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Measurements of the Strain-Rate Dependence of Spallation Strength in 304L Stainless Steel

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Session I02: Spall Nucleation I

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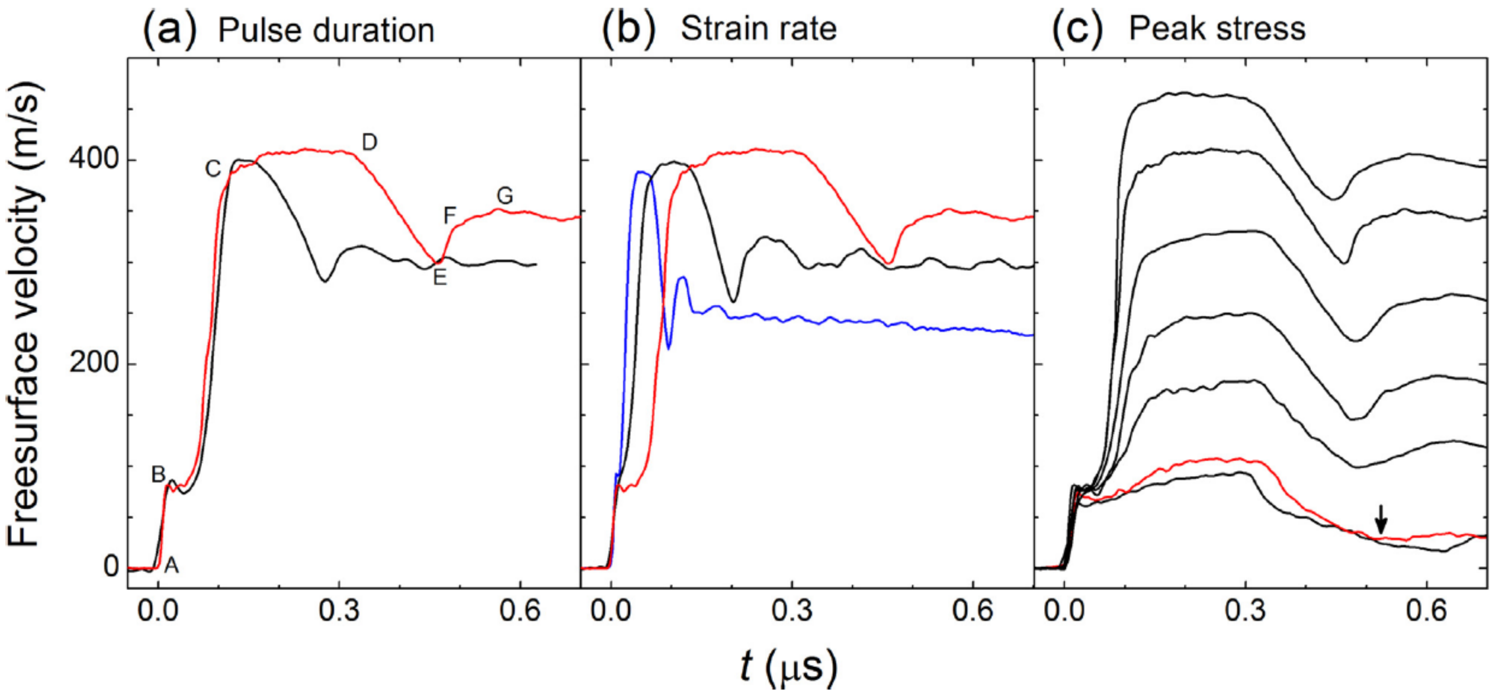
Spall Failure is a Complex Phenomena Dependent Upon the Loading History and Microstructure

- Numerous past works have looked at the influence of grain size, texture, compressive and tensile stress, tensile pulse duration, and tensile strain-rate
  - A complex interaction of all these parameters exists
- **Strong dependence of spallation strength of tensile strain rate**

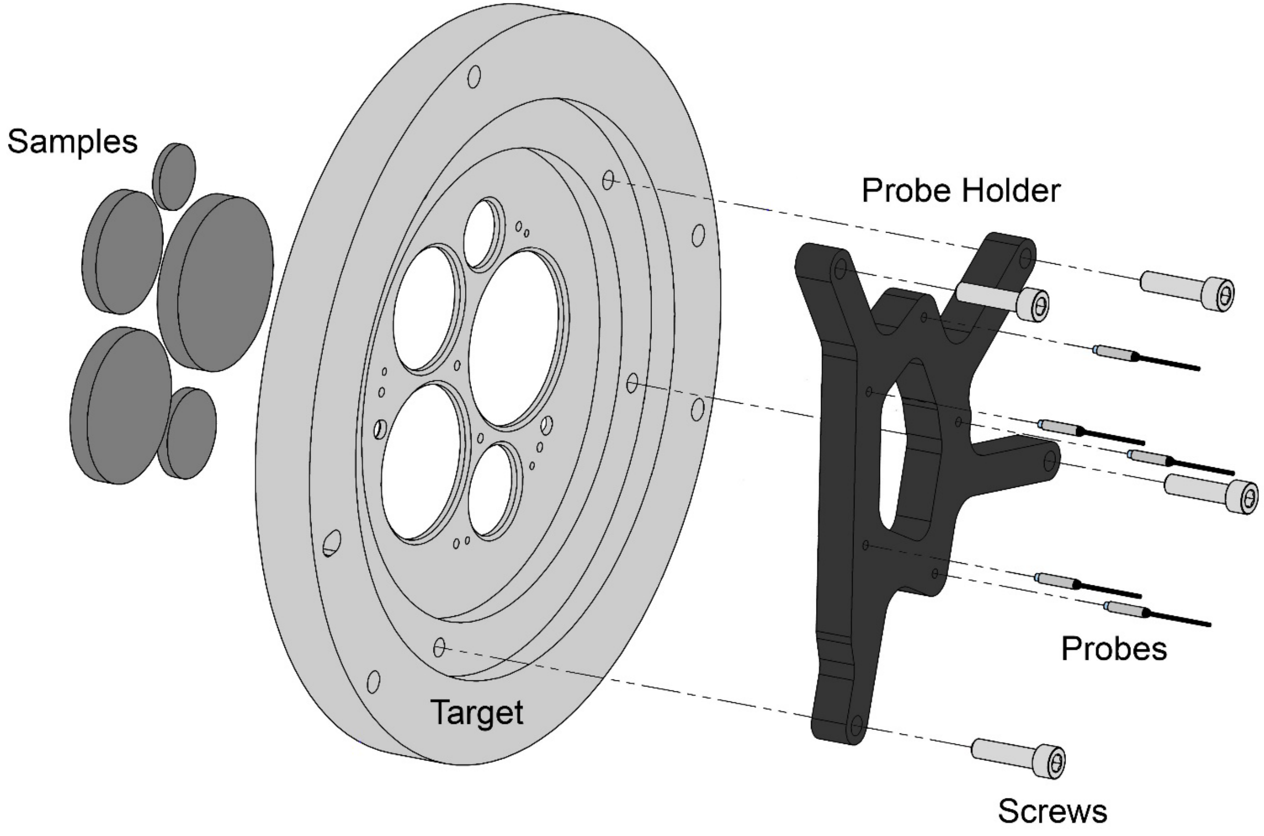


Li et al. *Mater. Sci. Eng., A* **660**, 139 (2016)

Performed a series of experiments to isolate tensile strain rate and/or pulse duration to better quantify it's influence on spallation strength in wrought 304L stainless steel

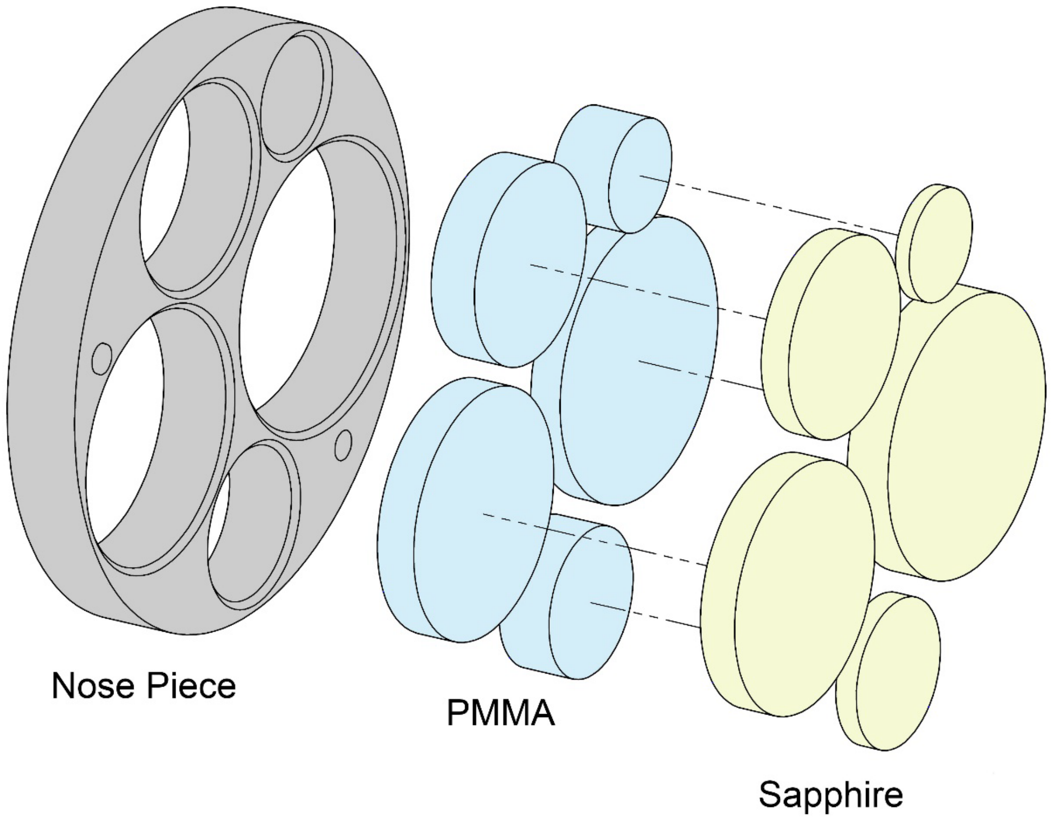
Performed Multi-Sample Experiments to Study the Influence of Tensile Strain-Rate and Pulse Duration

