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Research paper

Explosive fragmentation of gallium-embrittled aluminum alloy cylinders

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Received: November 18, 2017 Accepted: November 20, 2018

Abstract

Liquid metal embrittled (LME) aluminum alloy cylinders were studied to characterize and investigate fragmentation behavior during explosive loading. Localized reductions in material strength, ductility, and toughness are created by the embrittling action of small quantities of gallium applied to aluminum. Aluminum alloy cylinders were packed with Composition C-4 explosive and end-detonated to observe natural fragmentation behavior in representative geometries. A “low” pressure condition was induced in the embrittled material by inserting a polycarbonate buffer between the explosives and inner cylinder wall. Other tests featured the explosives in intimate contact with the cylinder walls to investigate a “high” pressure condition. Results indicated that embrittled aluminum cylinders fragment into significantly smaller particles compared to non-embrittled cylinders at both high and low-pressure conditions. Microstructure analysis indicated intergranular failure in embrittled fragments in contrast to the highly-ductile failure of non-embrittled aluminum alloy. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

Keywords: fragmentation, liquid metal embrittlement

1. Introduction

Liquid metal embrittlement (LME) is a process by which low melting point metals (e.g. gallium, mercury) penetrate a susceptible host metal (i.e. aluminum and cause dramatic changes in ductility and strength Kamdar[1]. During LME, liquid metal penetration into the substrate occurs along grain-boundaries and changes in material properties originate at this intergranular scale Hirvonen et al.[2] and Popovich[3]. Since material strength is affected at the grain boundary surface, explosive loading may result in smaller and more uniform fragments compared to non-embrittled material. This study investigated the embrittlement of 6061 aluminum alloy by gallium and the resulting effects on explosive fragmentation.

2. Experimental

A series of explosive tests were conducted at Sandia National Laboratories, Albuquerque, NM, USA Site 9920. Experiments investigated the natural fragmentation of both embrittled and non-embrittled 6061-Al cylinders. The amount of embrittling agent and explosive loading were controlled to determine effects on fragmentation.

2.1 Cylinder construction and explosive configuration

Cylinders were machined from 6061-T6 Al alloy stock; all cylinders measured 25.4 mm (inner diameter) × 127 mm (length). Three different cylinder wall thicknesses were considered: 2.54 mm, 5.08 mm, and 7.62 mm.

A column of circular RDX-sheet explosive cylinders was packed into each cylinder; this explosive formulation was identical to Composition C-4. A custom booster and RP-2 EBW detonator (Teledyne-Risi) were inserted into each cylinder to initiate the explosive column.

Because material strain rate affects fragment size and count, two explosive loadings were tested: a low- and a high-pressure configuration. The low-pressure configuration featured a polycarbonate buffer between the explosive column and the cylinder’s inner sidewall. The diameter of the explosive was reduced to 12.7 mm; the

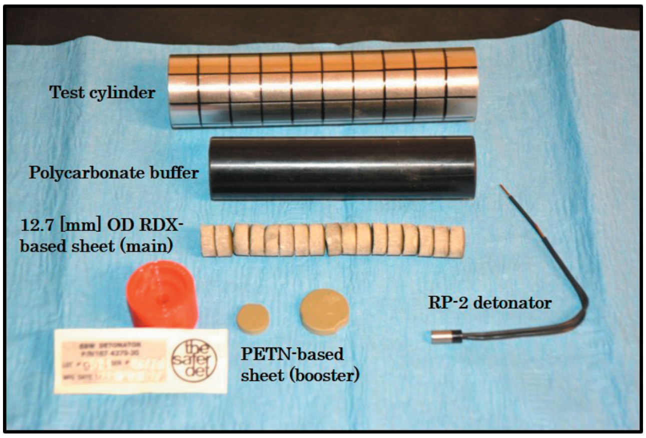

Figure 1 "Low-pressure" explosive components included a polycarbonate buffer between the fragmenting test cylinder and the RDX-based sheet main charge.

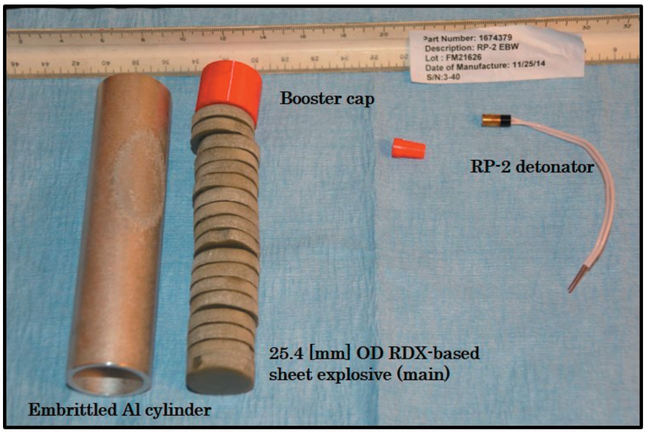

Figure 2 "High-pressure" explosive charges featured direct contact between the test cylinder and the main explosive charge.

