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The 12<sup>th</sup> Hypervelocity Impact Symposium

## High-velocity Impact Fragmentation of Brittle, Granular Aluminum Spheres

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### Abstract

We present ballistic and fragmentation data for brittle, granular aluminum spheres following high-velocity impact (0.5–2.0 km/s) on thin steel plates. These spheres, formed from isostatically pressed aluminum powder, are representative of a wide variety of metallic reactive materials currently being studied. Simple analytic theories are introduced which provide a reasonable description of the residual velocity and hole diameter following impact. With increasing velocity there is an intriguing transition to a power-law fragment distribution, which we have interpreted as arising from extensive microbranching of fast-running cracks. The key equations of an analytic theory describing the fragment distributions are also presented.

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**Keywords:** fragmentation, high-velocity impact, reactive materials

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### 1. Introduction

Recent years have seen increasing interest in the lethality of combustible metal composites, both as enhanced blast additives as well as for use in defeat of soft targets. These reactive materials, inert under normal conditions, are designed to fragment and combust rapidly under intense dynamic loading from a shock wave or high-velocity impact. The impact-induced fragmentation of these materials is a critical property in determining their ultimate lethality and combustion behavior. There is also considerable interest in the basic form of the fragment distribution of brittle materials, which possess very different failure characteristics than standard ductile metals.

In this work we present high-velocity impact experiments in which isostatically-pressed granular aluminum spheres were fired from a powder gun into a thin steel plate. An initial series of shots characterized the residual velocity and impact hole, and we develop simple analytic forms that can successfully describe the experimental trends. The spheres fully perforated the plate and were heavily fragmented in the process; several experiments were performed in which the resulting debris cloud was caught in a soft-catch apparatus and analyzed. These experiments reveal a

Table 1: Material properties of the porous, pressed aluminum projectiles and the steel impact plate.

<b>Property</b>	<b>Value</b>
Mean aluminum powder diameter	3.2 $\mu\text{m}$
Projectile density	2.39 g/cc
Projectile diameter	2.51 cm
Projectile tensile strength	8.27 MPa
Projectile longitudinal sound speed	5430 m/s
Plate density	7.85 g/cc
Plate longitudinal sound speed	5900 m/s

transition from an exponential type distribution at low velocity impact (610 m/s) to power-law behavior at higher velocities approaching 2 km/s. The power-law exponent is, in all cases, very close to the universal value for three-dimensional fragments suggested in recent work[1]. We introduce a normalized power-law distribution with a finite size cutoff which is used to analyze the mass distribution over a linear fragment scale. This form provides a very good description of experimental data at high impact velocities, and at the lowest velocity it was combined with a standard exponential form to model the behavior. The fragment distributions presented here provide a basis for analyzing the combustion damage from reactive material debris clouds.

## 2. Experimental

Spherical porous aluminum projectiles 2.51 cm in diameter were cut from a cylinder of Valimet H-2 aluminum powder which had been isostatically pressed into a monolith at 138 MPa at ambient temperature. The resulting density of the porous aluminum was 2.39 g/cc (about 15% porosity). No detailed measurements of the fracture toughness were made, but a simple Brazilian crush test on this material gave a tensile strength of 8.27 MPa, two orders of magnitude lower than standard 6061 aluminum. These spheres were then fired at a thin steel plate using sabotaged launchers from a 42 mm smooth-bore powder gun at Naval Surface Warfare Center, Indian Head Division. High speed video was used to ensure that the spheres remained coherent before impact and measure residual velocity of the debris cloud. Target muzzle velocities of the spheres were 610 m/s, 1220 m/s, and 1829 m/s, and were verified using a laser velocimeter at the end of the gun barrel. Projectiles impacted three thicknesses (0.912, 1.52, and 3.04 mm) of 1018 steel plates bolted to a supporting steel frame. Relevant material properties of the impact plate and the porous aluminum projectile are given in Table 1. The debris field from successful perforation events was caught in a 1.5 meter sonotube filled with low-density shaving cream. Following each shot, the shaving cream was washed from the tube with water and the remaining fragments were fed through a sieve stack to measure the mass distribution over linear particle size. Particles were sieved down to a size of 44  $\mu\text{m}$ , which was sufficient in all cases to recover approximately 90% or more of the original sphere's mass. A small amount of mass (less than 2%) was lost during the sieving process. A magnet was used to remove any steel fragments that were extracted from the catch tube; the steel was generally far larger than the fragmented aluminum and was easily identified and removed. The vibration of the sieve shaker was sufficient to break up any aluminum particles that may have agglomerated in the foam.

