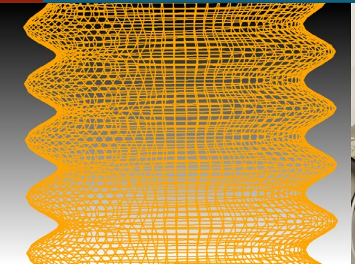
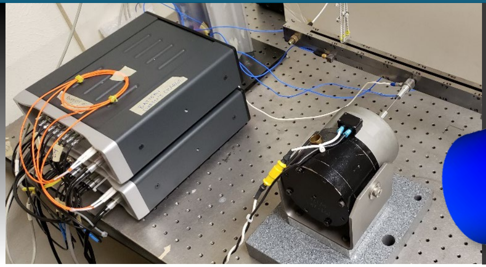
N-O-MAD Research Institute

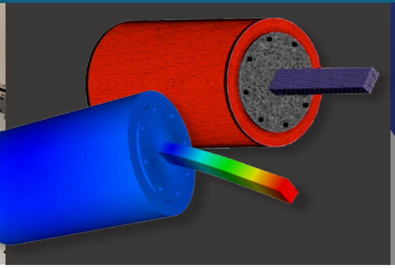
Sandia National Laboratories

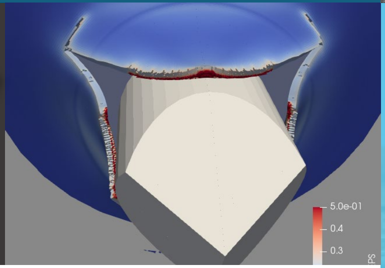
THE UNIVERSITY OF NEW MEXICO

Empirical Model of Puncture Energy for Metals









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NNSA National Nuclear Security Administration

