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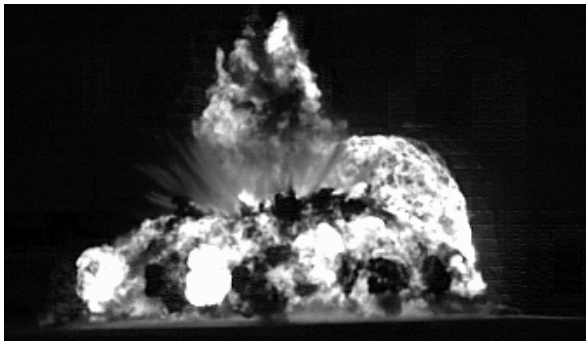

Explosive Fragmentation of Gallium-Embrittled Aluminum Alloy Cylinders

J. Rudolphi, M. Heister, W. Teague, E. Vieth, and M. Naro

6th International Symposium on Energetic Materials and their Applications – Session O12 "Shock Compression"

Tohoku University, Sendai, JAPAN – Nov. 8th, 2017

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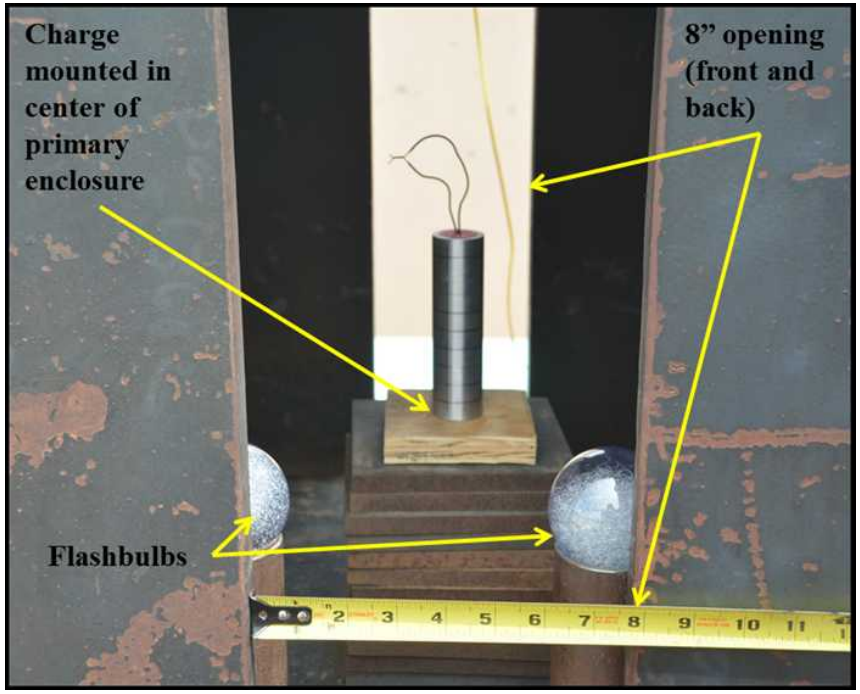
Liquid Metal Embrittlement

- Penetration of embrittling agent (metal; e.g. Ga, Hg) into substrate metals/alloys which results in a brittle material
- Study considered Al and Ga due to severity of embrittlement, ease of preparation, and use of Al as energetic material
- Gallium bonds more strongly to Al than itself – facilitates rapid diffusion along grain boundaries[1] (surface wetting)
- Al/Ga system exhibits time-dependency originating from mobility of Ga to each crack tip[2]
  - Laboratory observations indicate that speed is rapid (~cm/s) in highly stressed Al substrates
- Study by ARL using localized (i.e. controlled fragmentation) on steel casings[3]

[1] R. Stumpf and P. Feibelman, *Towards an understanding of liquid metal embrittlement: energetics of Ga on Al surfaces* (SAND96-0643J), 1996.
[2] R. C. Hugo and R. G. Hoagland, "In-situ TEM observation of aluminum embrittlement by liquid gallium," *Scripta Materialia* 38, no. 3 (1998): 523.
[3] J. C. Hirvonen et al., *Use of Liquid Metal Embrittlement (LME) for Controlled Fracture* (ARL-TR-4976), 2009.

Experiment summary

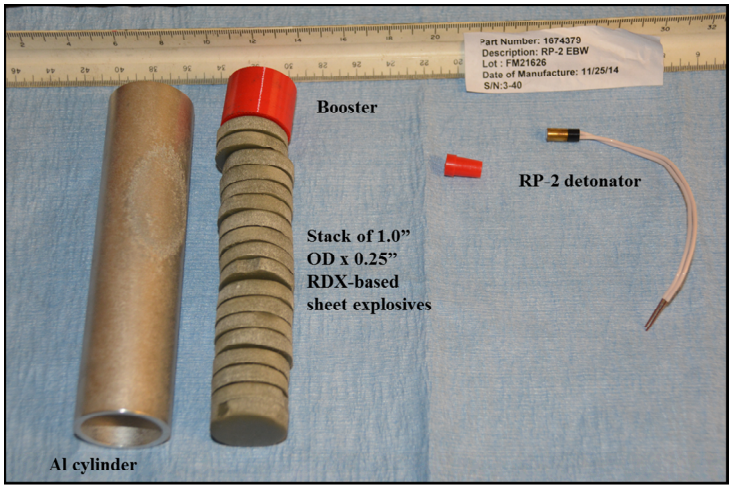
- Explosive fragmentation in low and high pressure configurations (SNL/NM Site 9920) – 21 tests



Explosives configuration

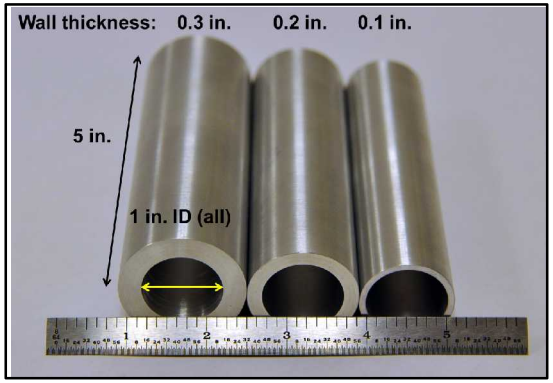
Explosive charges

- High and Low pressure configurations
  - Buffer to create lower pressure loading
  - NEW: 92 g (high); 24 g (low)
  - Peak: 22 GPa (high); 8 GPa (low) - CTH
- RDX sheet sections specified to improve density consistency
- 25.4 mm ID x 127 mm length (all)
- 2.54 mm, 5.08 mm, and 7.62 mm wall

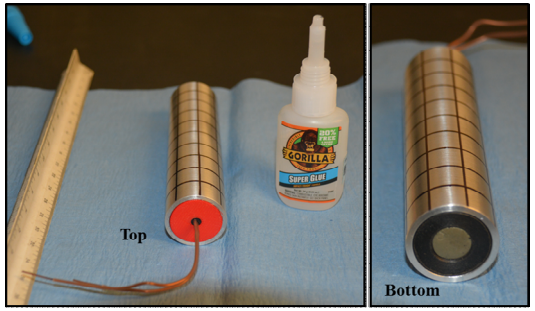


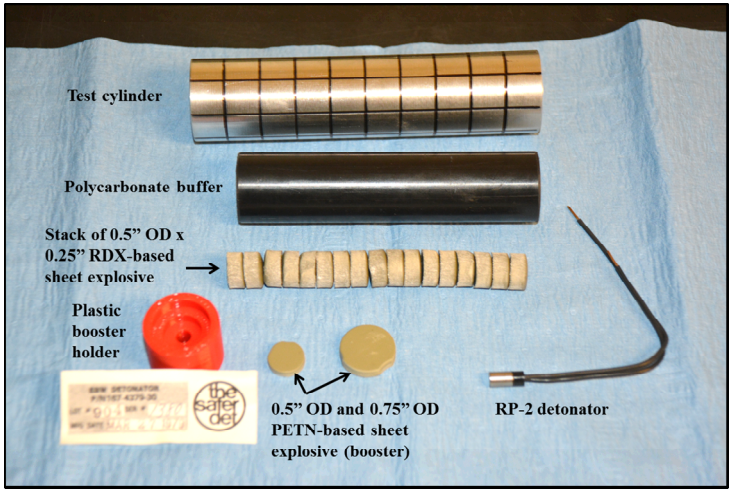
High pressure components

Base cylinders



Low pressure assembly





Low pressure components

Material processing

- Saturated gallium liquid at 50 C applied to cylinder surfaces
  - Amount applied to surface to achieve target percentage of embrittling agent (approx. 125%)
  - Final composition: 1.5% - 2.0% Ga
- Exposure duration:
  - Excess material removed following soak
  - Short duration: 8 hours
  - Long duration: 40 hours