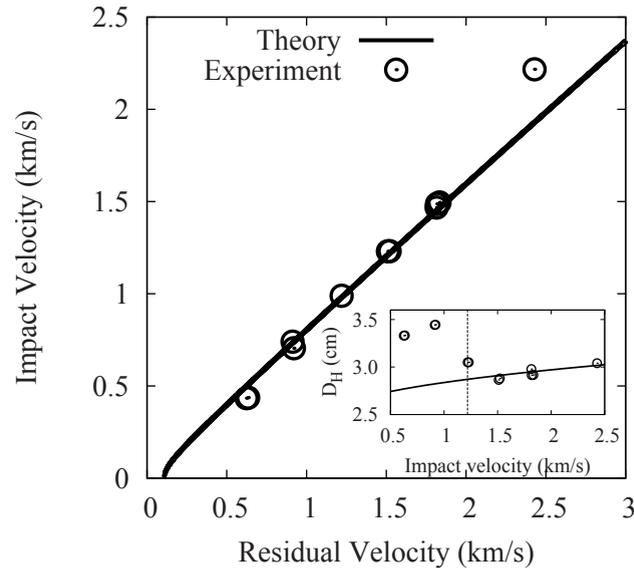


Figure 1: Residual velocity of the debris cloud as a function of initial impact velocity.

### 3. Results

#### 3.1. Ballistic Impact

In Figure 1 we present the residual velocity of the debris cloud's center of mass as a function of impact velocity. The inset shows the diameter of the impact hole post-shot, also as a function of impact speed. The velocity of the debris cloud is useful in determining lethality due to subsequent impacts behind the plate, and thus we seek to develop a simple analytic expression that captures the experimental data. Due to the extremely low fracture toughness of our samples, we expect that minimal energy will be dissipated during their fragmentation. This is consistent with post-mortem scanning electron microscopy images of the fragments, in which no sign of plastic deformation was observed; fracture surfaces were consistent with brittle intergranular failure. We assume in what follows that the initial kinetic energy of the sphere is dissipated by only two mechanisms: plastic deformation of the impact plate and dynamic work to accelerate the ejected steel mass to the residual velocity.

The plastic work required to deform the steel skin around the sphere can be treated in the following manner. We assume that the deformation takes place in a semi-circular dimple that is axisymmetric around the penetration point; the radius of this semi-circle,  $R_H$ , is often slightly larger than the original projectile. The total plastic work required for deformation of the entire volume is

$$W_p = \int_v \left( \int_0^\epsilon \sigma d\epsilon \right) dV. \quad (1)$$

If we assume a perfectly plastic material in which all plastic deformation of the impact plate takes place at the yield stress  $Y$ , then the work for one differential ring of radius  $r$  that is expanded circumferentially by the impacting sphere is

$$dW_p = 2Y\pi r h \ln\left(\frac{r_f(r)}{r}\right) dr, \quad (2)$$

where  $h$  is the plate thickness and  $r_f(r)$  is the final radius that the ring is deformed to; the latter varies depending on the distance from the initial sphere impact point. We then integrate over the entire penetration hole of radius  $R_H$  to find the total work,

$$W_p = 2Y\pi h \int_0^{R_H} r \ln\left(\frac{r_f(r)}{r}\right) dr. \quad (3)$$

For the spherical projectiles here,

$$r_f(r) = [r(2R_H - r)]^{\frac{1}{2}}. \quad (4)$$

The total work required for all such rings affected by the impacting sphere is then

$$W_p = 2\pi h Y \int_0^{R_H} r \ln\left[\left(\frac{2R_H}{r} - 1\right)^{\frac{1}{2}}\right] dr = \alpha\pi h Y R_H^2 \quad (5)$$

where  $\alpha \approx 0.39$ . To this we add a simple expression for the dynamical work required to accelerate that portion of the plate punched out by the sphere,