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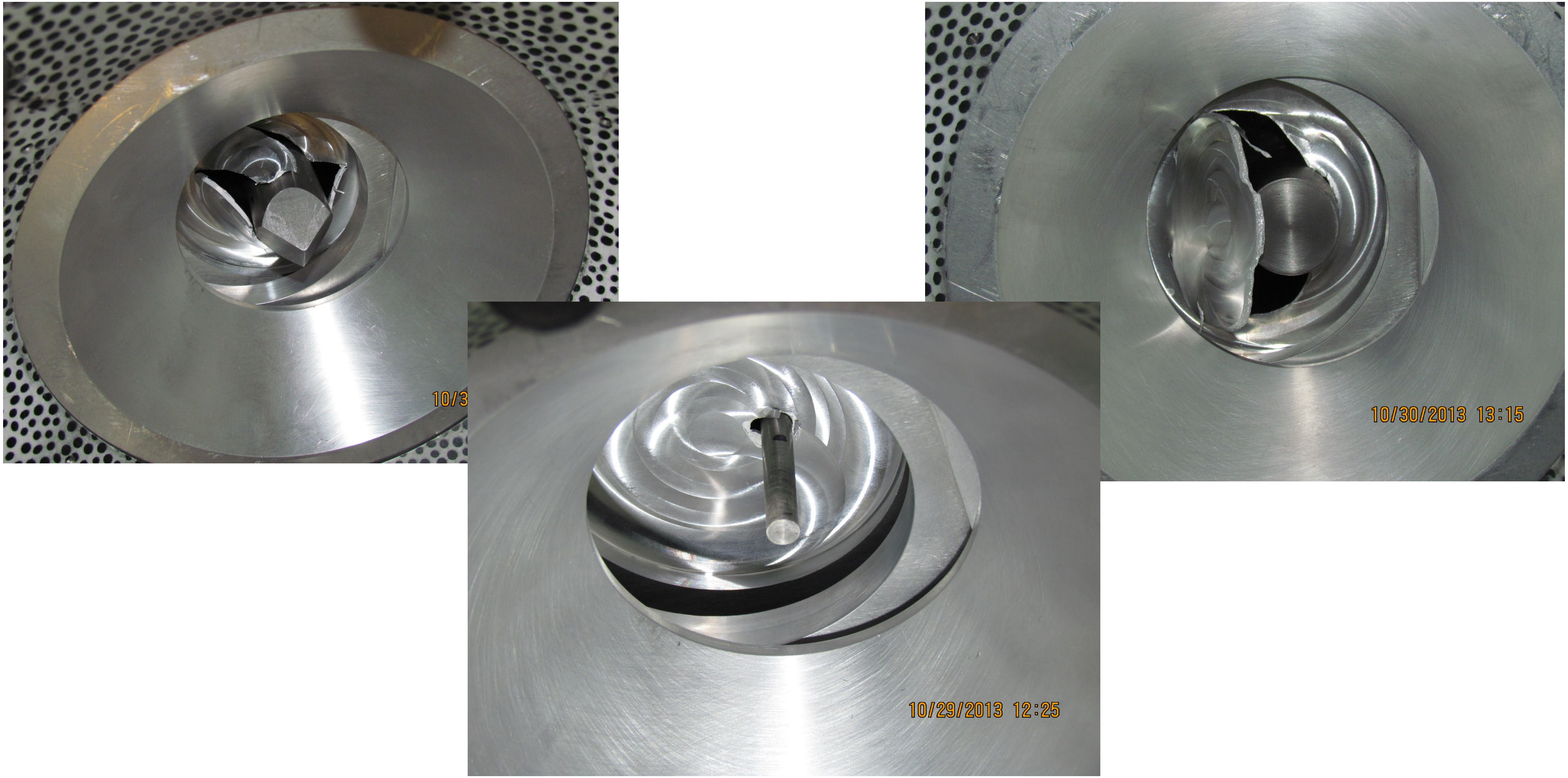
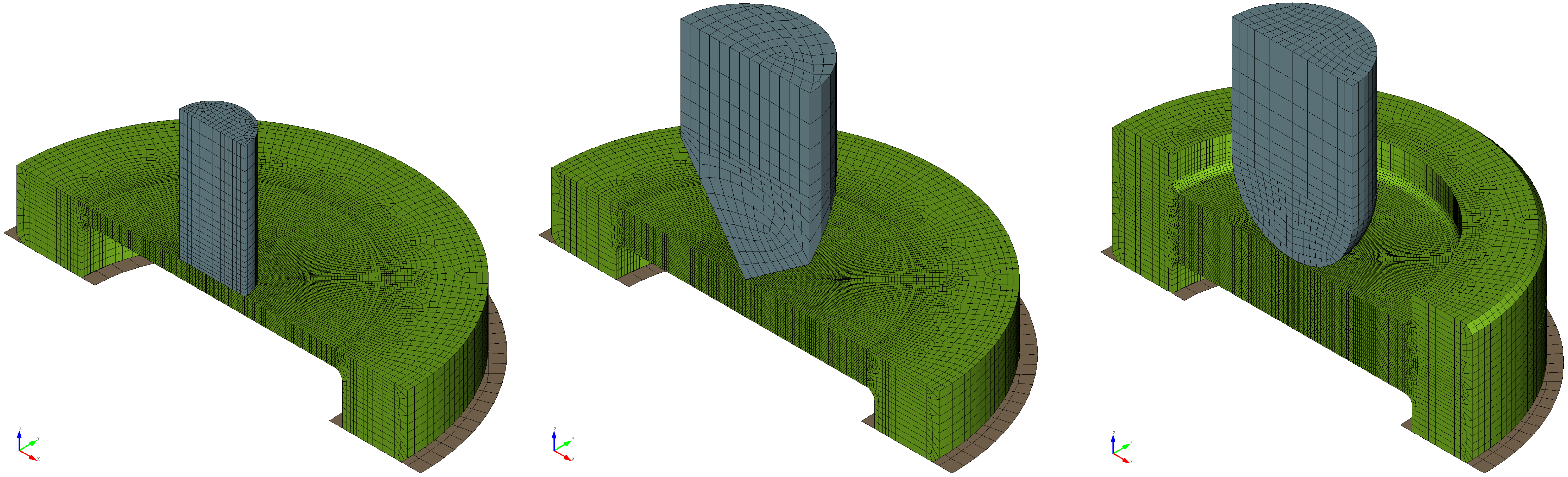
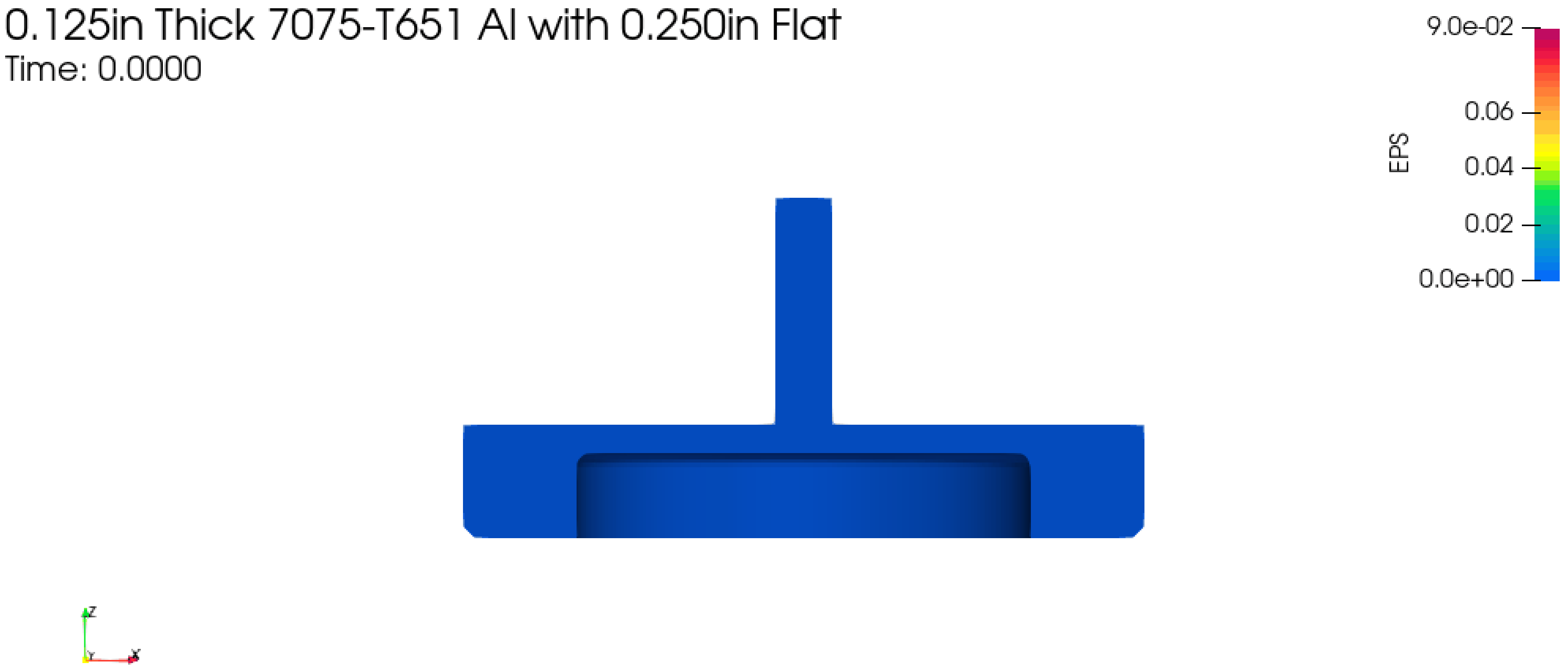
Motivation and Background