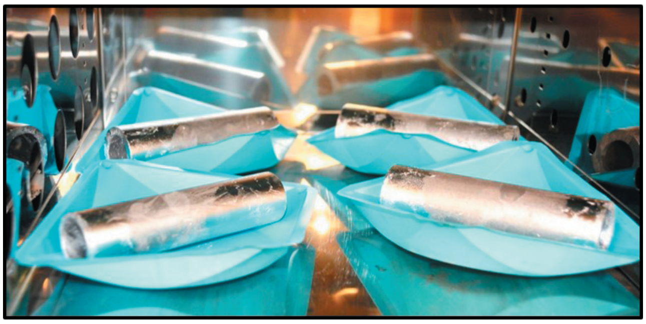

Figure 3 Al cylinders were coated with gallium and were held at an elevated temperature in an oven (4 cylinders shown).

buffer's wall thickness measured 6.35 mm. Peak shock pressure in the aluminum sidewall decreased by a factor of four in the low-pressure configuration compared to the high-pressure configuration. The high-pressure configuration did not include this plastic buffer; explosives were in direct contact with the cylinder's inner wall. Total explosive mass was 22 g and 90 g, respectively. Images of charge construction, explosives, and embrittlement processing are shown in Figure 1–3.

2.2 LME processing

A saturated gallium solution (98 wt. % Ga) heated to

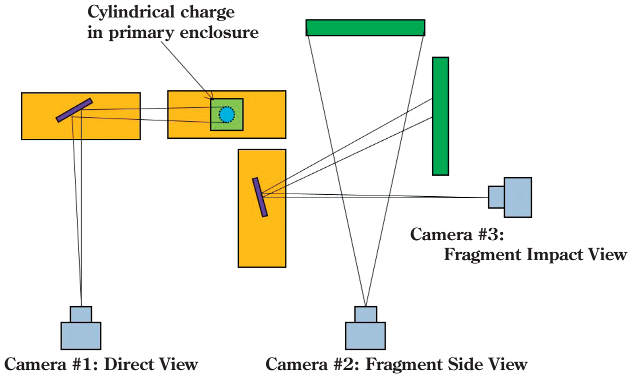

Figure 4 An overhead view of the test layout depicting high-speed camera locations and views relative to the explosive charge is detailed in this schematic.

50 °C was applied to all cylinder surfaces to induce embrittlement. Exposure to the embrittling agent was tightly controlled to create consistent samples. Additionally, samples were prepared for a maximum of three days before testing.

Following agent application, cylinders were heated in an oven at 50 °C for either 8 hours (short duration) or 40 hours (long duration). Figure 3 depicts cylinder treatment in the oven. After heat treatment in the oven, the samples were immediately removed and unabsorbed gallium metal was cleaned from the surface to prevent further absorption. Samples were weighed using a precision scale to determine total gallium mass absorbed.

2.3 Diagnostics and test setup

High-speed imaging of prompt cylinder fragmentation (< 100 μs after initiation) was the primary test diagnostic as it afforded prompt indications of cylinder breakup. Other high-speed imaging views, including fragment flight, witness panel impact, and an overall (wide) view, were collected but are not summarized in this paper. Additionally, SEM imaging and EDS analyses of test residue were conducted.

Cylinders were detonated inside a partially-enclosed steel containment box; fragments could escape through two open sections of the enclosure. Camera positions, fields -of-view, and charge placement are depicted in Figure 4.

3. Results

3.1 Fragmentation of 6061-Al cylinders

Non-embrittled 6061-Al cylinders characteristically fragmented in a ductile manner, creating large, elongated fragments in both low- and high-pressure configurations. Representative early-time fragmentation and expansion images for sample non-embrittled cylinders are shown in Figure 5.