Al cylinders in oven with Ga application

Embrittlement and hardness

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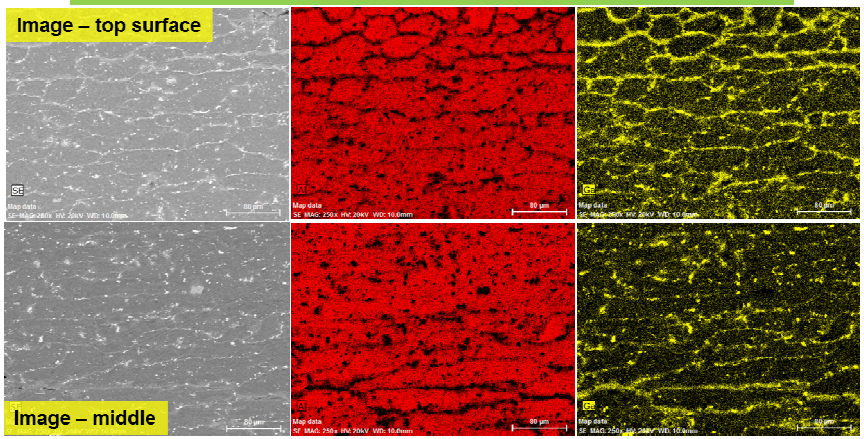
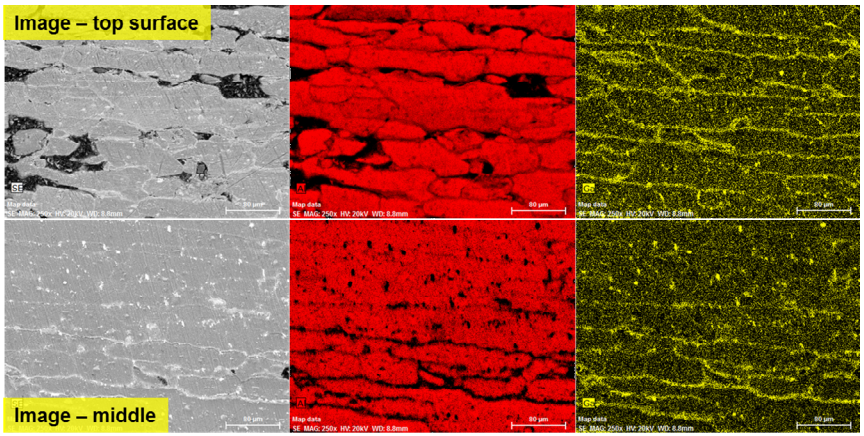
Short Duration, Low Concentration