- Initial experiments focused on wrought 304L stainless steel
- Target contained 5 unique samples
  - 16 mm diameter, 2mm thick
  - 22 mm diameter, 3 mm thick
  - 30 mm diameter, 4 mm thick
  - 38 mm diameter, 5 mm thick
  - 43 mm diameter, 6 mm thick
- Increasing the sample thickness decreases the tensile strain-rate



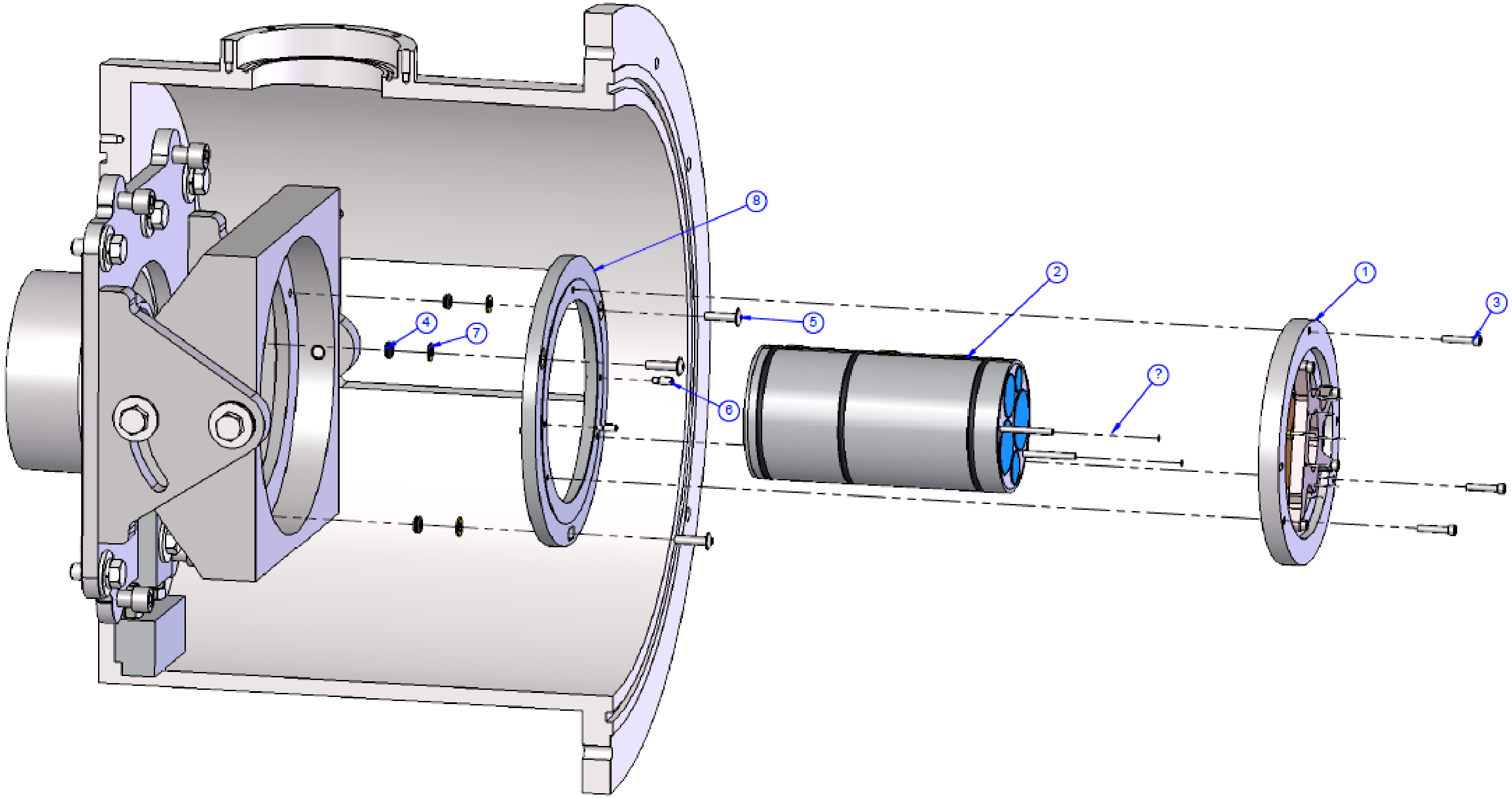
Performed Multi-Sample Experiments to Study the Influence of Tensile Strain-Rate and Pulse Duration

- The nose piece held 5 unique sapphire impactors
  - Each impactor was sized to induce a tensile pulse at the center of its corresponding sample
  - Each sapphire anvil was backed by PMMA to produce a release wave and ensure each impactor/backer set was the same height
  - Sapphire was chosen because:
    - It’s high wave speed produces essentially a rarefaction shock
    - It remains elastic at the impact conditions considered



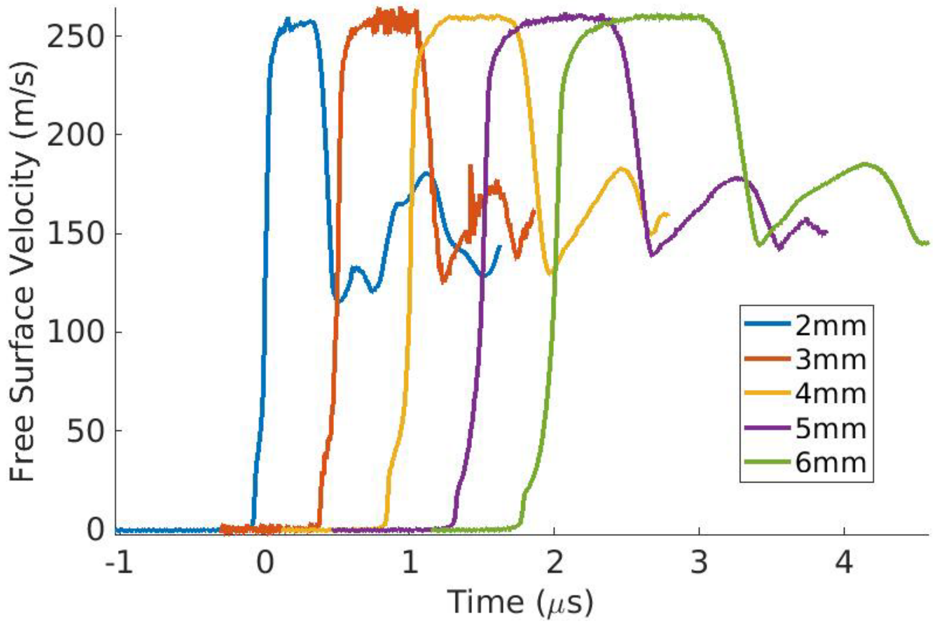
Performed Multi-Sample Experiments to Study the Influence of Tensile Strain-Rate and Pulse Duration

- Utilized the oblique gun at Sandia National Laboratories' STAR (Shock Thermodynamics Applied Research) facility
  - Keyed barrel, gimble system and two alignment pins were used to align the target and projectile