3.2 Fragmentation of embrittled 6061-Al cylinders

Compared to non-embrittled cylinders, embrittled cylinders fragmented into much smaller fragments in all configurations. Three figures summarize data from low-pressure (Figure 6) and high-pressure (Figure 7) experiments and a comparison between 2.54 mm wall

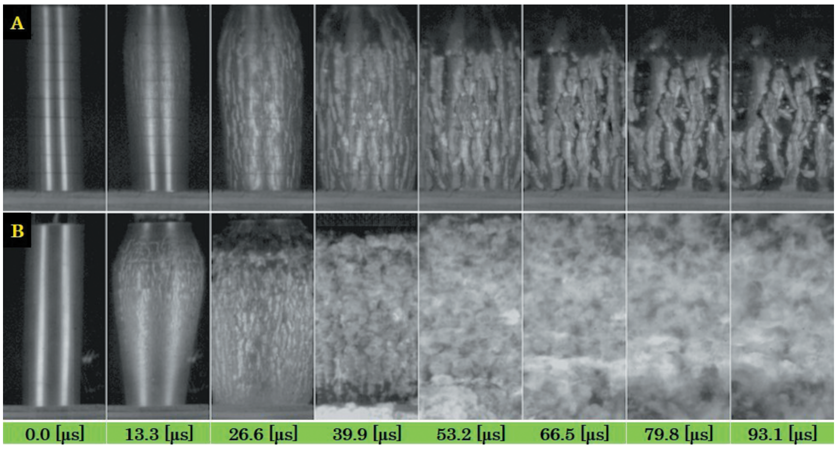

Figure 5 Non-embrittled 6061-Al cylinders (7.62 mm wall thickness) are shown: A) low-pressure configuration and B) high-pressure configuration. Note that the high-pressure configuration predictably creates faster and smaller fragments.

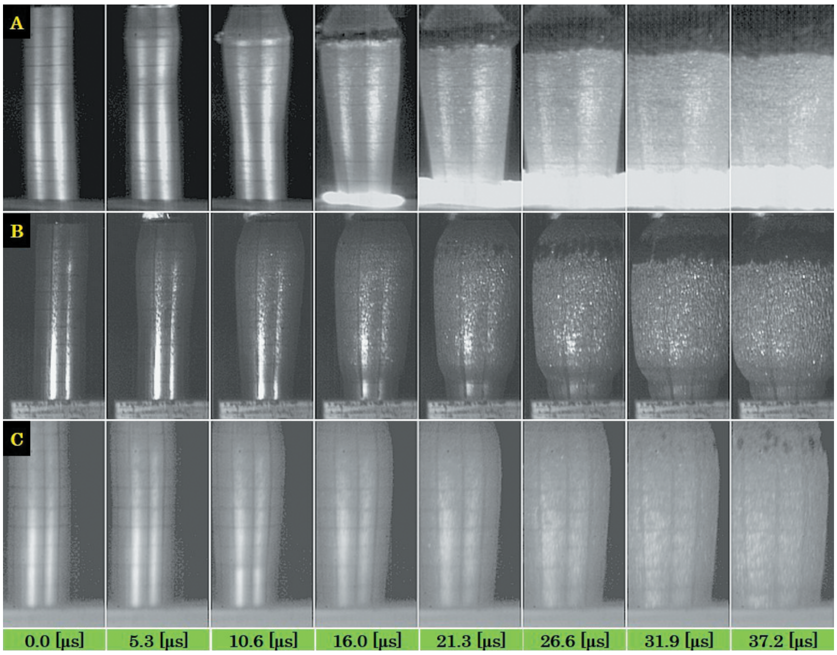

Figure 6 Low-pressure embrittled cylinder fragmentation results are shown in these images: A) 2.54 mm wall, B) 5.08 mm wall, and C) 7.62 mm wall. Note the uniformity in fragment size.

thickness cylinders (Figure 8). No apparent differences between long and short duration tests were observed.

4. Discussion

Fragments collected and imaged from non-embrittled experiments indicated fragment size and morphology consistent with ductile fracture. High-pressure configurations yielded more numerous and smaller fragments than comparable low-pressure experiments. Fragment dimensions ranged from 1.0–50 mm; a wide distribution of sizes was noted. Fragment sizes are similar to those reported in Frost et al[4]. Expected dependencies on charge mass and wall thickness were qualitatively observed.

Tests of embrittled cylinders, however, resulted in fragments of a much smaller size scale; nearly all fragments were smaller than 1.0 mm diameter. Similar to non-embrittled cylinders, fragments generated from the high-pressure configuration were smaller than low-pressure configuration fragments.

Fragment uniformity and ease of fracture are consistent with failure at intergranular surfaces caused by gallium embrittlement. It would be expected that the smallest fragment size would approach the average grain sizes; SEM images indicated boundaries penetrated by gallium created approximately 50–200 μm particles. Although failure appeared to originate from the grain boundary in embrittled samples, most collected fragments were larger than individual grains. Single grain fragments were not collected likely due to test conditions and setup.