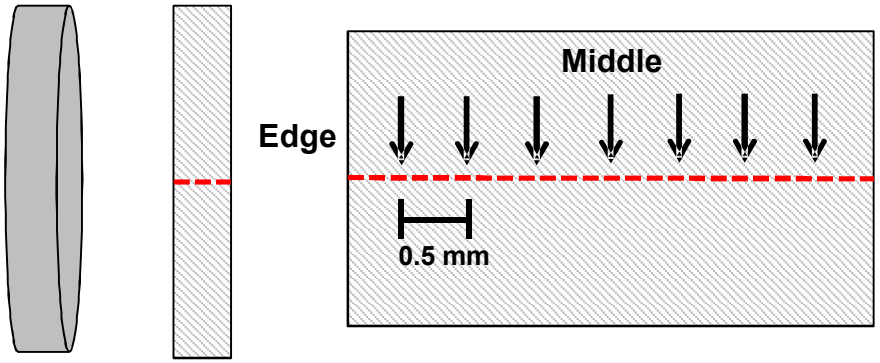


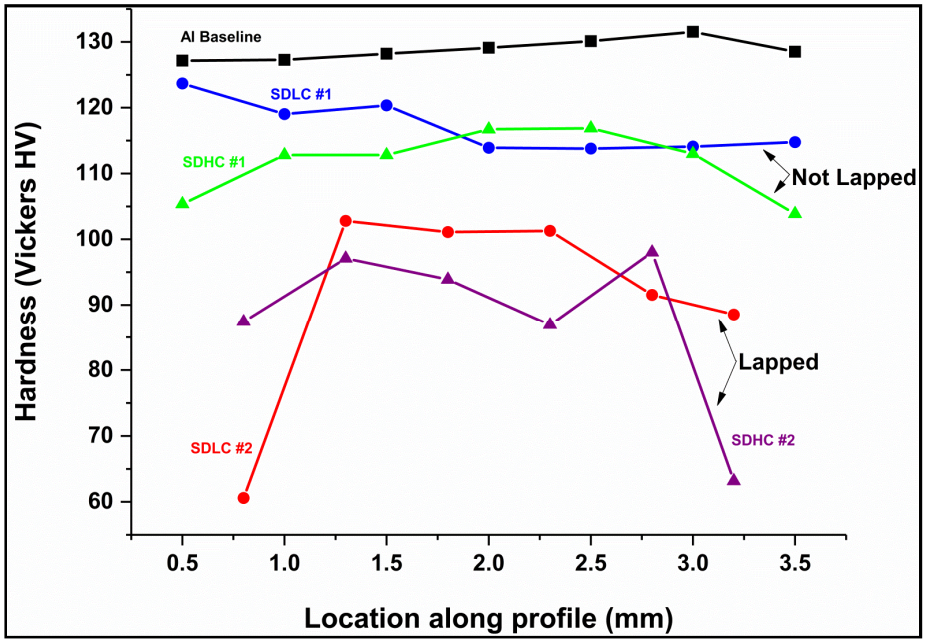
Raw | Al | Ga



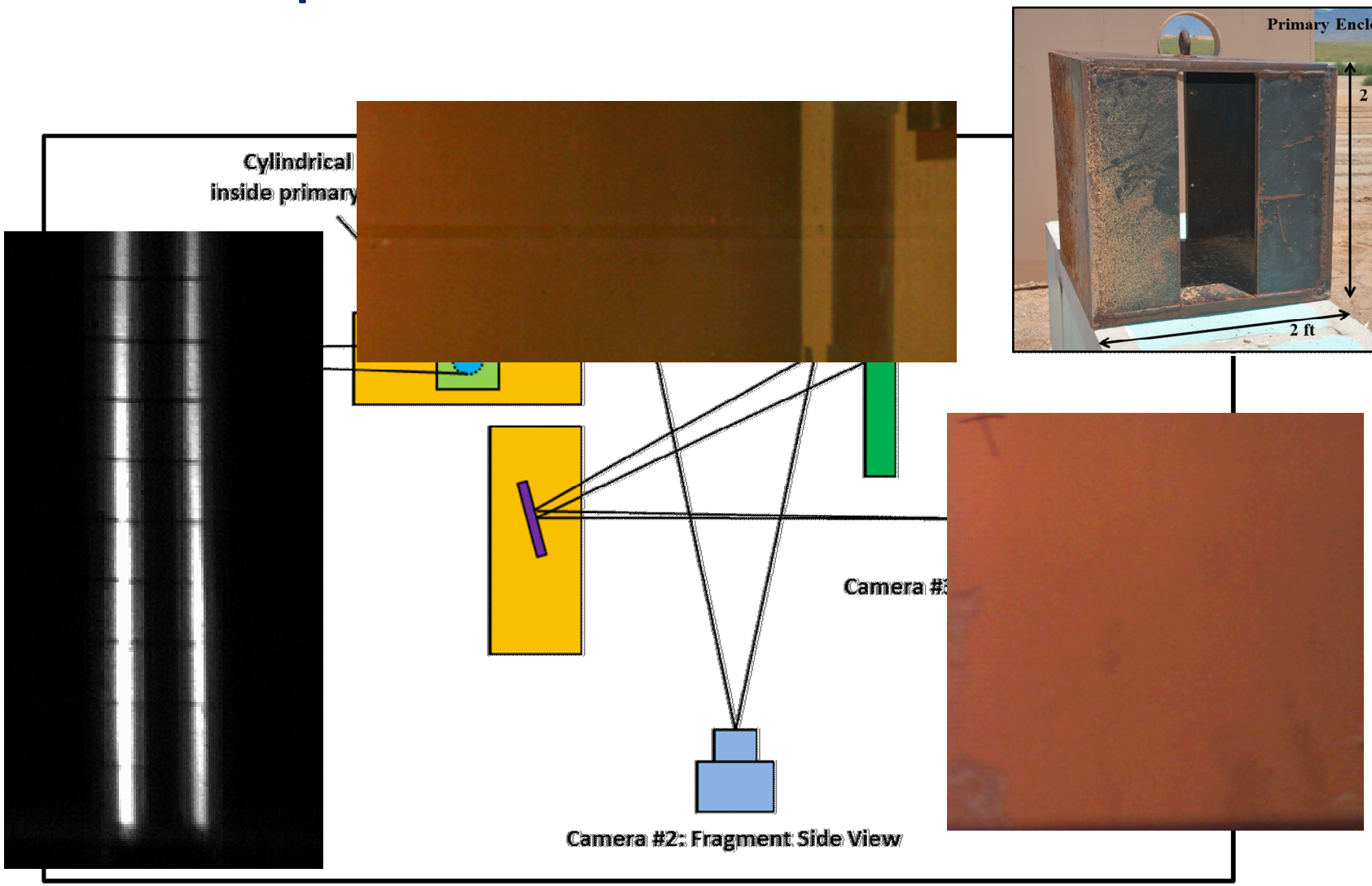
Short Duration, High Concentration

25.4 mm OD x 4 mm puck

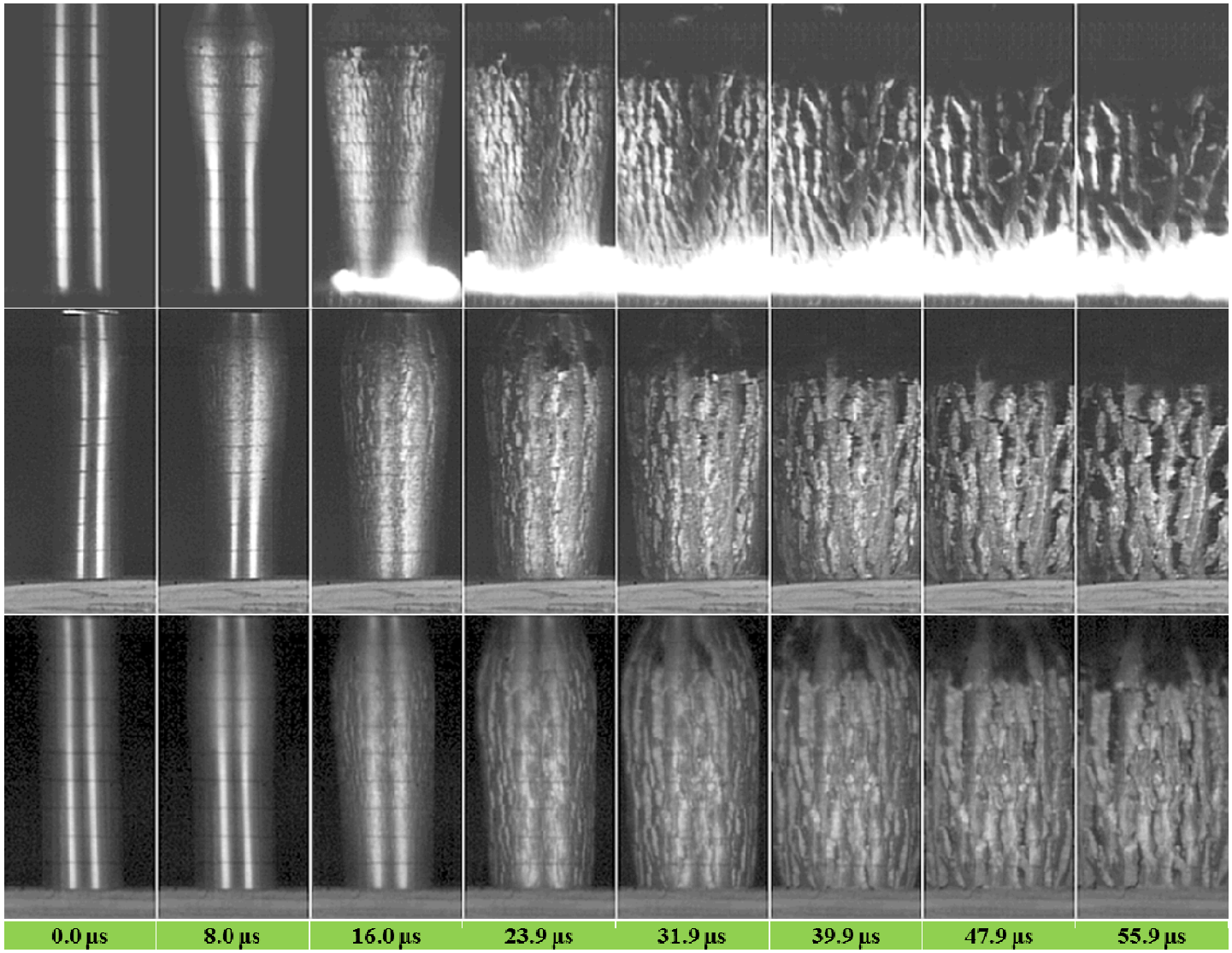




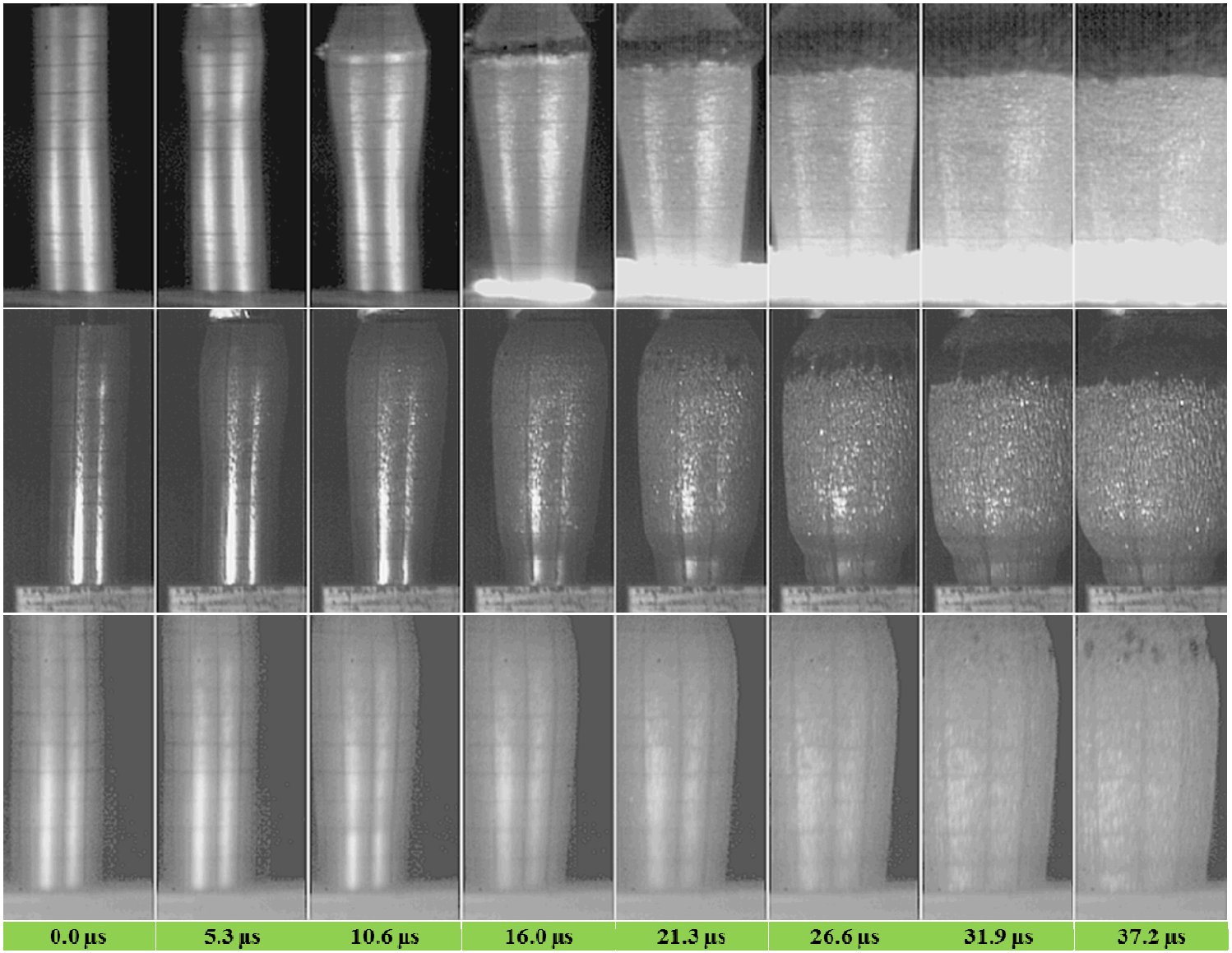
Test setup


Primary Enclosure
2 ft
2 ft
Cylindrical
inside primary
Camera #
Camera #2: Fragment Side View