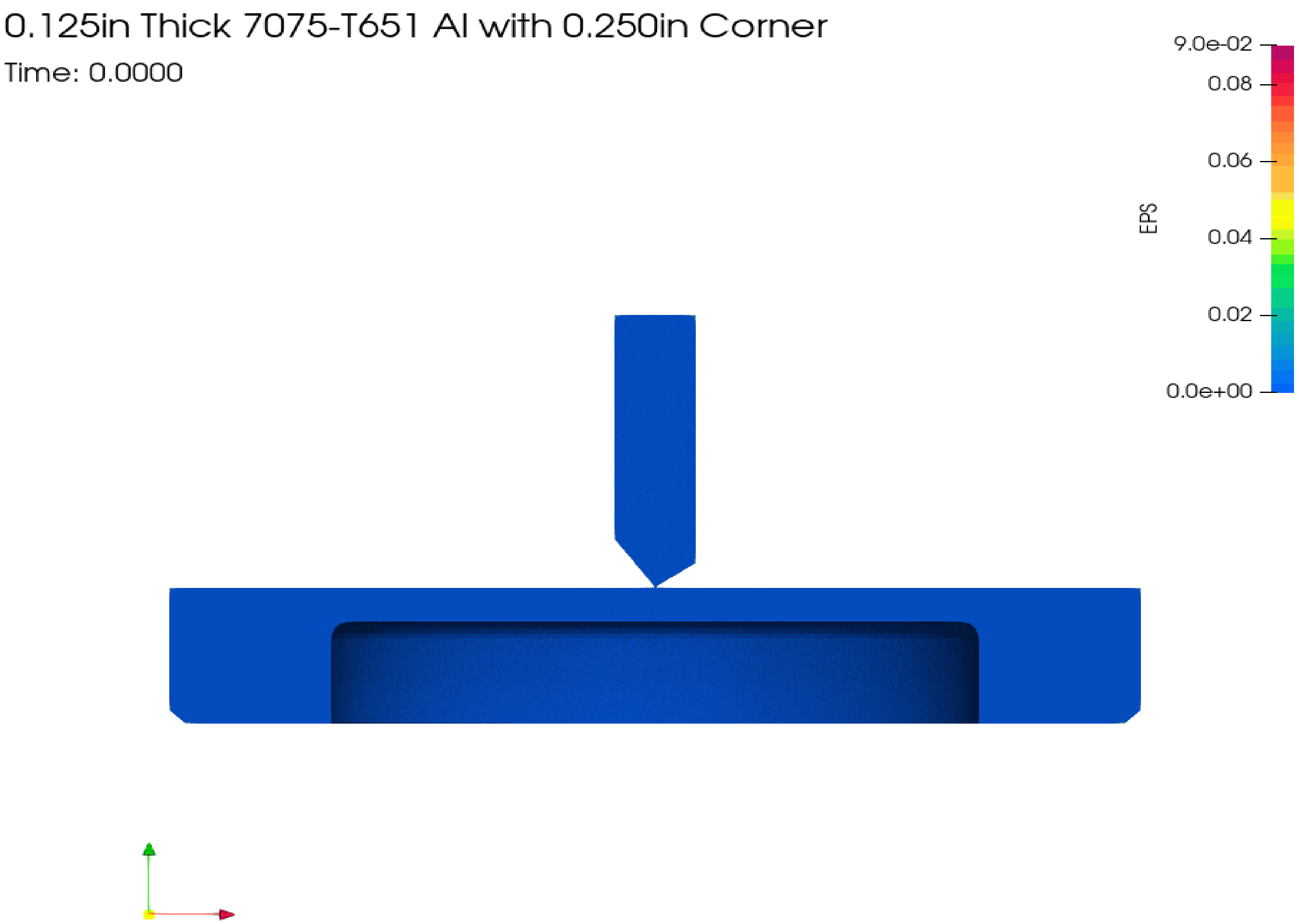
Multiple Probe Shapes and Coupon Thickness & Materials were Simulated