$$W_d = \frac{1}{2}\pi h \rho (R_H V_o)^2, \quad (6)$$

where  $\rho$  is its density, and  $V_o$  is its impact velocity. Assuming that the sphere mainly loses energy to these two terms, the residual velocity  $V_r$  can be written as

$$V_r(V_o) = \left[ V_o^2 - \frac{\pi h R_H^2}{m} (2\alpha Y + \rho V_o^2) \right]^{\frac{1}{2}}, \quad (7)$$

where  $m$  is the mass of the sphere. Equation 7 is plotted in Figure 1 along with the experimental data, and shows generally good agreement up to our maximum velocity. The experimental residual hole diameters are given in the inset of Figure 1, and are larger than the original sphere diameter of 2.51 cm. There is also a transition in the residual hole diameter around 1.25 km/s, corresponding to a change in the plate failure mode from asymmetric ductile hole formation to a shearing-dominated failure. As a rough estimate of the increased residual hole diameter, we have used an analytic form developed by de Chant [2, 3]; this is shown in the solid line of the inset in Figure 1, and shows reasonable agreement only above the transition at 1.25 km/s. Equation 7 predicts a ballistic limit  $V_{50}$  of around 100 m/s, though we would expect limited validity at very low velocities where other energy dissipation mechanisms (such as large membrane bending of the plate) may become relevant.

### 3.2. Fragmentation

The nature of the fragment distribution following ballistic impact is of key importance in the ultimate lethality and combustion of the reactive material debris cloud. These materials are brittle granular packs of metal particles, adding an additional layer of complexity beyond the fragmentation of standard ductile metals, which (at high strain-rates) are often characterized by

an exponential distribution with a characteristic length scale. Exponential type forms for fragmenting metals are generally considered to arise from uncorrelated nucleation of failure points or cracks governed by Poisson statistics. The distributions of Grady and Kipp[4, 5] and Mott and Linfoot[6] are widely used for high strain-rate fragmentation processes in which there is a characteristic length or mass scale.

In the case of brittle materials, several authors have noted that a power-law rather than an exponential form is often observed experimentally [7, 1, 8, 9, 10]. This corresponds to a regime in which the fragment distribution has certain aspects of scale-invariance and can be treated as a fractal with a particular dimensionality. A recent review by Åström discusses much of the relevant work on dimensionality in brittle fragmentation[11].

In Figures 2 and 3 we present probability density functions (PDFs) for impact on the thinnest plate, 0.912 mm. Data is presented as mass distributed over a linear length scale  $s$ . Solid lines represent fits to theoretical forms, which are discussed below. At low velocities, there is a distinct maximum in the fragment distribution and the overall form is that of an exponential distribution with a characteristic length scale. At higher impact velocities, the maximum disappears and behavior consistent with a power-law distribution emerges; below approximately 1 mm, the fragment PDF is nearly constant on a logarithmic scale. The smallest fragments in the low velocity impact shot also deviate from the exponential form and show a small region of power-law type behavior, suggesting a mixture of the two distributions is already occurring at an impact velocity of 610 m/s. The very largest fragments, in the size range of 0.7 to 1.0 cm, are generally large mass chunks from the initial impact point of the sphere and deviate slightly from the overall fragment trend. The vast majority of the collected mass is below 1 mm for all shots.

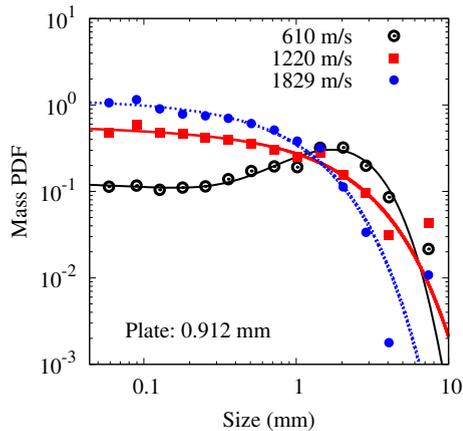


Figure 2: Log-scale mass probability density function (PDF) for fragments generated by impact on a 0.912 mm plate.