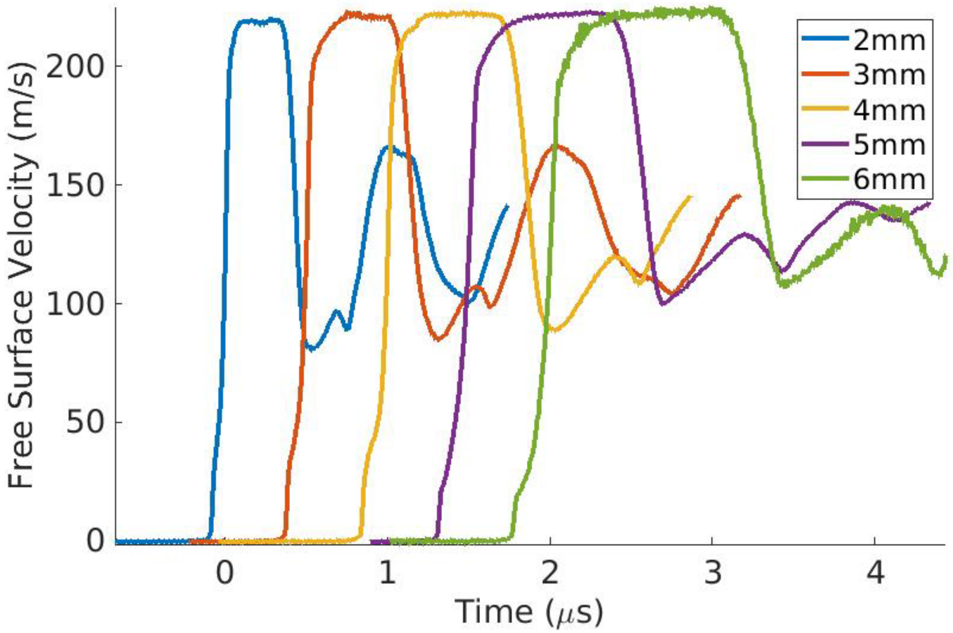


Experiments Show a Clear Strain-Rate Dependence on Spallation Strength

- Experiment 1
  - Impact velocity of 243 m/s



- Experiment 2
  - Impact velocity of 208 m/s



PDV traces artificially shifted in time for clarity

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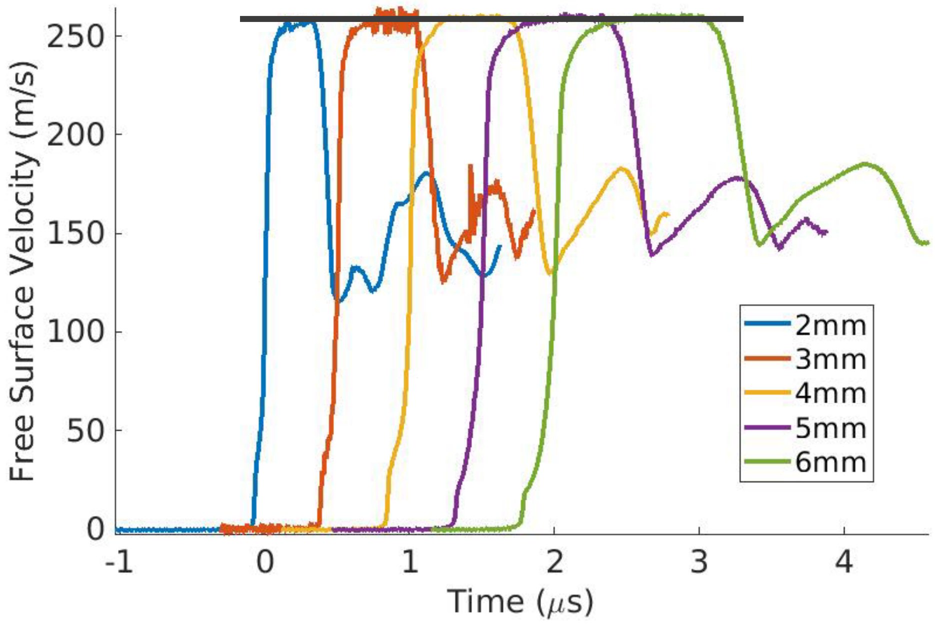

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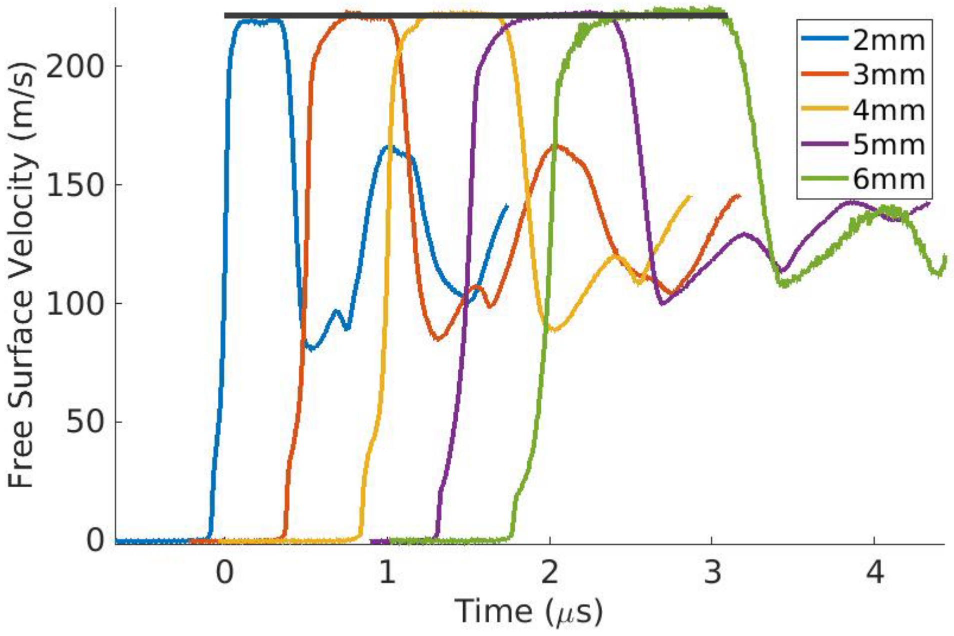

PDV traces artificially shifted in time for clarity

Consistent compressive stress in all samples

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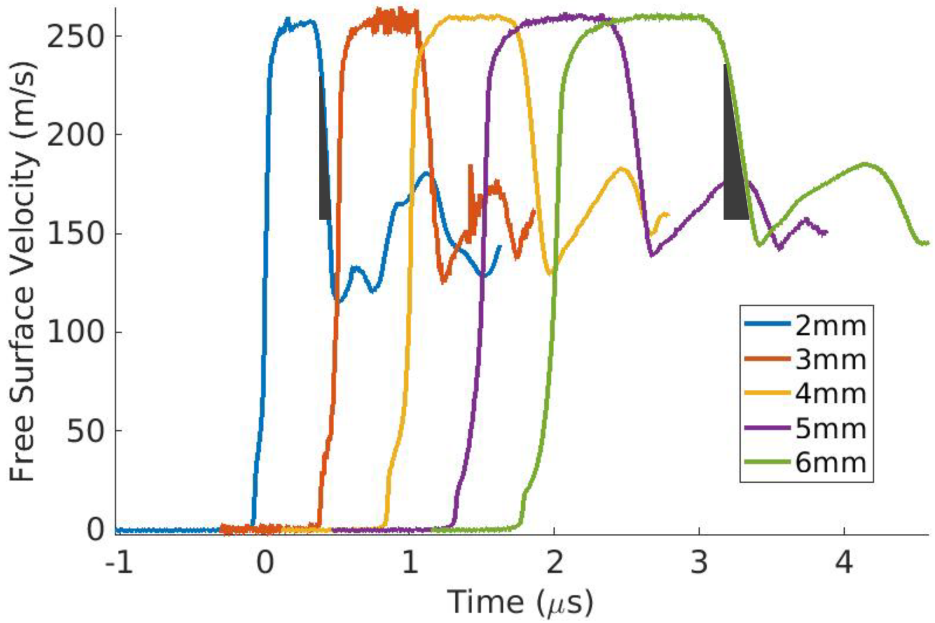