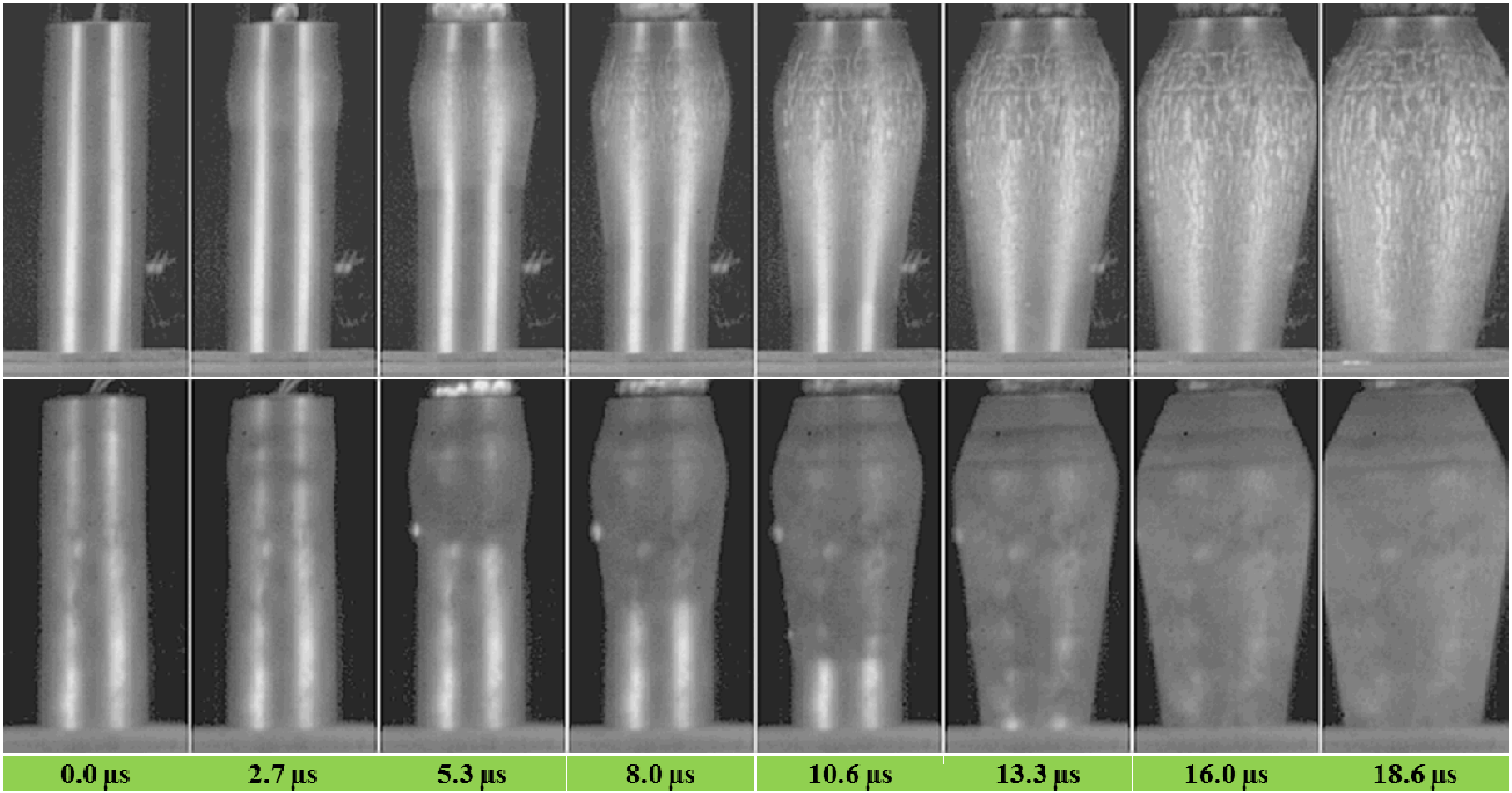
Low-pressure Al



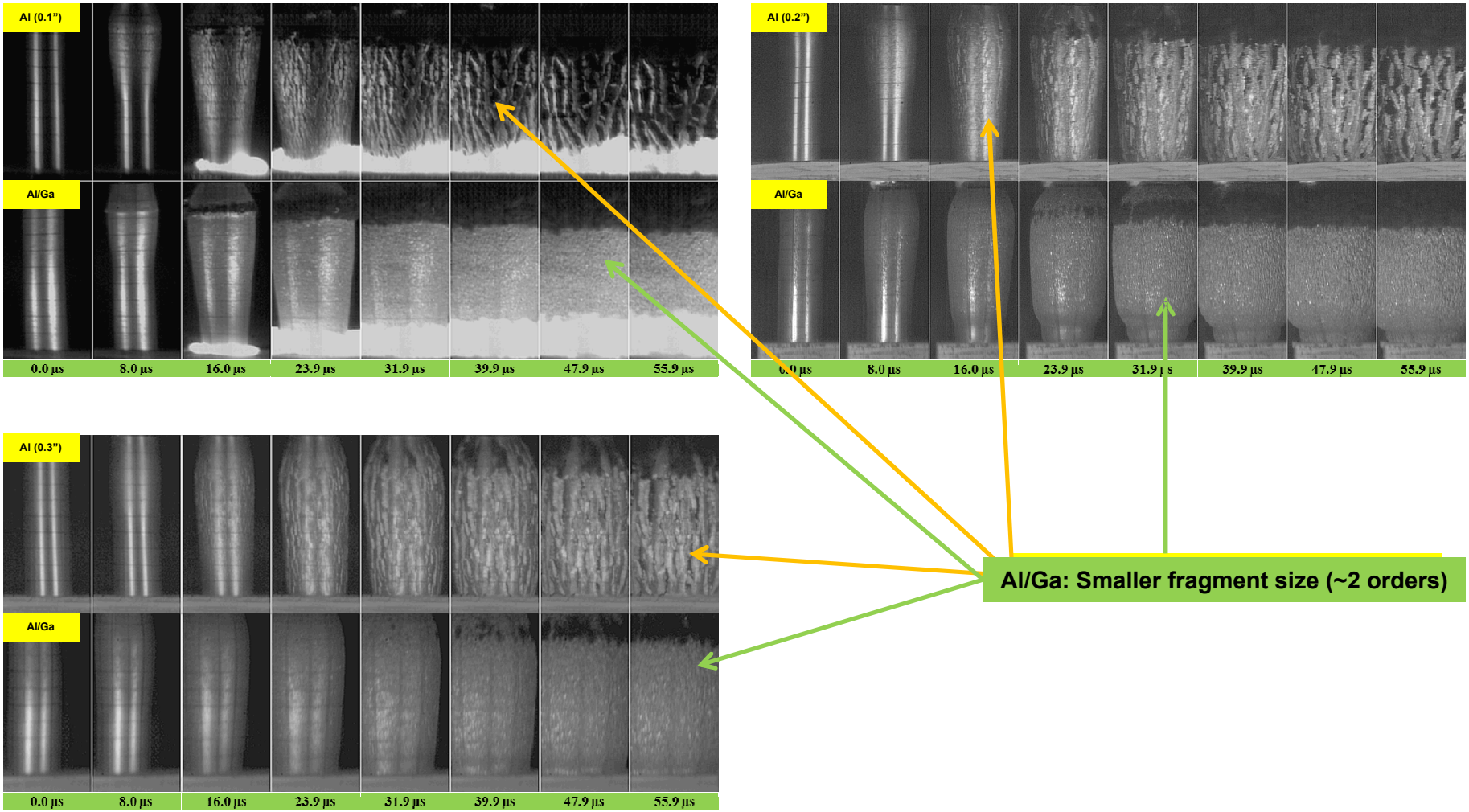
Low pressure Al/Ga



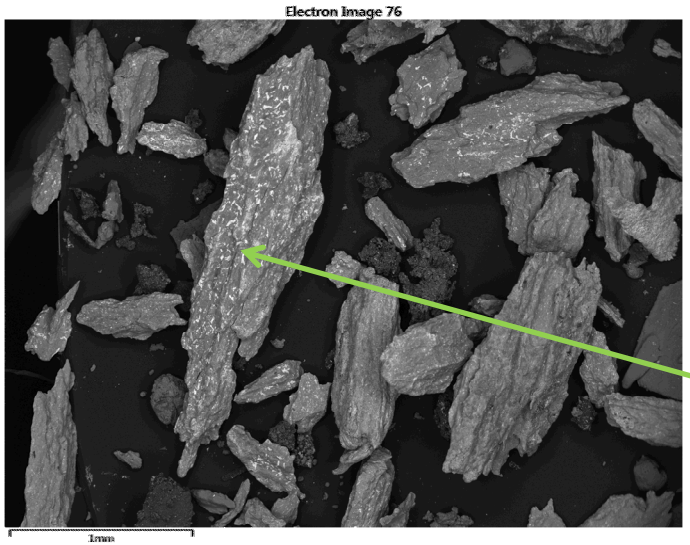
High pressure comparison (0.3”)

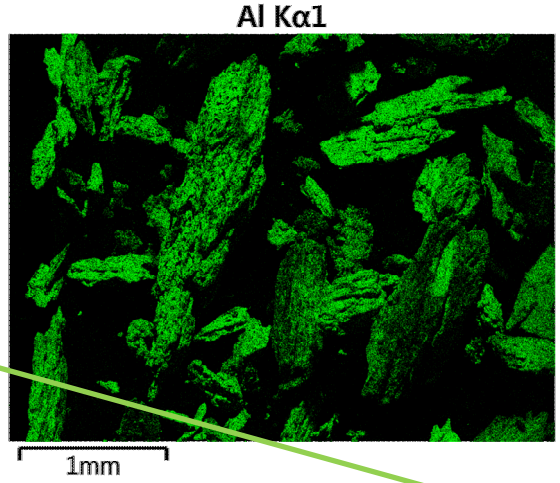


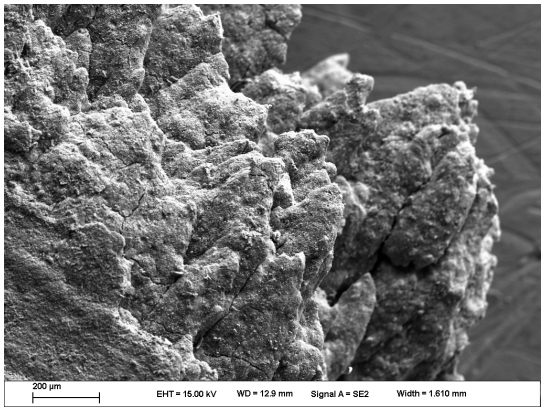
Low pressure comparison (all)



