Characterization of shocked beryllium

E N Brown, C M Cady, G T Gray III, L M Hull, J H Cooley, C A Bronkhorst and F L Addessio
Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.
E-mail: en_brown@lanl.gov

Abstract. Explosively driven arrested beryllium experiments were performed with post mortem characterization to evaluate the failure behaviors. The test samples were encapsulated in an aluminum assembly that was large relative to the sample, and the assembly features both axial and radial momentum traps. The sample carrier was inserted from the explosively-loaded end and has features to lock the carrier to the surrounding cylinder using the induced plastic flow. Calculations with Lagrangian codes showed that the tensile stresses experienced by the Be sample were below the spall stress. Metallographic characterization of the arrested Be showed radial cracks present in the samples may have been caused by bending moments. Fractography showed the fractures propagated from the side of the sample closest to the explosives, the side with the highest tensile stress. There was evidence that the fractures may have propagated from the circumferential crack outward and downward radially.

1. Introduction
Arrested, explosively driven shock experiment were performed to provide insight into the ability of the equation of state, plasticity models, and damage models to capture the high-rate deformation characteristics of Be and to assess the probability of material failure under characteristic states of loading [1,2]. The design was fixed to minimize the tensile stresses generated within the sample during standard shock experiments. The focus of these experiments was to determine if Be fails in shock compression and if so what were the damage mechanisms causing failure. Post-test characterization of the Be samples in the arrested shock experiments was performed to evaluate the microstructure and fracture behaviors seen in these experiments. Similar to other brittle materials like Tungsten Heavy Alloy [3], beryllium has a relatively low spall strength that is insensitive to loading kinetics. Under plate impact and explosively driven shock experiments, spall values of 0.78 to 1.3 GPa and 1.04 to 1.8 GPa respectively are measured. An extensive presentation of the characterization of the Be used in the current work and the experimental design has been reported by Cady et al. [4]. The current work focused on the fractography of the damage evolution observed in the recovered Be samples.

2. Experimental configuration
In this study, tests were performed on S-200F beryllium from Brush Wellman, Inc. The total impurity level for this grade is typically below 1% and the grain size is about 11 μm [5]. Specimens were machined such that the samples were loaded along the hot-pressing axis. The crystallographic texture in such samples is modest at two or less multiples of a random distribution. Based on computational simulations using the ALE and Lagrangian analyses, an experiment was designed that would provide
the appropriate stress levels and cause a compressive shear failure rather than a tensile failure within the sample. The simulations were also used to determine the offset of the Be sample from the high explosive (HE) that would provide the appropriate shock stress levels in the sample.

![Figure 1](image1.png)  
**Figure 1.** Shock recovery assembly for the arrested Be experiments. HE drive from top down in all images.

![Figure 2](image2.png)  
**Figure 2.** (a) Simulation with a 30 mm offset at t = 50 μs and (b-d) microscopy from Mg test showing strain concentrations (arrows) and curvature.

The final design of the test assembly (figure 1) consists of Al cylinders surrounding the test sample and the HE drive assembly. The inner cylinder is comprised of upper and lower halves (gray and purple in figure 1). The height of the upper piece was chosen to be 35, 45, or 55 mm and the height of the lower piece is adjusted to maintain the overall height of this inner cylinder at 100 mm. The test sample, either Mg or Be, was 5 mm thick by 25 mm in diameter, placing the leading edge of the sample at 30, 40, and 50 mm from the explosive charge. The blue and red layers were designed as radial and axial momentum traps. In the experimental configuration the explosive drive was produced with a polyethylene sleeve surrounding a detonator, plane wave lens and a disk of PBX-9501.

Drive validation experiments were performed using AZ31B Mg to verify that the Be would be contained within the Al assembly and to measure the shock stress and particle velocity. The recovered inner cylinder, plug, and Mg sample assembly is shown in figure 2. Note that the magnesium did not deform uniformly and that there are regions of stress concentrations (red arrows). The final geometry of the plug agree with the results of the simulation. Recovered Be samples exhibited nominally vertical cracks, parallel to the loading direction (figure 3). A network of radial and circular cracks is observed in all of the Be samples, but not in the more ductile Mg.

![Figure 3](image3.png)  
**Figure 3.** (a) Idealized schematic of crack orientation, (b) Test sample #5 located at 30 mm from HE, and (c) Test sample #7 located at 50 mm from He. Missing pieces have been used for other characterization. Discs are 25 mm in diameter.
3. Metallography and fractography

An investigation of the fracture morphology using optical metallography and scanning electron microscopy, was performed to address the dominant fracture mechanisms. As the recovery assembly was specifically designed to minimize rarefaction waves from loading the sample to induce tensile failure, a focus of the fractography was to understand how and where nucleation of damage occurred. Metallographic characterization (figure 4) observed that deformation twins are found in all samples. There also appears to be evidence of void nucleation at grain boundaries.

**Figure 4.** Metallographic image of the Beryllium samples taken by grinding the fracture surface off, polishing the sample, and imaging the surfaces. These images were all taken using an optical microscope. (a) Sample 5 (30 mm from HE) and (b) sample 7 (50 mm from HE).