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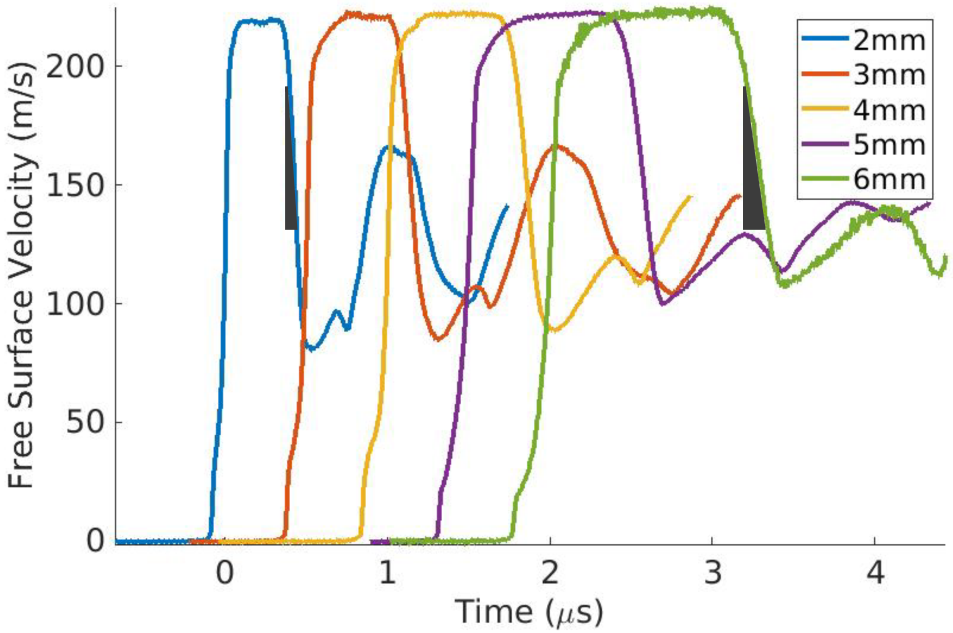
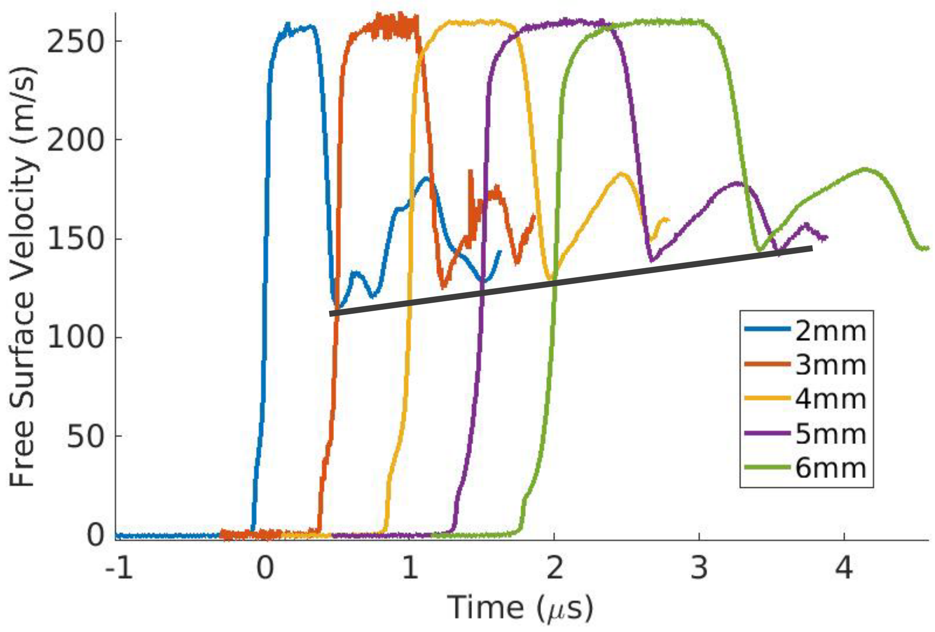


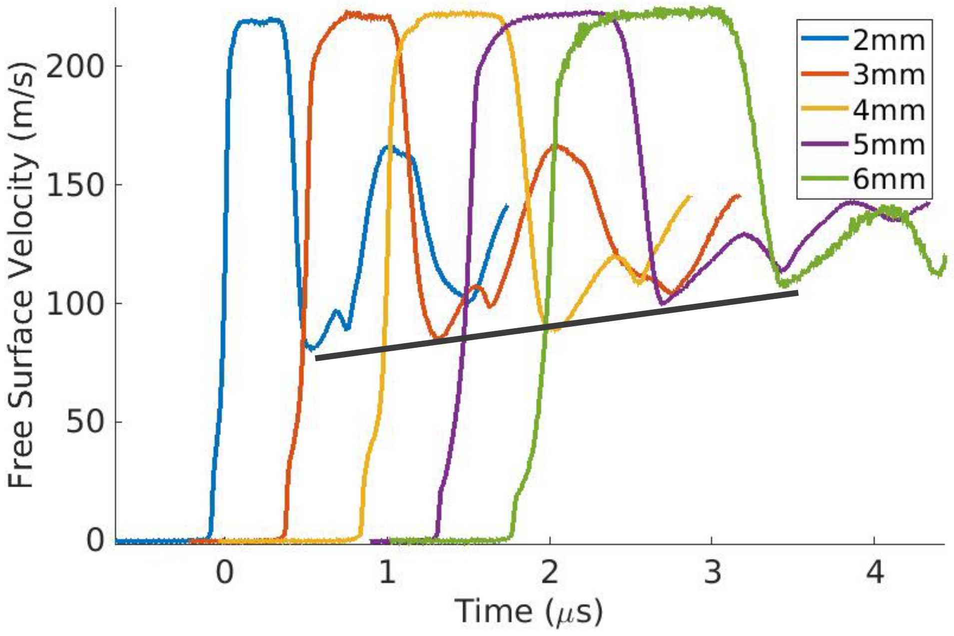
PDV traces artificially shifted in time for clarity

Change in slope on release indicates change in tensile strain-rate

Experiments Show a Clear Strain-Rate Dependence on Spallation Strength

- Experiment 1
  - Impact velocity of 243 m/s
- Experiment 2
  - Impact velocity of 208 m/s





PDV traces artificially shifted in time for clarity

Decrease in velocity pull-back indicates decrease in spallation strength

Experiments Show a Clear Strain-Rate Dependence on Spallation Strength

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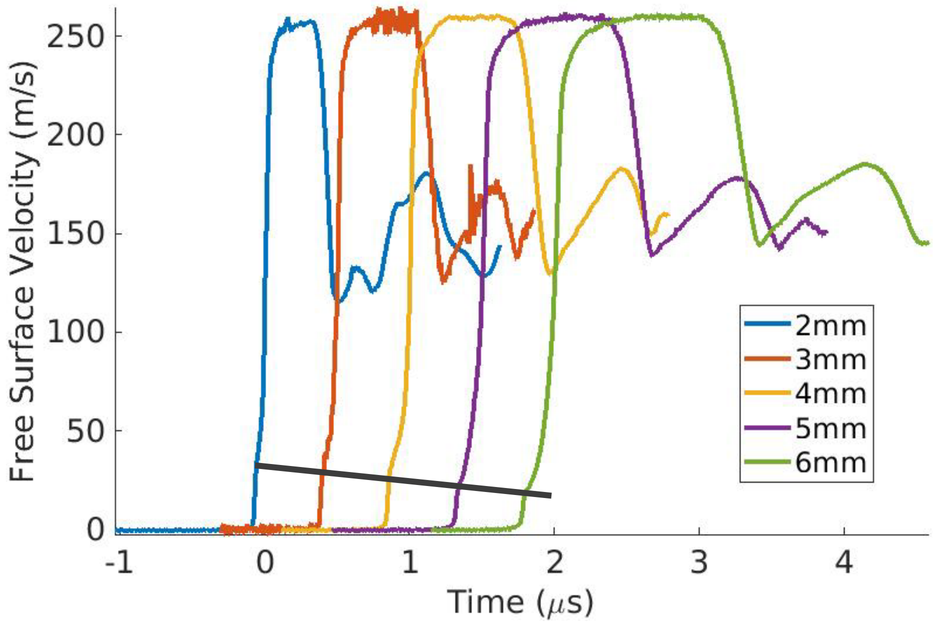

- Experiment 2
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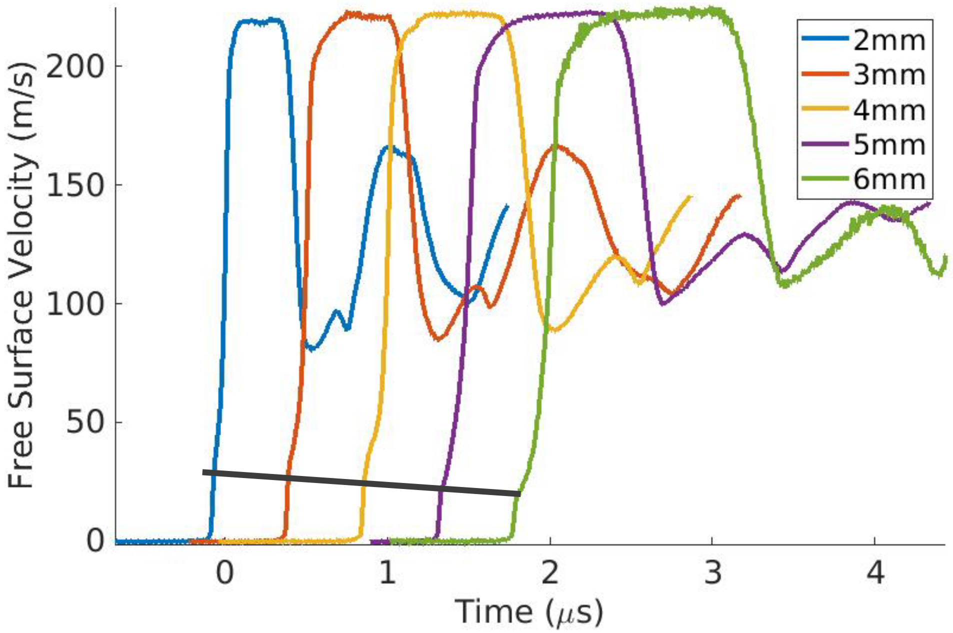