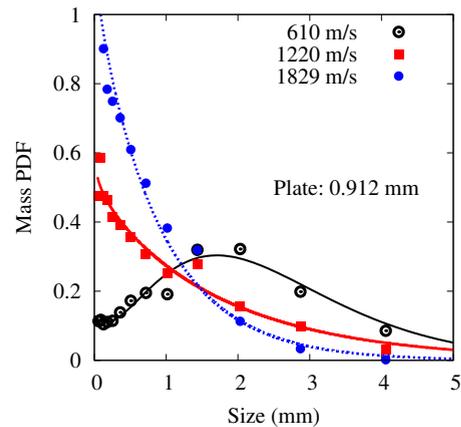


Figure 3: Linear-scale mass PDF for impact on a 0.912 mm plate. Fits are based on equations described in the text.

We have interpreted the impact-induced fragmentation data as a transition from an exponential to power-law behavior, arising from widespread crack microbranching at higher velocities. Here we consider the main points of this analysis, and direct the reader to a more complete discussion given in our recent work[12]. Brittle fragment distributions are frequently presented in the form of fragment number distributed over mass or volume,  $n(m)$  or  $n(v)$ . For brittle materials

with a power-law distribution, Åström and coworkers have suggested the general relation

$$n(v) \propto v^{-\kappa} f(\beta v),$$

describing the number distribution of particles over the volume  $v$  [1]. The function  $f$  is a damping function that cuts off the power-law behavior above some length scale governed by  $\beta$ . We utilize the flexibility in the damping function so that a single form covers the power-law behavior (which is the majority of the mass) and also incorporates the effect of a small number of larger fragments. We thus introduce the following form:

$$n(v) \propto v^{-\kappa} \exp\left(-(\beta v)^{\frac{1}{b}}\right).$$

The linear scale is the most relevant for comparison with data from a sieving process. Assuming that  $v = s^D$  where  $s$  is a linear size of our three-dimensional fragment, we have

$$n(s) \propto s^{D-(D\kappa+1)} \exp(-\beta s),$$

where  $\beta$  is, as above, a damping constant that cuts off the power-law behavior at larger sizes. The majority of the fragment mass at the higher impact velocities is well below 1 mm, and counting fragments in this size range is not viable experimentally. Instead, we convert the fragment number distributions to mass distributed over a linear length scale using the relation

$$dM = mdN = \rho s^D N_o n(s) ds,$$

where  $M$  is the cumulative mass distribution function (CDF) and  $N_o$  is the total number of fragments. Based on the above expressions we introduce our final form for the fragment distribution, suitable for direct comparison with a full normalized distribution from the experimental sieve data:

$$m(s) = \frac{1}{s_o} \left(\frac{s}{s_o}\right)^{-\alpha} \frac{\exp(-\beta s)}{E_\alpha(\beta s_o)}, \tag{8}$$

where  $\beta$  is a constant controlling the cutoff of the power-law behavior,  $s_o$  is a minimum fragment size, and  $E_\alpha(x)$  is the generalized exponential integral function

$$E_n(x) = \int_1^\infty \frac{\exp(-xt)}{t^n} dt.$$

Based on self-similar crack branching arguments, several authors have suggested that the exponent in a power-law brittle fragment distribution (which is related to the fractal dimensionality) may have a universal value [1, 11]; in our form, this proposed universal value corresponds to  $\alpha$  equal to zero, in which case the distribution reduces to the simple shifted exponential

$$\begin{aligned} m(s) &= \beta \exp(-\beta(s - s_o)) \\ M(s) &= 1 - \exp(-\beta(s - s_o)) \end{aligned} \tag{9}$$

where  $m$  and  $M$  refer to the PDF and CDF, respectively. We note that the *number* distribution of fragments over a linear size  $s$ , which is the form often presented by authors in discussing the fragment distribution, still has a power-law term in this case and does not reduce to a standard Grady-Kipp exponential form. For  $\beta s \ll 1$  (IE, for small fragments), this reduces to the empirical Gaudin-Schuhmann type cumulative mass distribution function