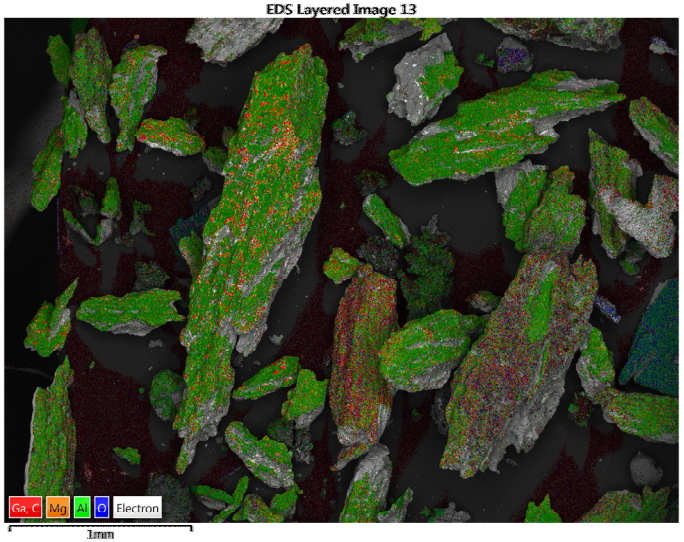
Particle surface

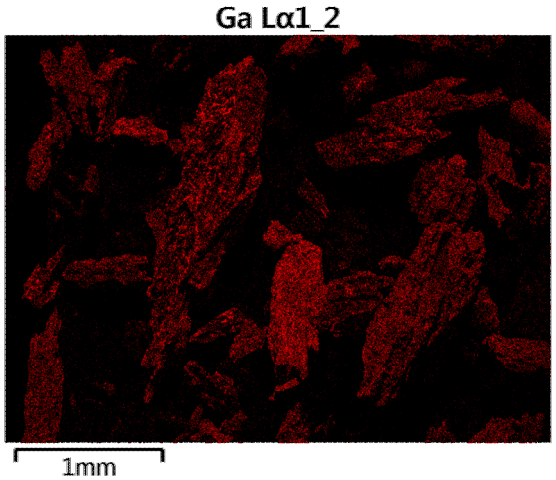


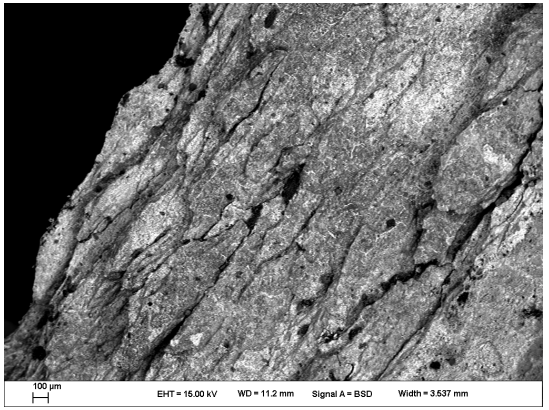




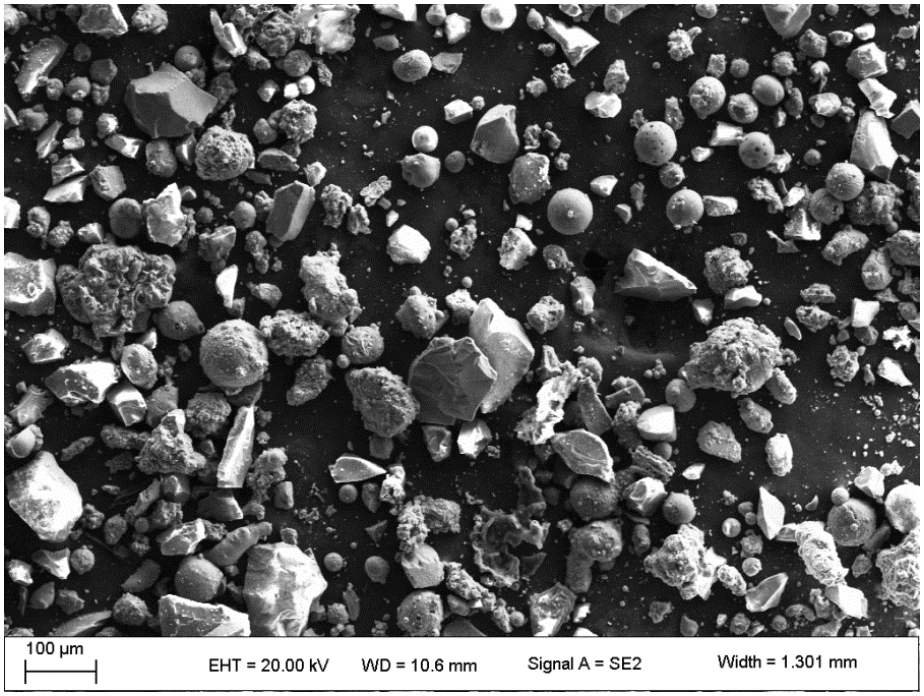
Bright areas on surfaces (Ga)

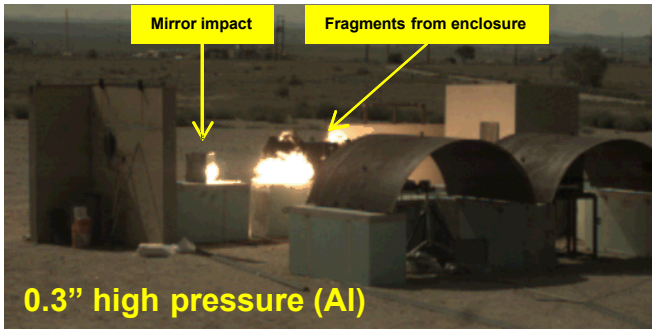


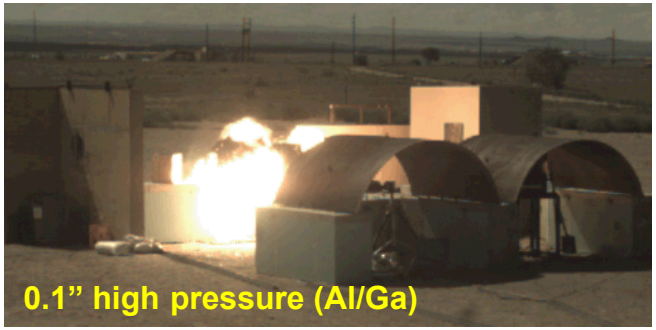




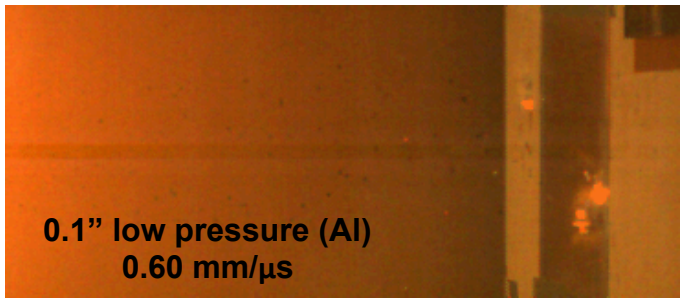
Indicators of reaction

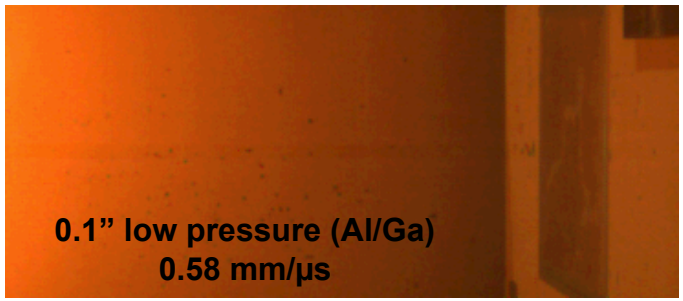






Wide view





Side view

Summary

- Aluminum alloy materials were embrittled with liquid gallium to investigate shock response and fragmentation behavior to explosive loading
- Materials exhibited a time-dependent, heterogenous, microstructure with gallium concentrations along grain boundaries
- 6061 aluminum alloy, when embrittled with liquid gallium, generates multiple grain fragments significantly smaller than non-embrittled material
  - Behavior exhibited in low and high pressure expanding cylinder configurations
- Method may be applied to other metals susceptible to LME

Acknowledgements

- SNL/NM Site 9920 Operators (W. Teague, M. Naro, M. Heister, E. Vieth) for facilitating explosives experiments
- SNL/NM Laboratory Directed Research and Development (LDRD) program for project funding
- B. McKenzie and A. Allen for SEM and material preparation