PDV traces artificially shifted in time for clarity

Experiment also probes elastic precursor decay

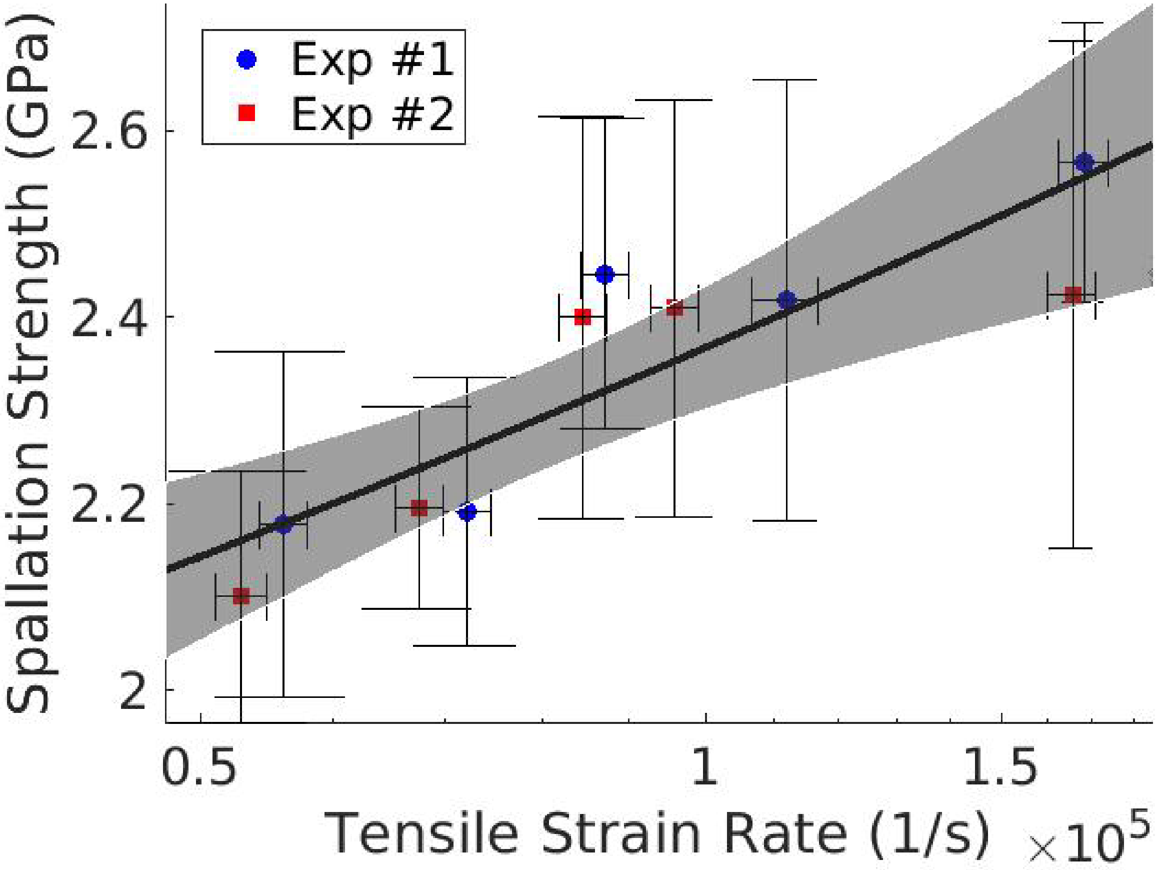
Experiments Show a Clear Strain-Rate Dependence on Spallation Strength

- Using the pull back signals we can determine the dependence of spallation strength on tensile strain rate
  - Used Kanel's 2001 correction to account for elastic-plastic effects

$$\sigma_{sp} = {}^{1}/_{2}\, \rho_0 C_b \left(\Delta u_{fs} + \delta\right)$$

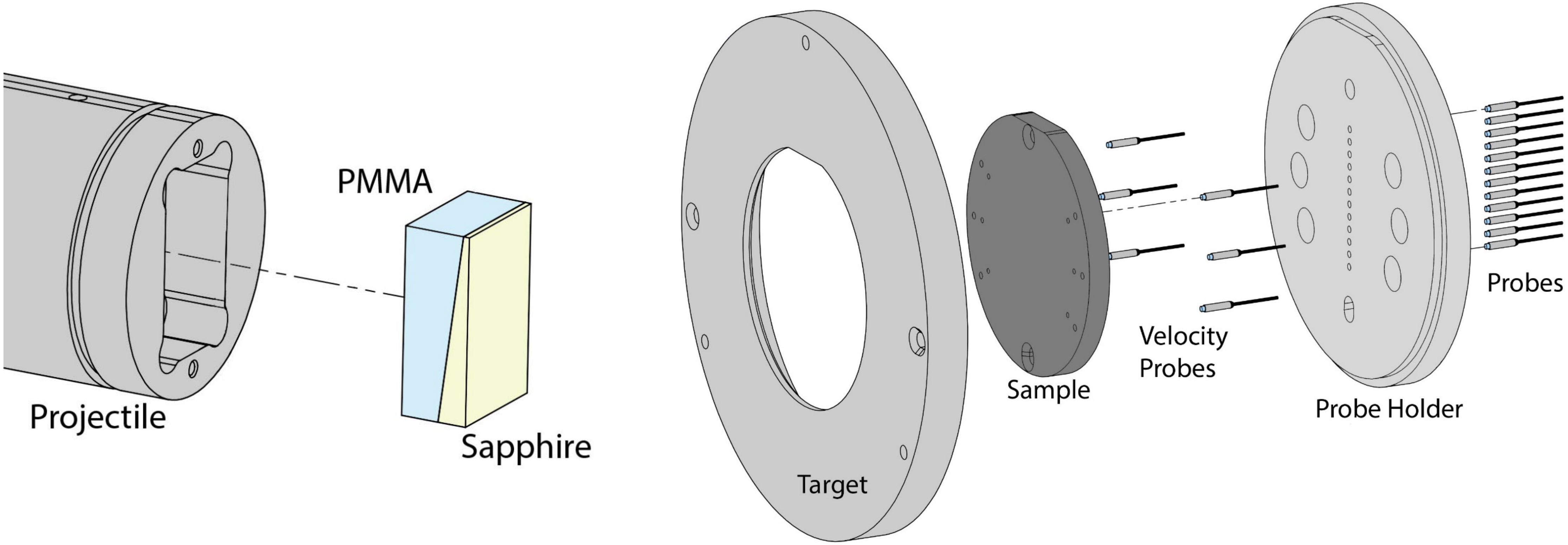
$$\delta = \left(\frac{h_s}{C_b} - \frac{h_s}{C_F}\right)|\dot{u}_1|$$

$$C_F = C_B C_l \sqrt{\frac{\dot{\sigma}_x^+ - \dot{\sigma}_x^-}{\dot{\sigma}_x^+ c_l^2 - \dot{\sigma}_x^- c_b^2}}$$



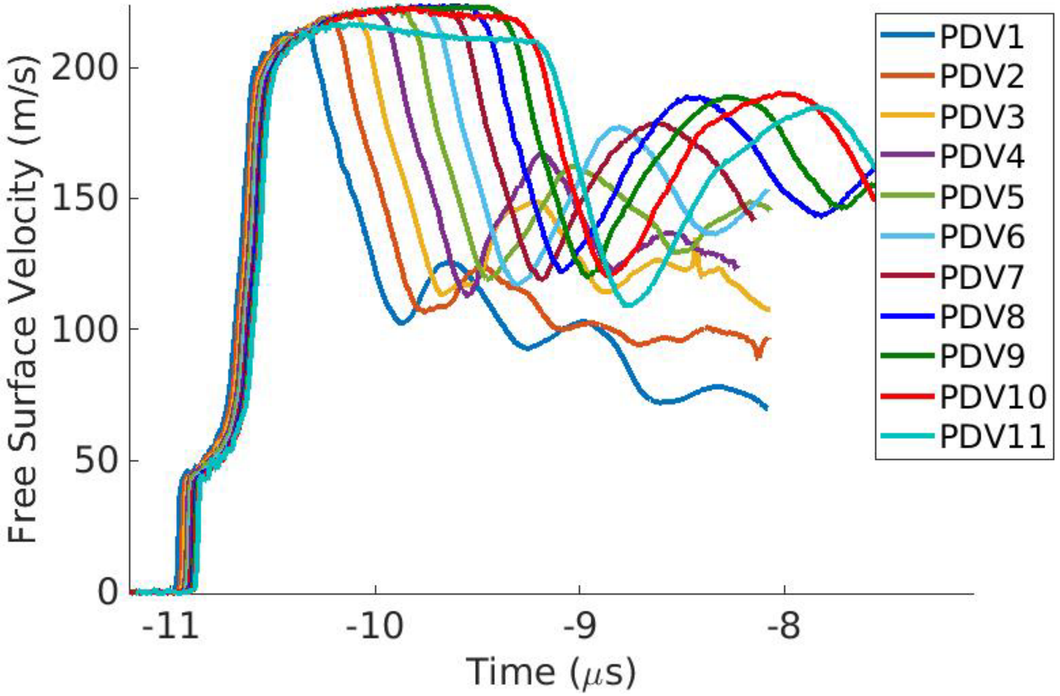
Performed Wedge Experiments to Continuously Vary the Tensile Strain-Rate and/or Pulse Duration

