302.37          | 0.96             |

on a metal driver can achieve stable loading and ensures that each ring possesses similar fracture properties.

In addition, table 2 displays the experimental data of the three experimental tests, and the table includes the maximum expansion velocity, the fragment numbers and the total fragment masses. For the aluminium tests, three experiments approach the maximum velocity of 110 m/s, fragment numbers of 6-10 and average fractured strain of 0.17-0.2. However, for OFHC copper, the results are given by the maximum velocity of 82 m/s, 19-24 fragments were recovered, and the average fracture strains were 0.14-0.15. Thus, the three experiments further reveals the stable loading for multiple metal rings.

For each test, all the fragments are recovered to count the fragment number and weight their mass. To predict the statistical distribution of fragments, we define a complementary cumulative function \(N(m)\), denoting the fragment number as a function of the fragment mass which is larger than \(m\). The statistical distribution of three experiments for the pure aluminium is depicted as figure 3(a). However, because of limited number of fragments, we only present the experimental observations and do not fit the fragments to \(N(m)\). Otherwise, the statistical distributions from the three experiments are in good agreement; specifically, the fragment mass analysis primarily focuses on two regimes: \(m < 100\) mg (smaller fragments) and \(m > 250\) mg (larger fragments).

Figure 3(b) displays the experimental and fitting curve of OFHC copper fragments. The adopted fitting function is three-parameter Weibull function [1, 4, 5], written by

\[
N(s) = N_0 \exp[-(m - m_{\text{min}}/m_0)^\beta], \beta > 0, \quad (1)
\]

where \(m_0\) is a relevant characteristic mass, \(\beta\) is the Weibull modulus and \(N_0\) is the total number of fragments. Note that this function includes a term of \(m_{\text{min}}\), suggesting that there exits a minimum fragment mass for the broken expanding ring, which has been described by previous experiments [18, 19]. The parameter \(\beta\) is chosen to be 1 and the remained parameters are shown in table 3, including the defined parameter \(\chi\). Seen from this Table, the fitted parameters for three testing are close very well, indicating a consistent statistical behavior.

The statistical analysis presented here indicates that statistical distribution associated with numerous fragments can be explicitly revealed with respect to the fragmentation of multiple rings undergoing the same loading while few fragments of the individual ring cannot. Figure 3 depicts the fitting result for OFHC copper in good accordance with the experimental finding, which represents that the Weibull distribution is highly predictive of the recovered fragments.

4. Conclusion

In this work, the statistical behavior of fragmentation for multiple rings stacked on a metal driver was investigated on the basis of an expanding ring experiment platform. The statistical analysis of the collected fragments by considering the individual ring of a testing and the fitting of multiple experiments both reveals the reproducibility of loading techniques very well. The statistical distribution of the recovered fragments makes a good prediction of a Weibull fit. In terms of this experimental platform, the ongoing work will allow for the statistical behavior of dynamic fragmentation at the different loading strain rates.
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References
[1] Grady D E 2006 Fragmentation of Rings and Shells: The Legacy of N. F. Mott (Springer; New York).
[2] Grady D E and Benson D A 1983 Exp. Mech. 12 393
[3] Grady D E and Olsen M L 2003 Int. J. Impact Eng. 29 293
[4] Zhou F, Molinari J F and Ramesh K T 2006 Appl. Phys. Lett. 88 261918
[5] Levy S, Molinari J F, Vicari I and Davison A C 2010 Phys. Rev. B 82 066105
[6] Gourdin W H, Weinland S L and Boling R M 1989 Rev. Sci. Instrum. 60 427
[7] Hoggat C R and Recht R F 1969 Exp. Mech. 9 441
[8] Mott N F 1947 Proc. R. Soc. London, Ser. A 189 300-8
[9] Zhang H and Ravi-Chandar K 2006 Int. J. Fract. 142 183
[10] Tang T, Ren G, Guo Z and Li Q 2013 Rev. Sci. Instrum. 84 043908
[11] Al-Maliky N S and Parry D J 1996 Meas. Sci. Technol. 7 746
[12] Hiroe T, Fujiwara K, Hata H and Takahashi H 2008 Int. J. Impact Eng. 35 1578
[13] Cummins H, Knable N, Gampel L and Yeh Y 1963 Appl. Phys. Lett. 2 62-4
[14] Cummins H Z, Knable N and Yeh Y 1963 Appl. Opt. 2 823–5
[15] Yeh Y and Cummins H Z 1964 Appl. Phys. Lett. 4 176–8
[16] Forman Jr J W, George E W and Lewis R W 1965 Appl. Phys. Lett. 7 77–8
[17] Strand O T, Goosman D R, Martinez C and Whitworth T L 2006 Rev. Sci. Instrum. 77 083108
[18] Grady D E 1982 J. Appl. Phys. 53 322
[19] Zhang L, Jin X G and He H L 1999 J. Phys. D: Appl. Phys. 32 612