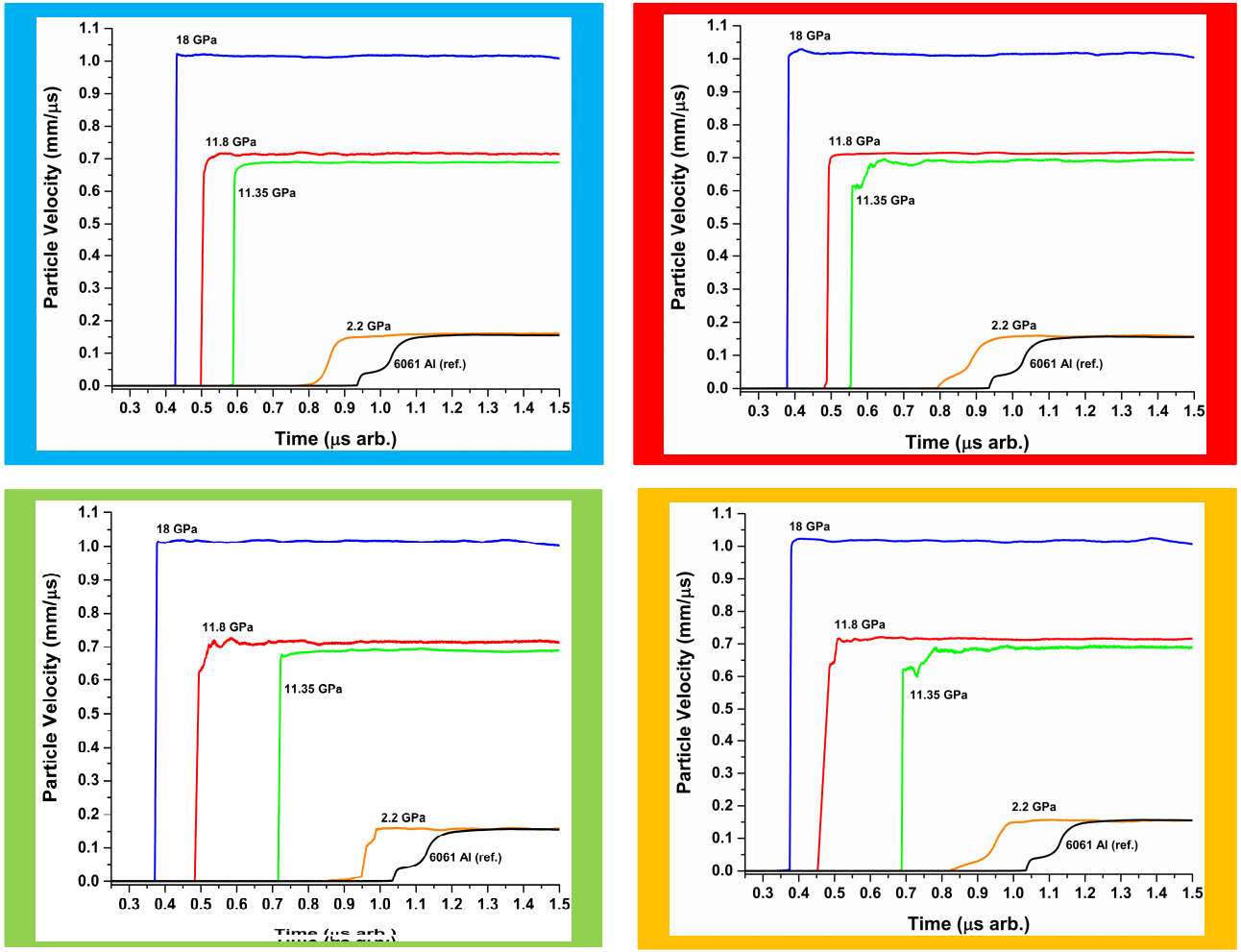
Future work

- Modeling comparison
- Particle size distribution comparison
- Quantify energetic potential
- Compare to PM compacts

LGG test results

Concentration (% Ga)

Duration (Time)



Material consistency

More tests to characterize

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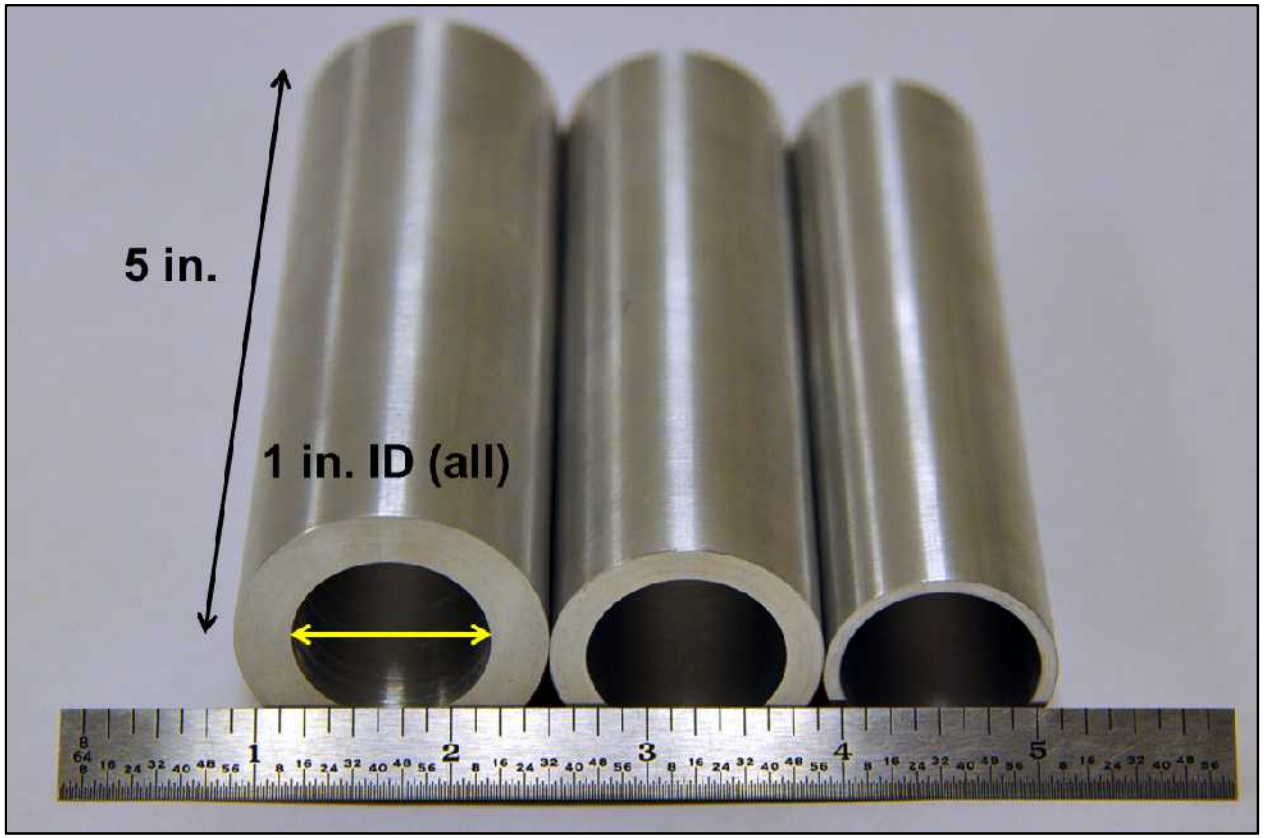

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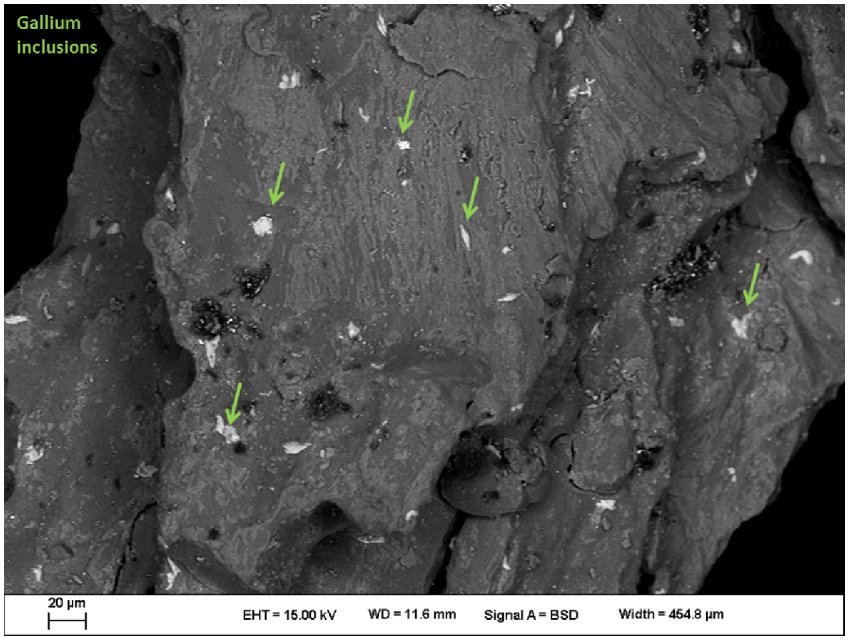