- Designed a target with an 8 mm thick wrought 304L stainless steel sample
- Impact is by a sapphire wedge backed by PMMA
  - Changes duration along slope but not strain-rate
  - 12 velocimetry probes along the slope of the wedge
- Inherently 2 dimensional

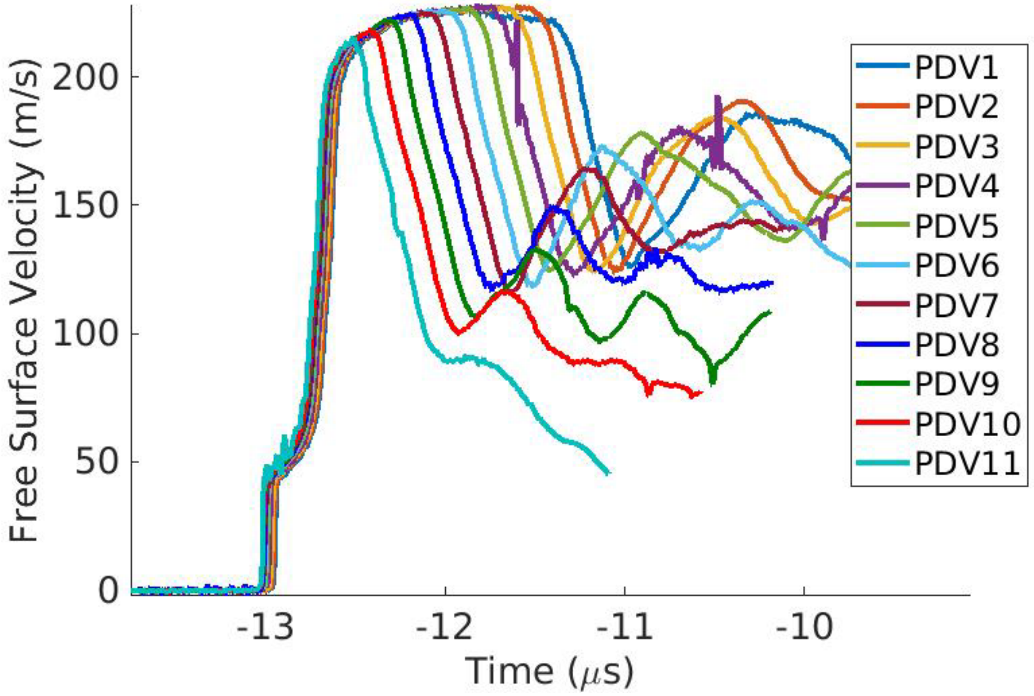


No Evidence of a Dependence of Spall Strength on Tensile Pulse Duration was Observed in 304L Stainless Steel

- Experiment 3
  - Impact velocity of 213 m/s



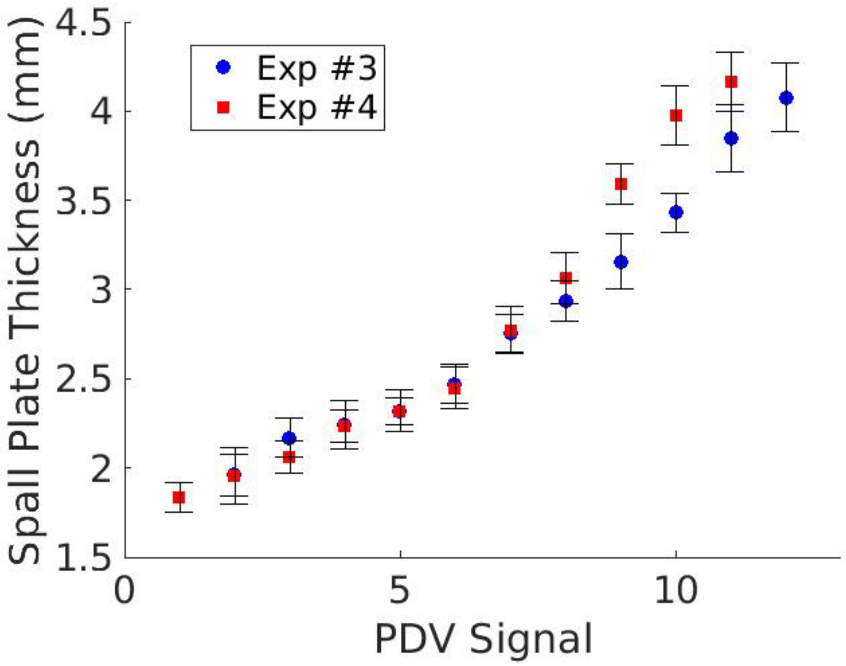
- Experiment 4
  - Impact velocity of 217 m/s

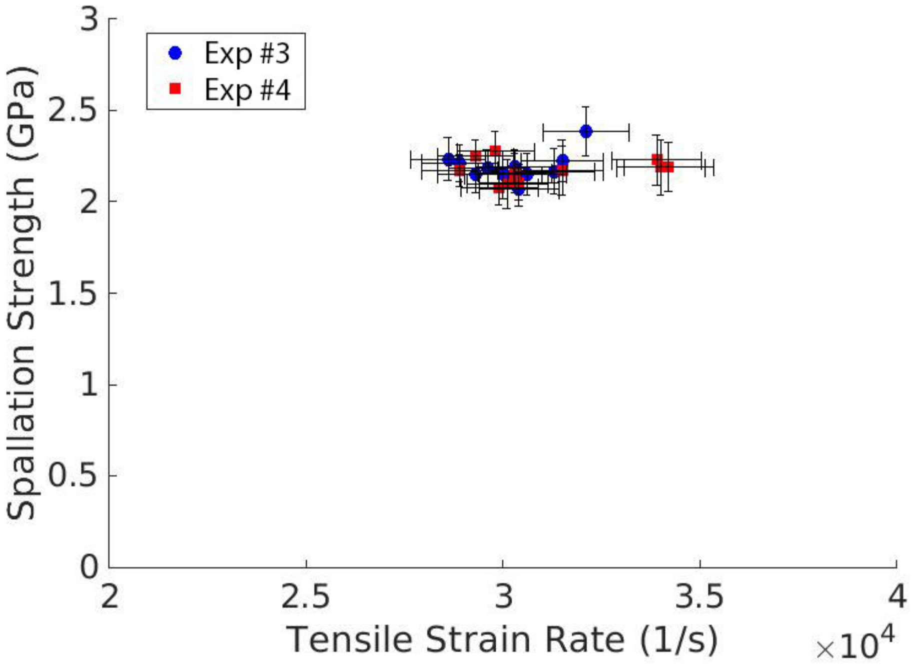


Edge effects occur at the edges of the measurement array

No Evidence of a Dependence of Spall Strength on Tensile Pulse Duration was Observed in 304L Stainless Steel

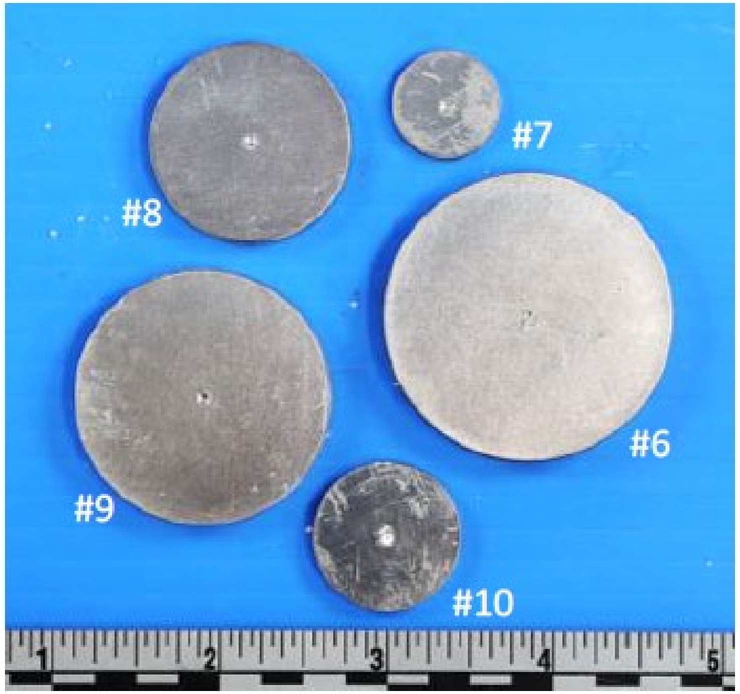
- Wedge Impactor moves the spall plane continuously in the sample
  - Changes the duration of tensile pulse
- Using the sapphire impactor keeps the strain-rate relatively constant
  - No change in measured spall strength