5. Conclusions

Liquid metal embrittlement was shown to decrease fragment sizes of explosively-expanding 6061-Al cylinders. Fragments sizes approaching the grain size of the substrate material were created without any localized machining or scoring using liquid metal embrittlement. This method of material preparation may prove beneficial to energetic material enhancement as it allows control over particle size and surface condition without requiring

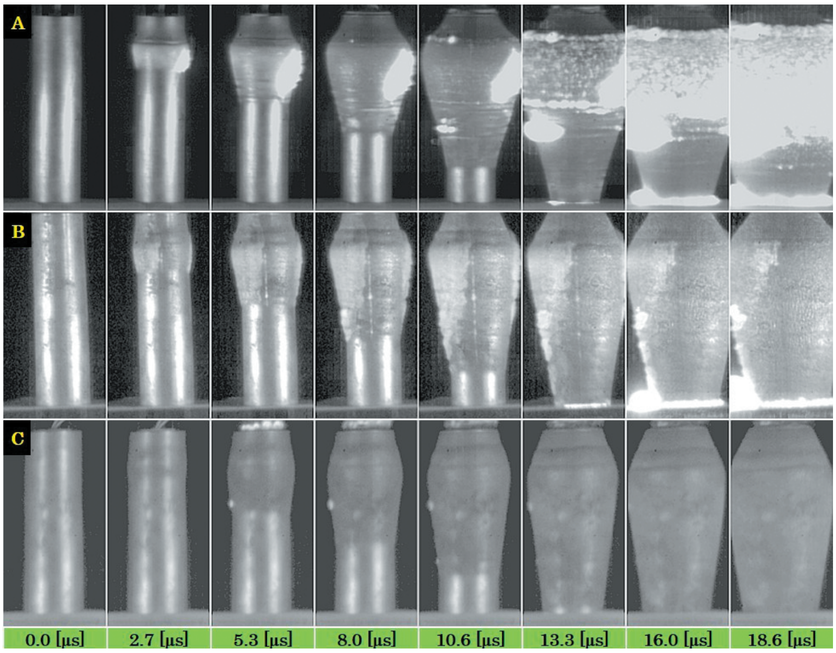

Figure 7 High-pressure configuration fragmentation of embrittled cylinders are shown in these images: A) 2.54 mm wall, B) 5.08 mm wall, and C) 7.62 mm wall. Compared to low-pressure experiments, these tests indicate even smaller fragments.

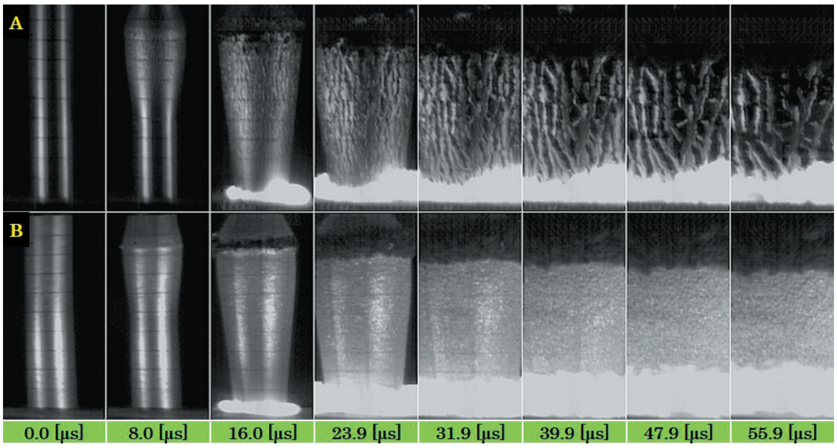

Figure 8 Images from non-embrittled (A) and embrittled (B) low-pressure configuration experiments (2.54 mm wall thickness) indicate fragmentation differences.

a pressed powder compact structure. Furthermore, these experiments have demonstrated beneficial particle size reductions without requiring direct explosive contact (i.e. reduced pressure conditions).

References

1) M. H. Kamdar, Progress in Materials Science, 15, 289–374 (1973).
2) J. C. Hirvonen, D. J. Snoha, J. S. Montgomery, L. J. Kecskes, D. M. Gray, and W. S. de Rosset, "Use of Liquid Metal Embrittlement (LME) for Controlled Fracture", ARL-TR-4976, Army Research Laboratory, Aberdeen Proving Ground, MD, USA (2009).
3) V. V. Popovich, "Mechanisms of Liquid-Metal Embrittlement" (translation), Plenum Publishing Corporation (1980).
4) D. L. Frost, J. Louiseau, S. Goroshin, F. Zhang, A. Milne, and A. Longbottom, Proc. Shock Compression of Condensed Matter, 120019-1 – 120019-6, AIP, Tampa Bay (2017).