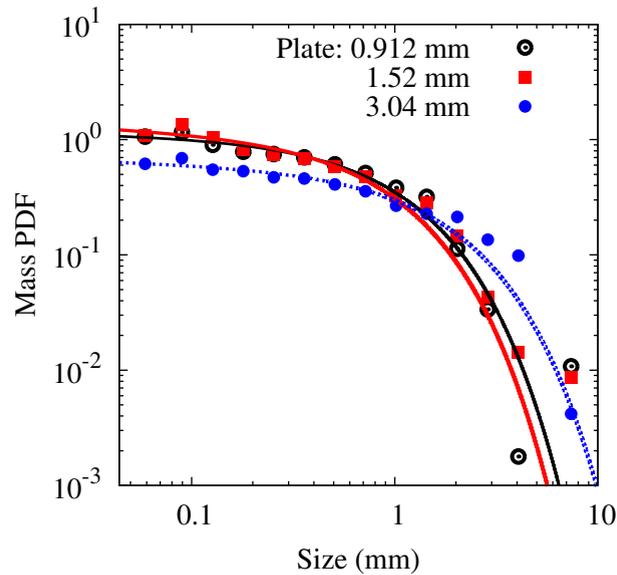


Figure 4: Mass PDF for impact at 1829 m/s on plates of varying thickness. All distributions converge to a similar trend at this impact velocity.

$$\frac{M(s)}{M_o} \propto (\beta s)^n,$$

where  $n$  is close to one and  $M_o$  is the total fragment mass[13].

At low velocities, a power-law form does not provide a suitable fit for the full data range, as there is a clear characteristic length scale in the distribution. Instead we employ a standard exponential form, the Mott distribution[6, 5], for fragment mass over a linear length scale. Assuming the fragments are three-dimensional, the relevant distribution is

$$m(s) = \frac{1}{6\mu} \left(\frac{s}{\mu}\right)^3 \exp(-s/\mu).$$

where  $\mu$  is a characteristic average fragment size. A combination of the Mott and power-law forms is introduced in Ref. [12] and used to fit the 610 m/s impact data.

The statistics of the fragment pattern provides only indirect information on the mechanism, but recent work has suggested that the power-law behavior may arise from the microbranching of high-velocity cracks[14]. Sharon and Fineberg report increasing side-branch lengths as the crack velocity approaches the limiting Rayleigh wave speed, suggesting that higher rates of loading may lead to an increase in the amount of material affected by the side branching[15, 16, 14].

Solid lines in Figures 2 and 3 represent fits to the experimental data using the above theoretical forms. At the lowest impact velocity, a combination of the Mott and power-law expressions is necessary for a satisfactory description, suggesting that a combination of fragmentation processes may be occurring even at modest velocities. The value of  $\alpha$ , the power-law exponent in

our expressions, is indeed very close to zero in all cases, suggesting the possibility of a universal power-law behavior consistent with recent literature. Combined with simple physically-based expressions for the cutoff parameter  $\beta$  (see Ref. [12]), our data may suggest that at high strain rates there is a simple, universal form for natural brittle fragmentation. Additional fragment collection experiments using explosive loading and gas-gun impact are underway to determine the reproducibility of this data under different dynamic loading conditions and any variation with aluminum particle size.

#### 4. Conclusions

In summary, we report the ballistic and fragmentation properties of brittle, cold-pressed aluminum reactive materials at velocities of 610, 1220, and 1829 m/s on thin steel plates. Residual velocity and impact hole diameter were measured and simple theoretical forms were introduced to provide analytic expressions for these properties. Fragments were recovered after impact in a soft-catch apparatus and analyzed down to a scale of 44  $\mu\text{m}$ . With increasing velocity, we observe a transition in the character of the fragment distribution from an exponential to a power-law form. A normalized power-law distribution with a finite size cutoff is introduced and used to analyze impacts at the two higher velocities. The exponent of the power-law behavior is very close to the universal value discussed in recent work. At the lowest velocity, a combined fragment distribution is used, containing both an exponential type form (specifically, the Mott distribution) and a simplified power-law term. For granular materials with very low fracture toughness such as the pressed aluminum considered here, this may be a general behavior and a means of predicting the fragment distribution of reactive materials at sufficiently high strain rates. The measured distributions also provide a basis for future estimates of combustion damage following high velocity impact of reactive materials.

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