**Figure 5.** Representative fracture plane propagating from near the center of the sample on the left to the outer edge on the right (as illustrated in the inset (a)). (b) Composite of multiple SEM images of the fracture surface. (c) Map of the key features with crack direction as inferred from the hackle marking (in red) initiating at the top and propagating from the center towards the outer edge. This crack path is consistent with the rib marks (in green). Due to the multiple initiation points, the cracks come together at the two dominant intersection scarps (in blue) (sample 7 - 50 mm from HE). In all of the fractography images, the general appearance of the fracture surfaces is consistent with that of cleavage in a characteristically brittle material. At the macroscopic level, the surfaces are flat with sharp edges and uniform metallic luster, free of any shear lips that would be suggestive of ductile
plastic deformation. At the microscopic level, the failure is dominantly transgranular. As shown in figure 5, the dominant surface morphology is that of hackle markings—the feather-like fracture morphology resulting from small-scale secondary crack formation parallel to the fracture plane—which can be accurately used to determine the crack propagation path. There are a limited number of intersection scarps—the line at the locus of intersection of two cracks (or two fronts of the same crack) with each other—that are likely more indicative of the intersection of multiple initiated cracks in the specimens. Rib marks—the curved line on the crack face, typically convex in the general direction toward which the crack is running—are present. However, there are no clear Wallner lines—the rib marks with a wavelike profile that result from interaction of the crack front with an elastic or plastic wave—perhaps adding additional support to the observation that the samples were all very effectively momentum trapped and hence there were no inwardly reflected waves for the crack fronts with which to interact. Consistent with the literature on quasistatic crack growth in beryllium associated with either failure of a tensile specimen [6,7] or crack propagation of a fracture specimen [8,9], the hackle marking can be traced back to the origin of crack initiation. Moreover, consistent with this literature, there is no gross transition in fracture mechanism from the area of the initiation and regions of fast crack propagation (such as the mirror to hackle transition typically observed in brittle glasses). Mackay [6] reported that for a tensile test at room temperature the fracture origin was internal, but near the surface, and, in the crack propagation region, fracture occurred by transgranular brittle cleavage. Murr [7] reported localized, predominantly transgranular, brittle fracture with negligible ductility. Murr hypothesized from examination and comparison of the residual microstructures, tensile fracture data, and the acoustic emission data that beryllium deforms initially by grain boundary straining (localized slip in the grain boundaries) which gives rise to the pre-yield acoustic emission signal. Yielding then occurs when strain localization within the grain boundaries creates microcracks in the grain interiors that occur heterogeneously to create catastrophic brittle, transgranular fracture. Conrad [8] reported fracture in a compact tension specimen occurred by cleavage of the grains along planes nearly parallel to the general fracture surface with no one dominant cleavage plane. Conrad also reported some tearing in the vicinity of the grain boundaries. Shabbits [9] reported predominantly flat brittle transgranular fracture in Be with the grain surfaces all showing some cleavage steps and markings with only a few confined areas of ductile rupture in a compact tension specimen.

In addition to the sample having been successfully momentum trapped with no formation of a spall plane, a few gross observations can be made from the fracture surfaces (see figures 5 to 7). First, the cracks always initiates on the top surface of the sample, consistent with the hypothesis that the sample experienced some nominal bending that puts the top of the specimen in tension. Second, once initiated, the cracks consistently propagate from the center of the sample towards the outer edge. This crack propagation path directly contradicts the proposed failure mechanism observed in Taylor impact experiments where unconfined compression at the impact surface leads to a large expansion and resultant large tensile hoop stress. This is contrary to Taylor impact tests that can lead to radial cracks propagating inward from the outer edge. Unlike the idealized schematic of the crack orientation shown...
in figure 3, the actual crack patterns are not uniformly spaced and the circular cracks do not always form a complete ring. While it is clear that cracks initiate at the top surface and propagate outward consistent with the sample experiencing bending, the crack paths are clearly stochastic. Under quasi-static loading, beryllium follows linear elastic fracture mechanics (LEFM) with a relatively low fracture toughness ($K_{IC}$ of 5 to 20 MPa m$^{1/2}$ [8,10]) consistent with the observed brittle failure mechanisms. On fracture surfaces of the circular cracks in the current work (see for example figure 6), the cracks clearly propagate from the top to the bottom with no strong propagation component in the circumferential direction. Therefore, it is likely that the circular cracks grow independent of the radial cracks. On fracture surfaces of the radial cracks (figure 7), the cracks clearly propagated from the top to the bottom and from the intersection with a circular crack to the outer edge. Therefore, it is likely that the radial cracks either are initiated from the circular cracks or grow with a strong interaction with the circular cracks. Although dominant initiation points are near the center of the sample, additional nucleation sites are observed along the crack length including near the specimen edge. Figure 7 shows a series of higher resolution images of penny-shaped cracks initiating along the length of the crack but growing only a short distance into the sample before being overtaken by the dominant crack propagating radially from the center towards the outer edge. This would suggest that either the bending experienced by the samples is greatest near the center of the sample, giving the cracks at the center the greatest driving stress, or the bending is experienced at later time, the further towards the edge of the specimen so that these secondary cracks simply do not have time to propagate.

![Fracture surface of a radial crack in sample #3 (40 mm from HE)](image)

FIGURE 7. Fracture surface of a radial crack in sample #3 (40 mm from HE) ((a) SEM image and (b) fracture map, inset (c) illustrates surfaces being viewed). The crack clearly propagated from the intersection with a circular crack to the outer edge. (d & e) Additional nucleation sites are observed along the top edge of the crack, with higher resolution. However, these cracks only grow a short distance into the sample before being overtaken by the dominant crack. The shock is propagating from the top to the bottom.

4. Conclusions
Arrested beryllium experiments were focused on quantifying if Be fails in compression and to observe failure behaviors. Visual characterization of the Mg sample shows regions of stress concentration that are likely reproduced in the Be sample and may be a source of the load that created the circumferential crack in the Be samples. There were also radial cracks present in the samples that may have been
caused by bending moments. The fractography showed that failure in the Be discs was not tensile spall, as designed. Typically, fracture propagated from the side of the sample closest to the explosives, the side with the highest tensile bending stress. There was evidence that fracture may have propagated from the circumferential crack outward and downward radially.

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