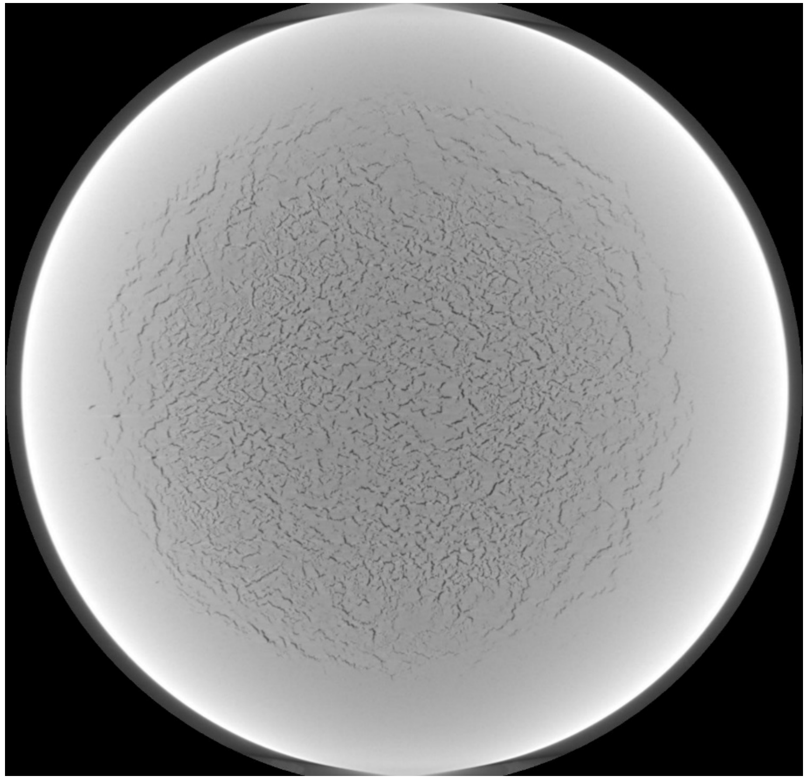


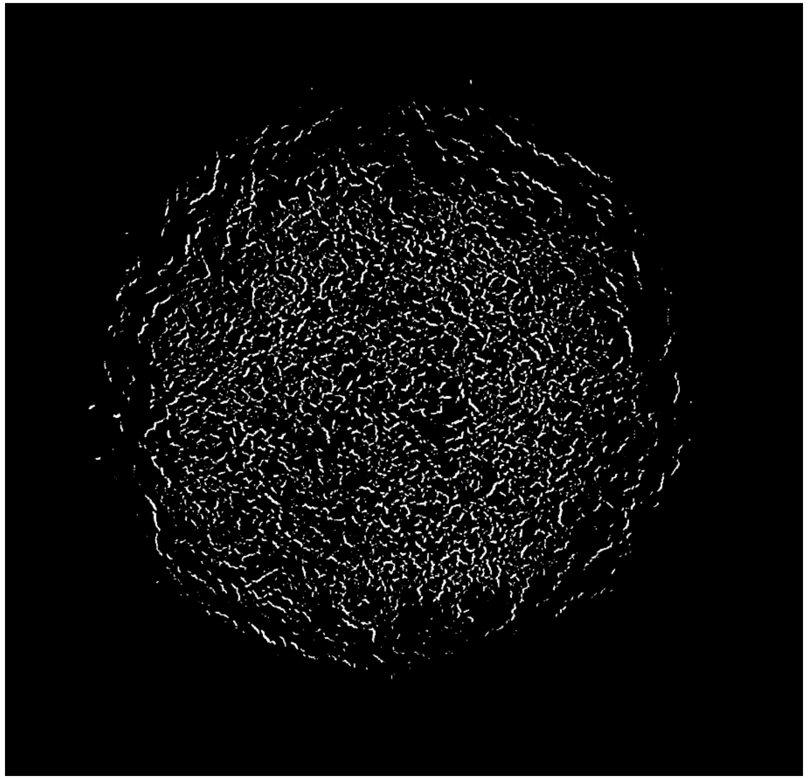
Void Structure in the Recovered Samples Characterized with Micro-CT

- Micro-CT images are processed using machine learning to identify the voids
  - Produces binary images of the void structure



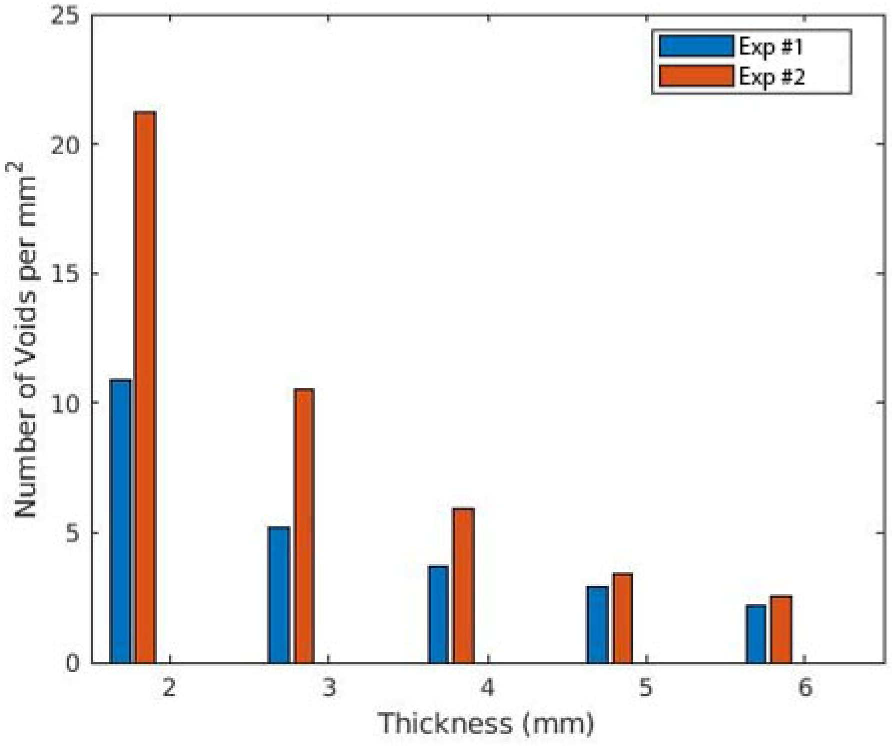
Recovered samples from Exp #3

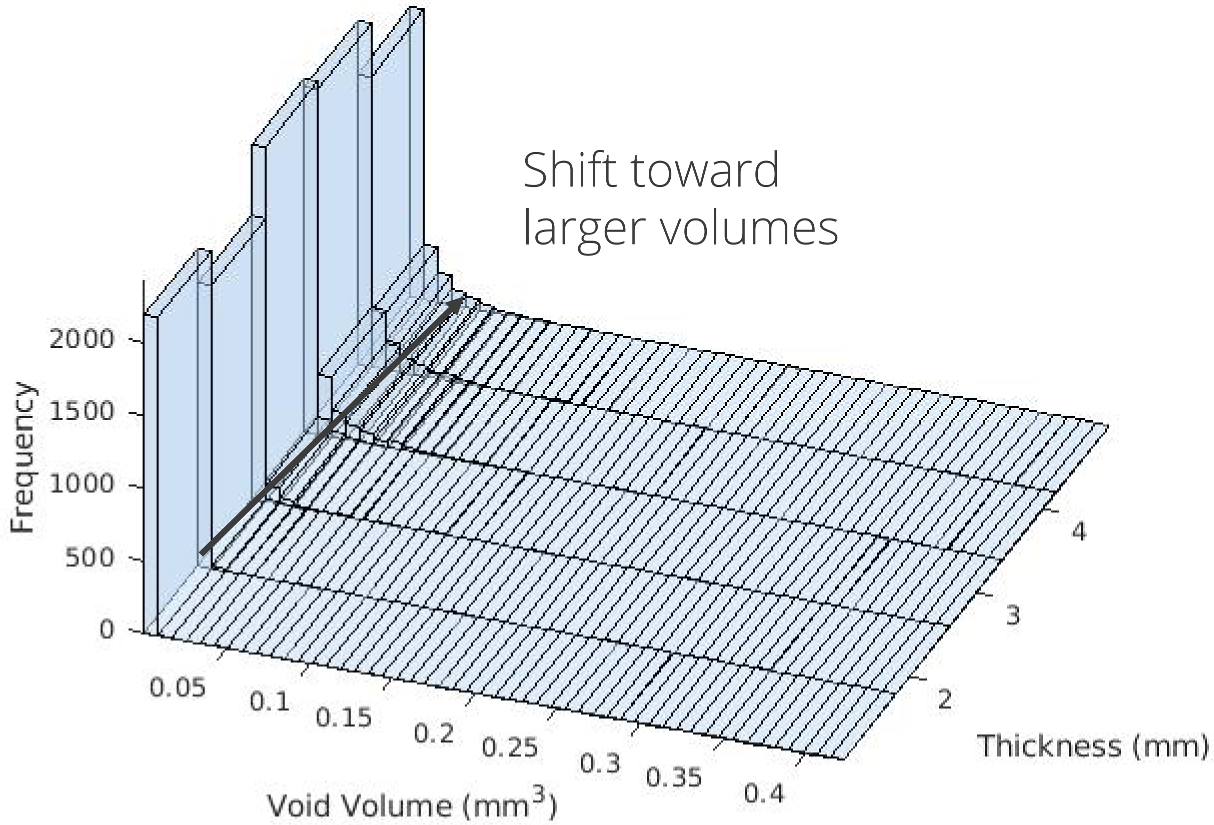

Micro-CT images from 6 mm thick sample on Exp #3


Binary image of voids obtained with machine learning

Post Processing the CT Images To Probe the Evolution of Void Growth

- Post process the images with a custom MATLAB routine to get information on void volume, aspect ratios, surface area, etc.