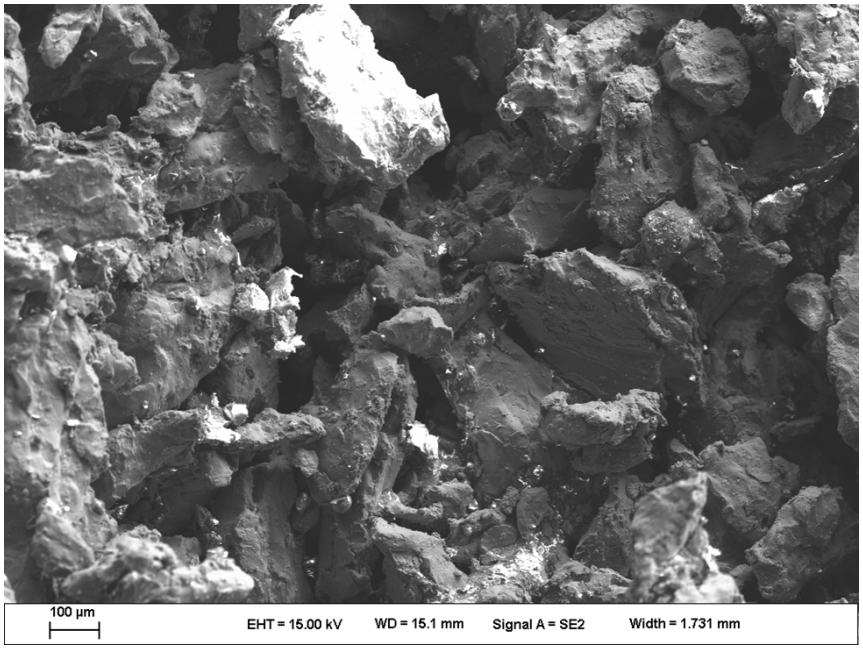

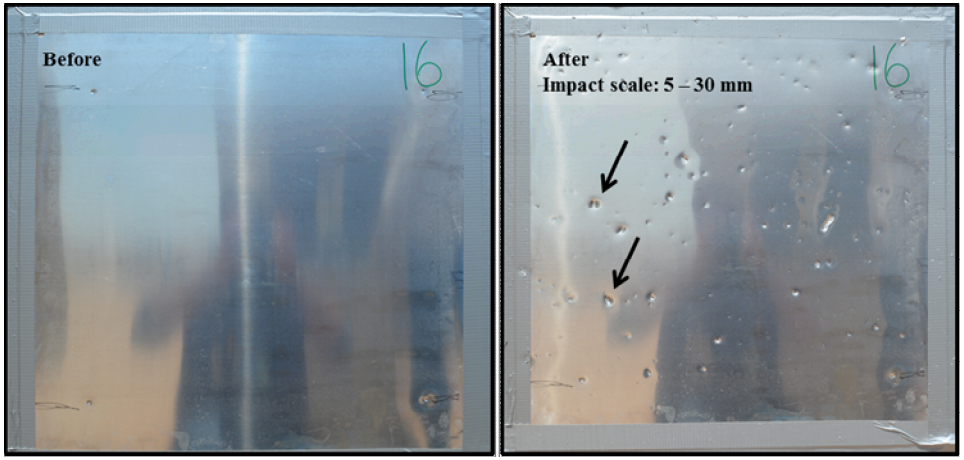

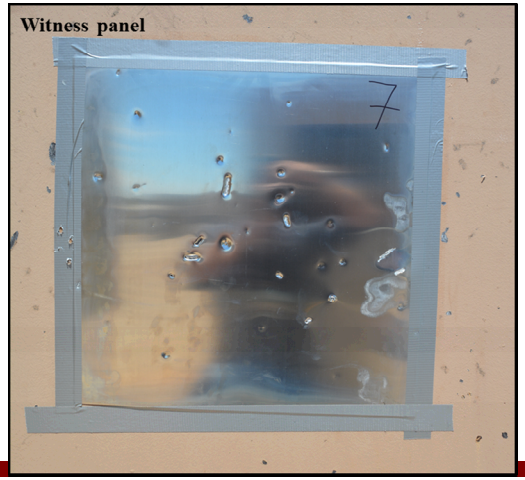

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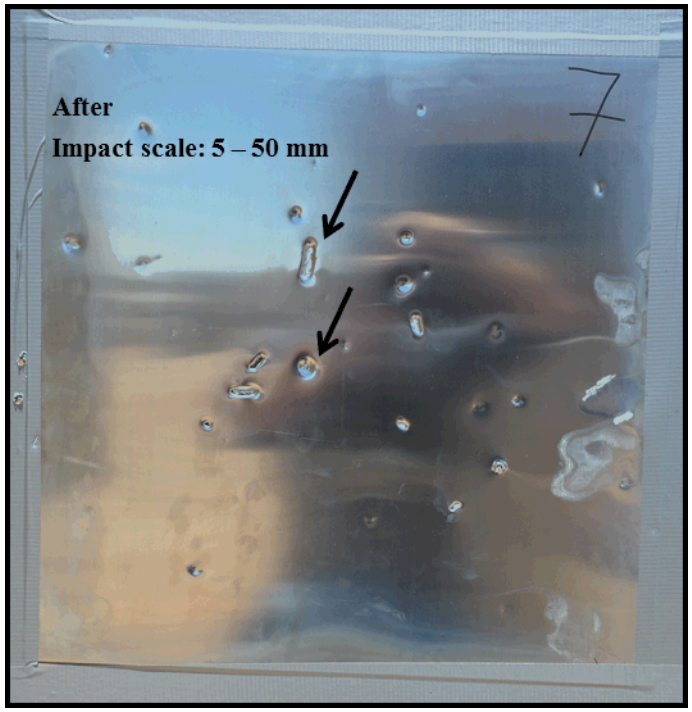

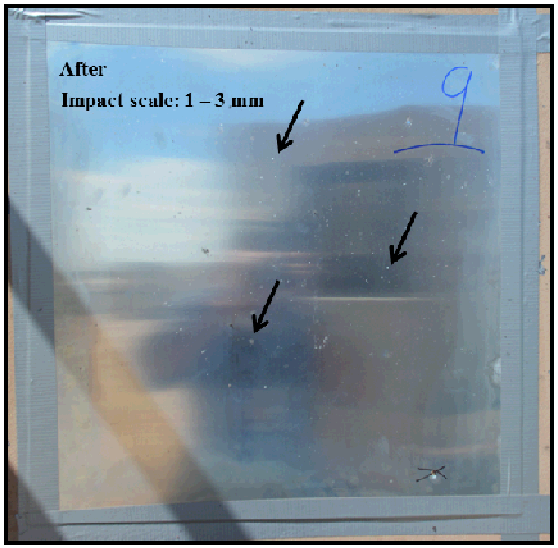

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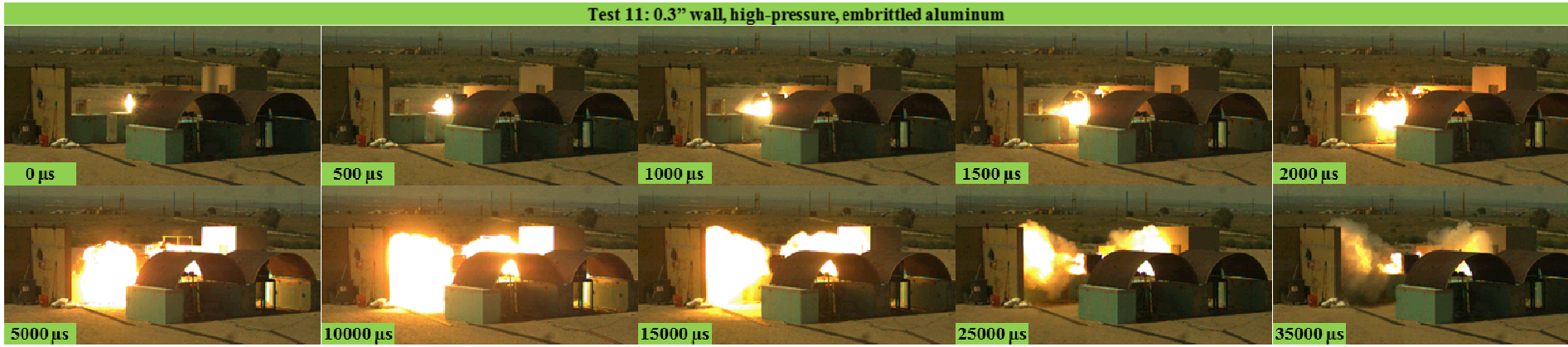