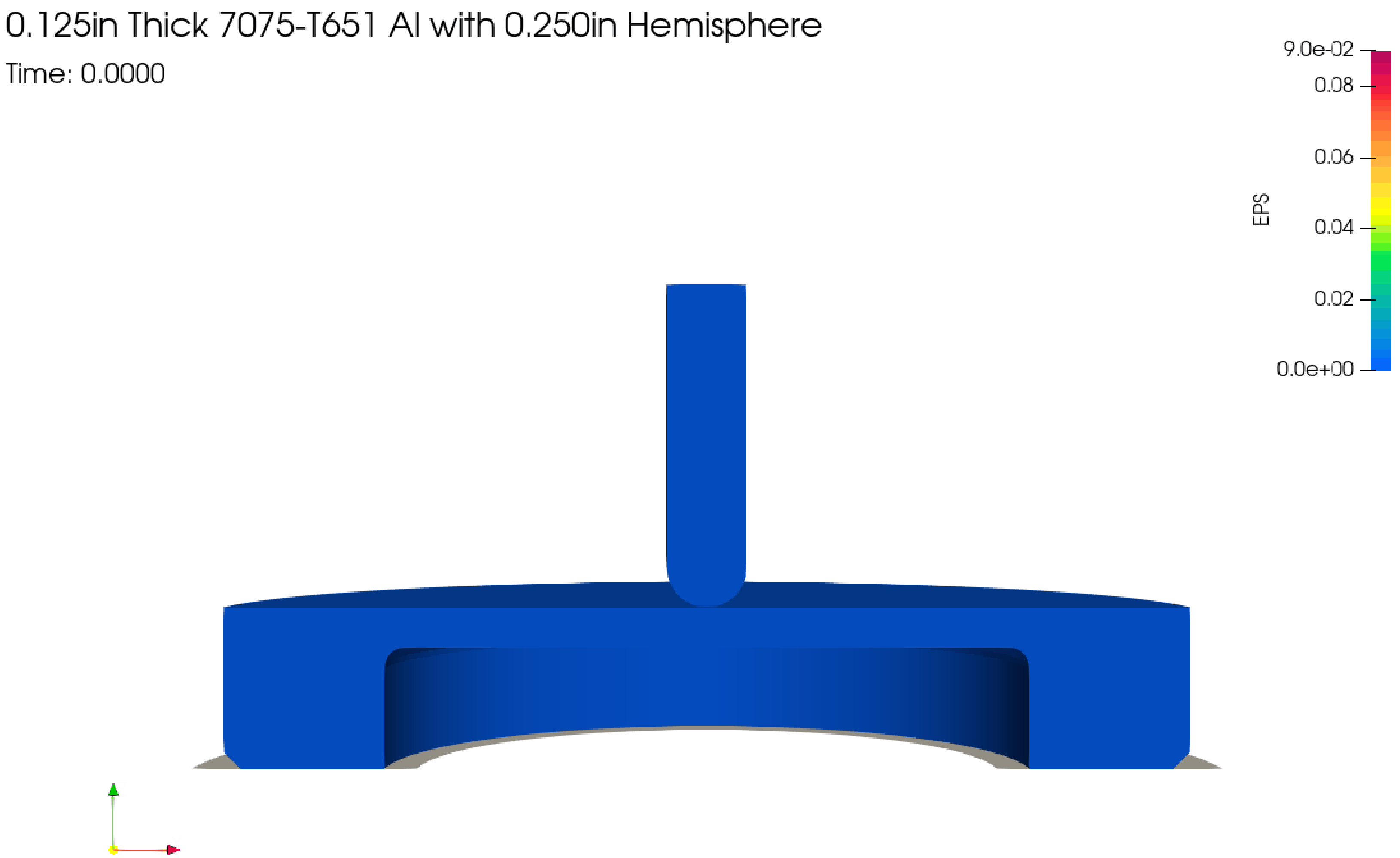
Flat : 0.25in Probe Through 0.125in 7075 Al