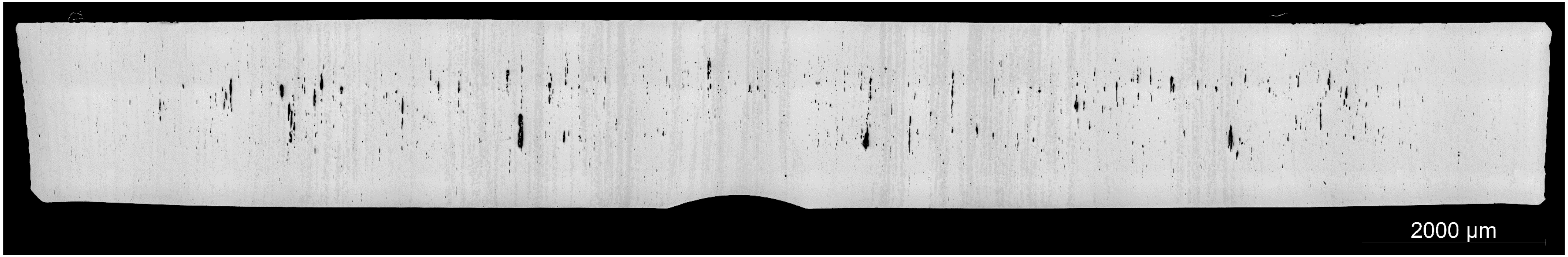


Shift toward larger volumes

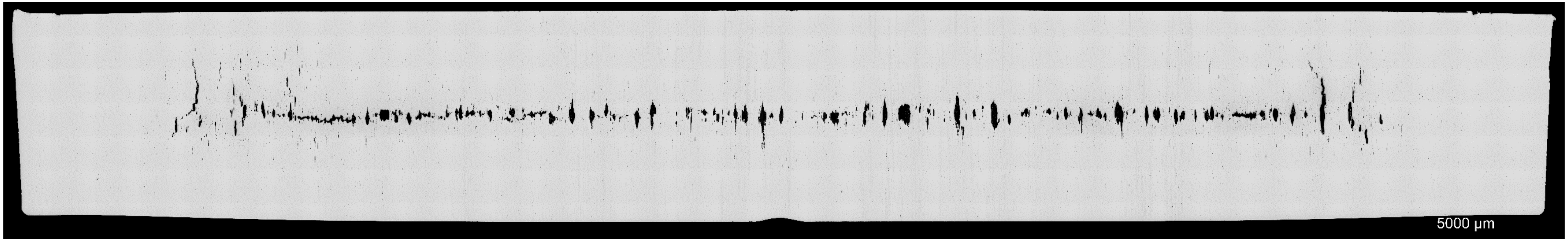
Histograms of void volume for Exp #3

Using Post Mortem Optical and Electron Microscopy to Further Understand the Nucleation of Voids

- See large ferrite stringer form in this 304L stainless steel
- The nature of the spall plane changes with strain-rate
- Evidence of void formation at these ferrite stringers



Exp #1 2mm thick Sample



Exp #1 6mm thick Sample

Using Post Mortem Optical and Electron Microscopy to Further Understand the Nucleation of Voids

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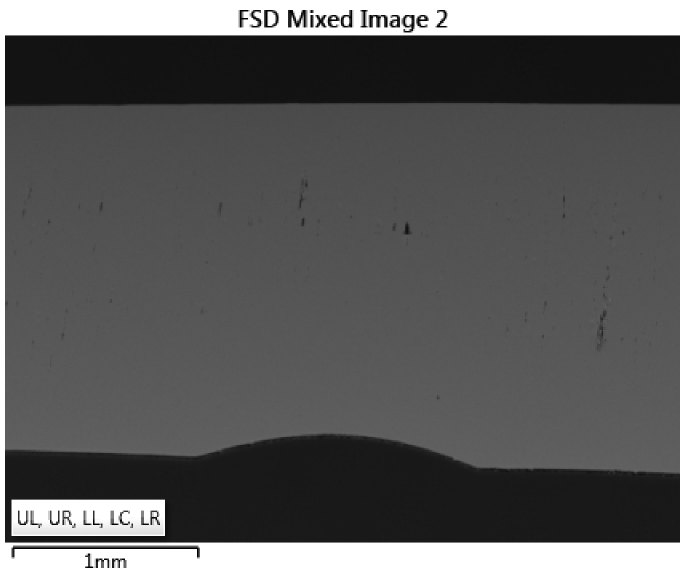
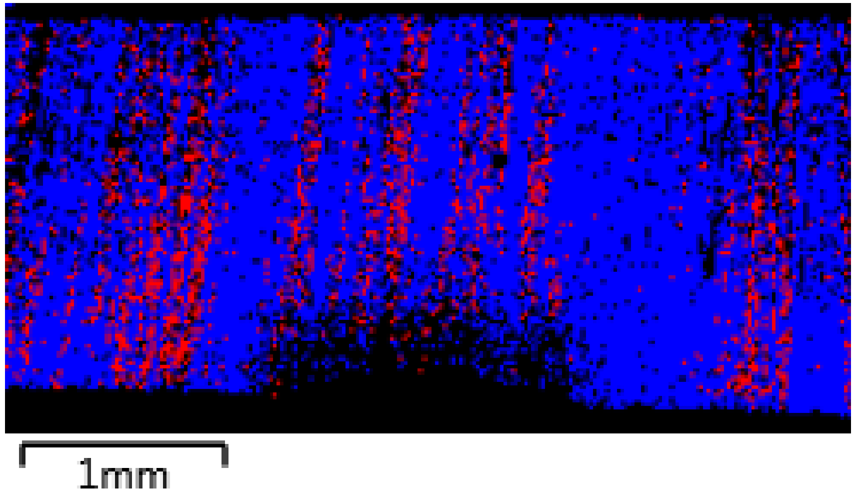
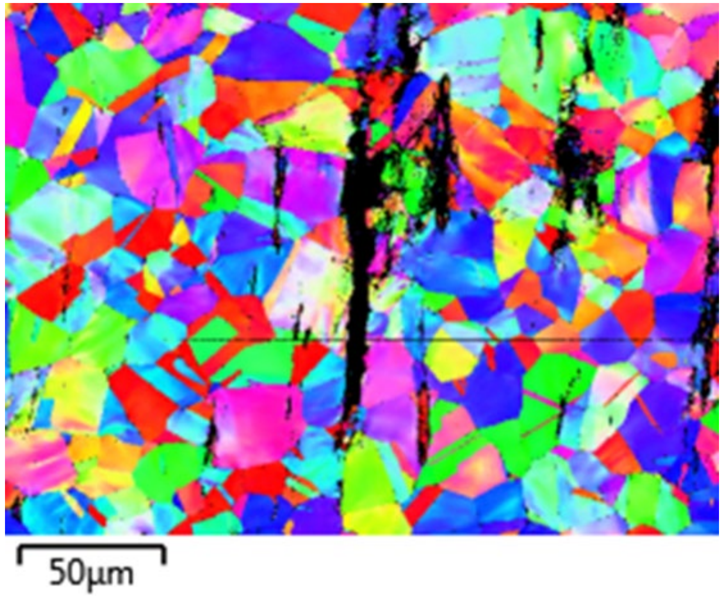


SEM Image



Phase Map
Blue-FCC
Red- BCC



Inverse pole figure (IPF) map near void

Conclusions and Future Work

- Employed an experimental platform to study the dependence of the spallation strength on tensile strain rate and/or pulse duration
  - Multi-sample experiment with 5 different tensile strain rates
  - Wedge experiment that continuously varies the state along the sample.
- Preliminary experiments on 304L stainless steel show a strong dependence on tensile strain rate but no dependence on tensile pulse duration
- Post mortem microscopy and micro-CT are being collected to help further understand the nucleation and growth of voids
  - Still a work in progress

- Future efforts will apply this technique to additively manufactured (AM) 304L stainless steel and AlSi10Mg alloys