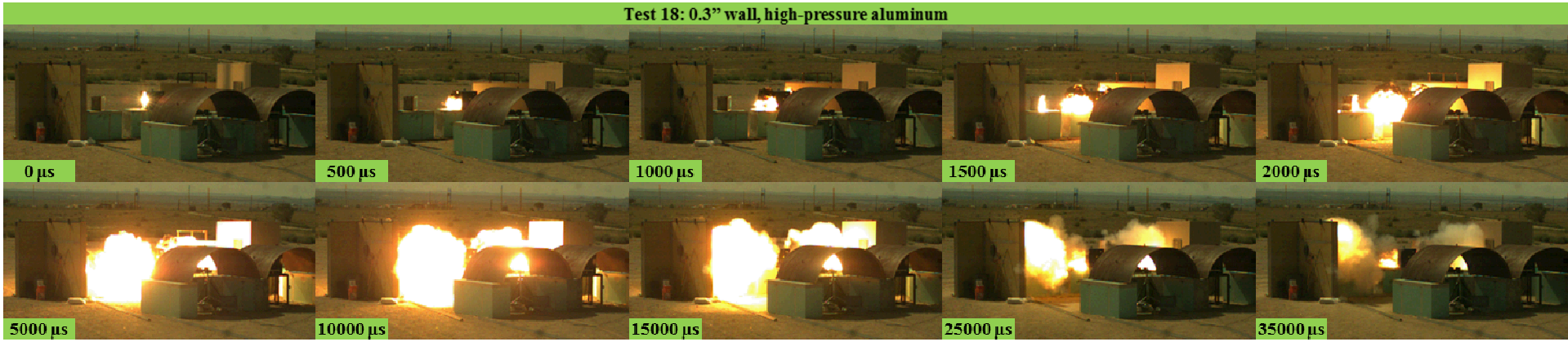

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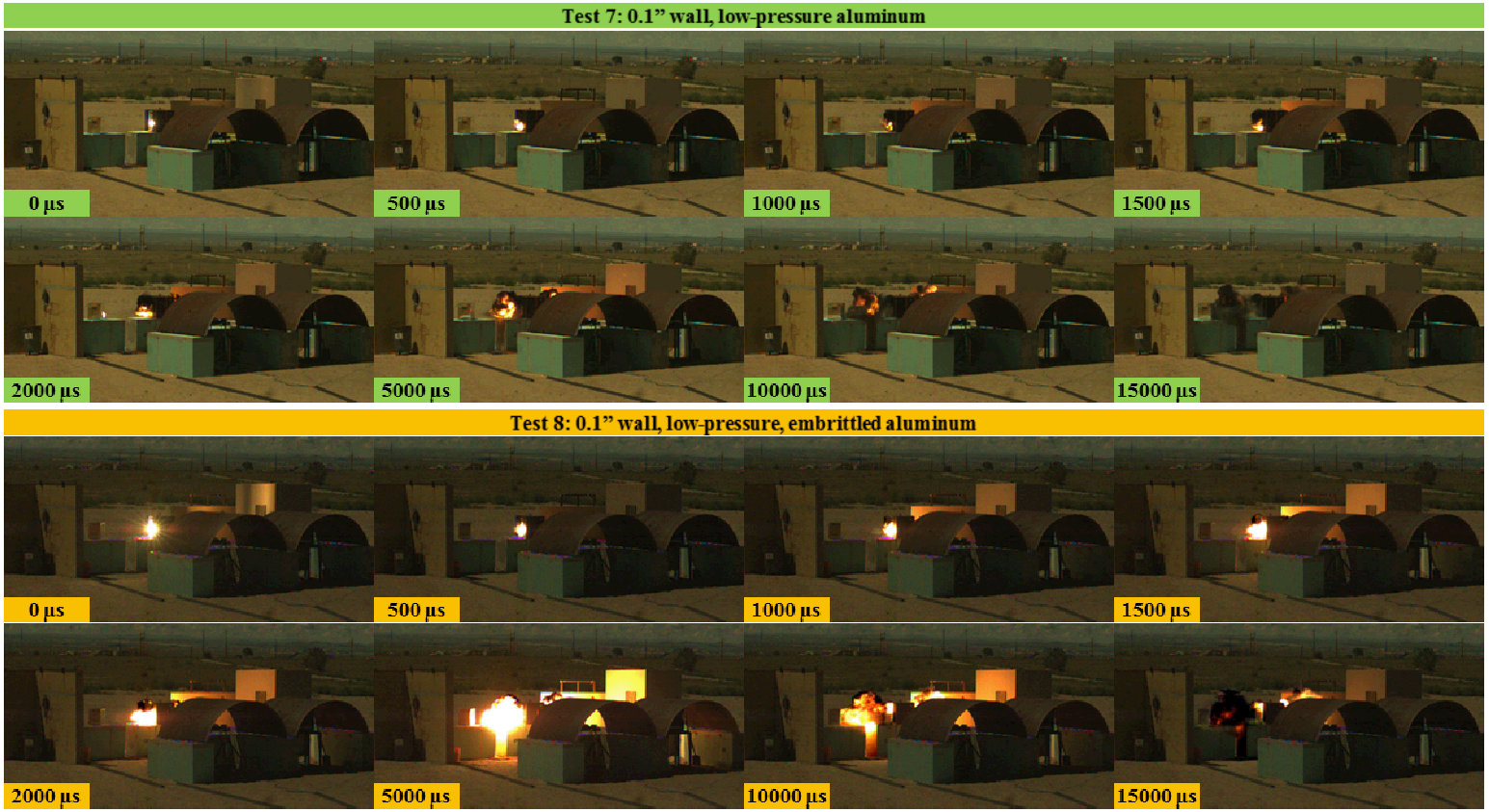

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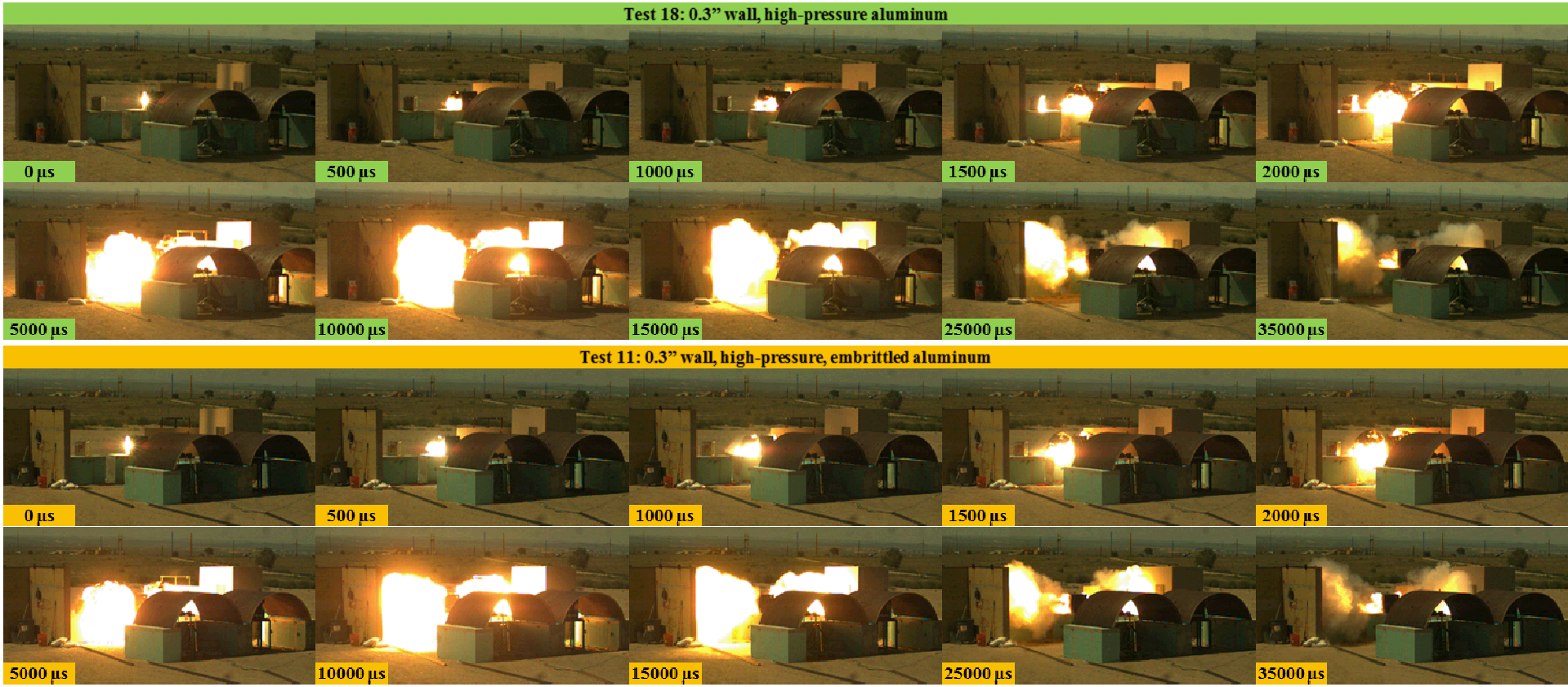

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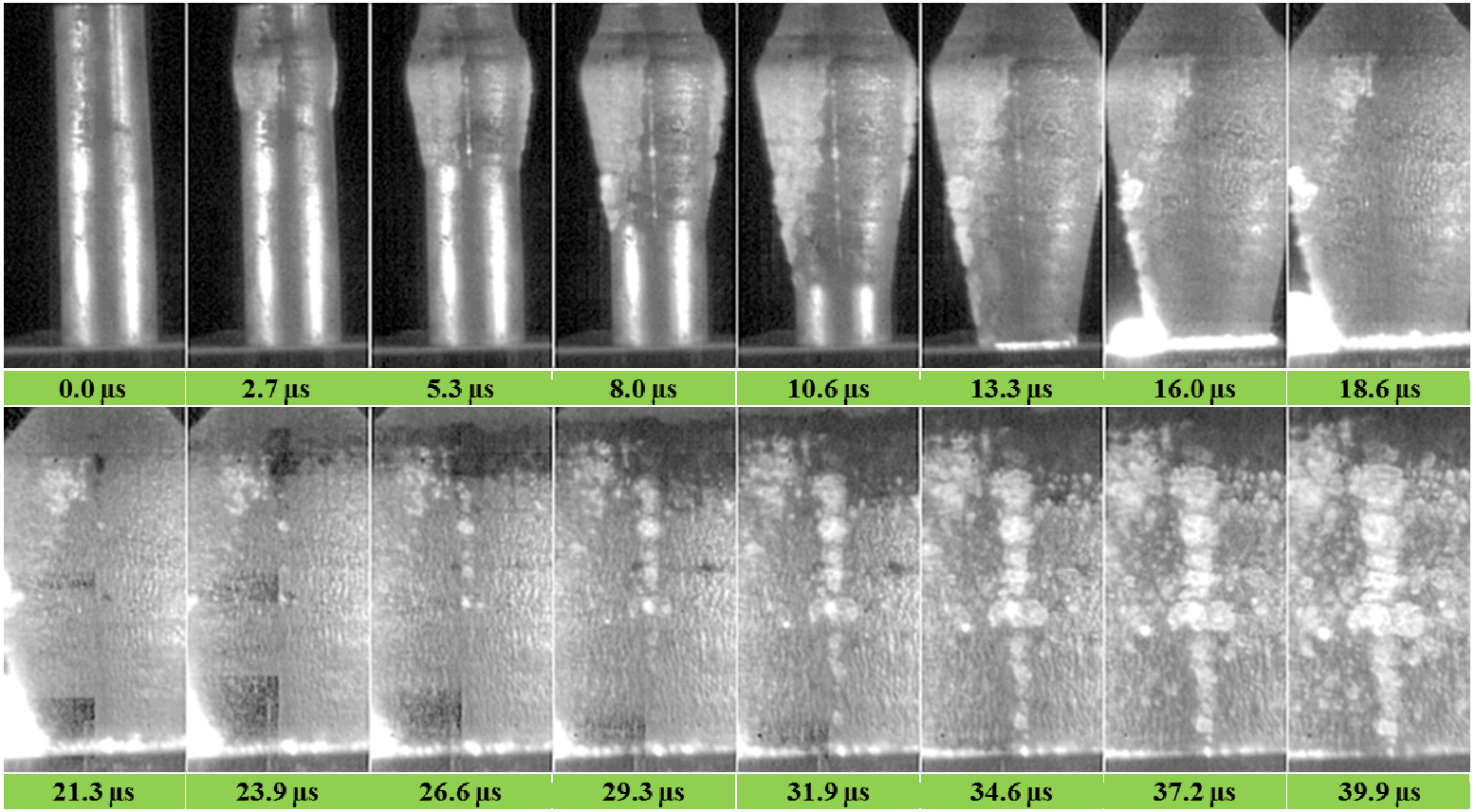

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