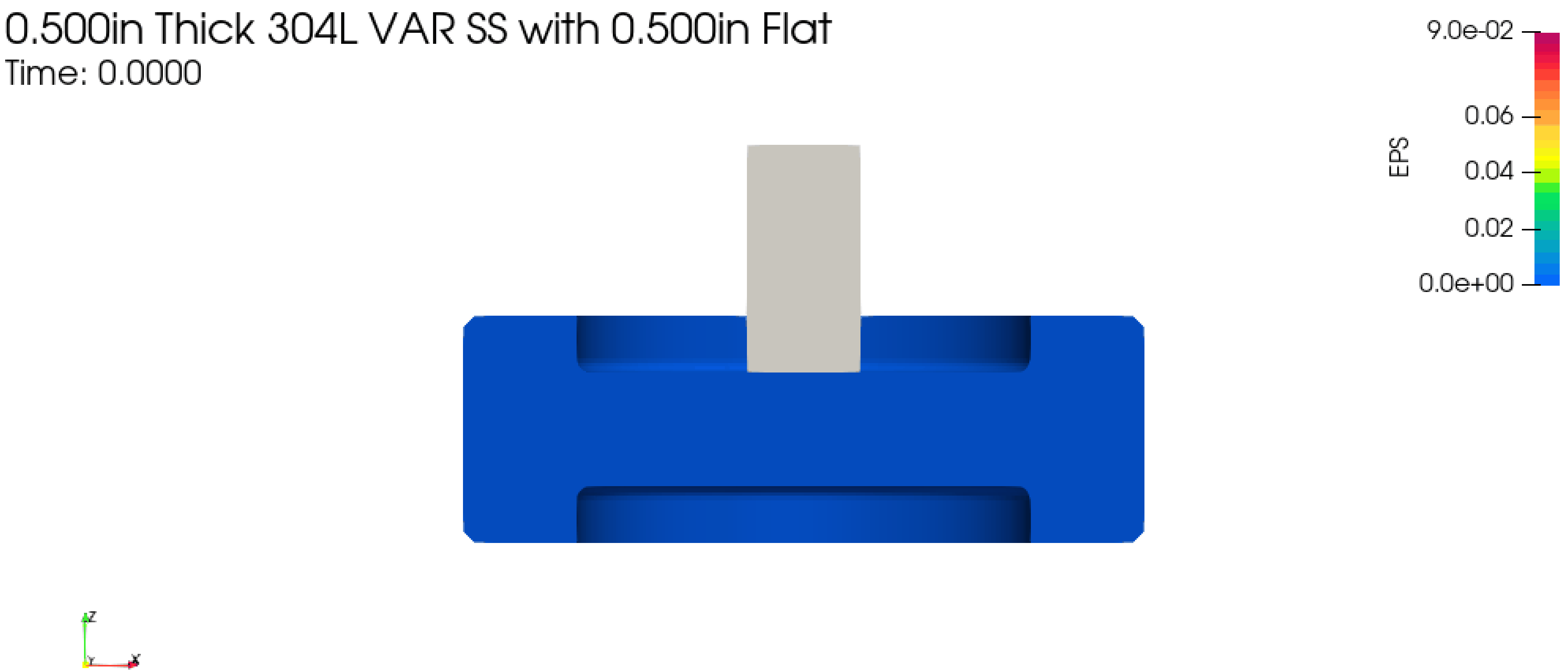
Corner : 0.25in Probe Through 0.125in 7075 Al



Hemisphere : 0.25in Probe Through 0.125in 7075 Al

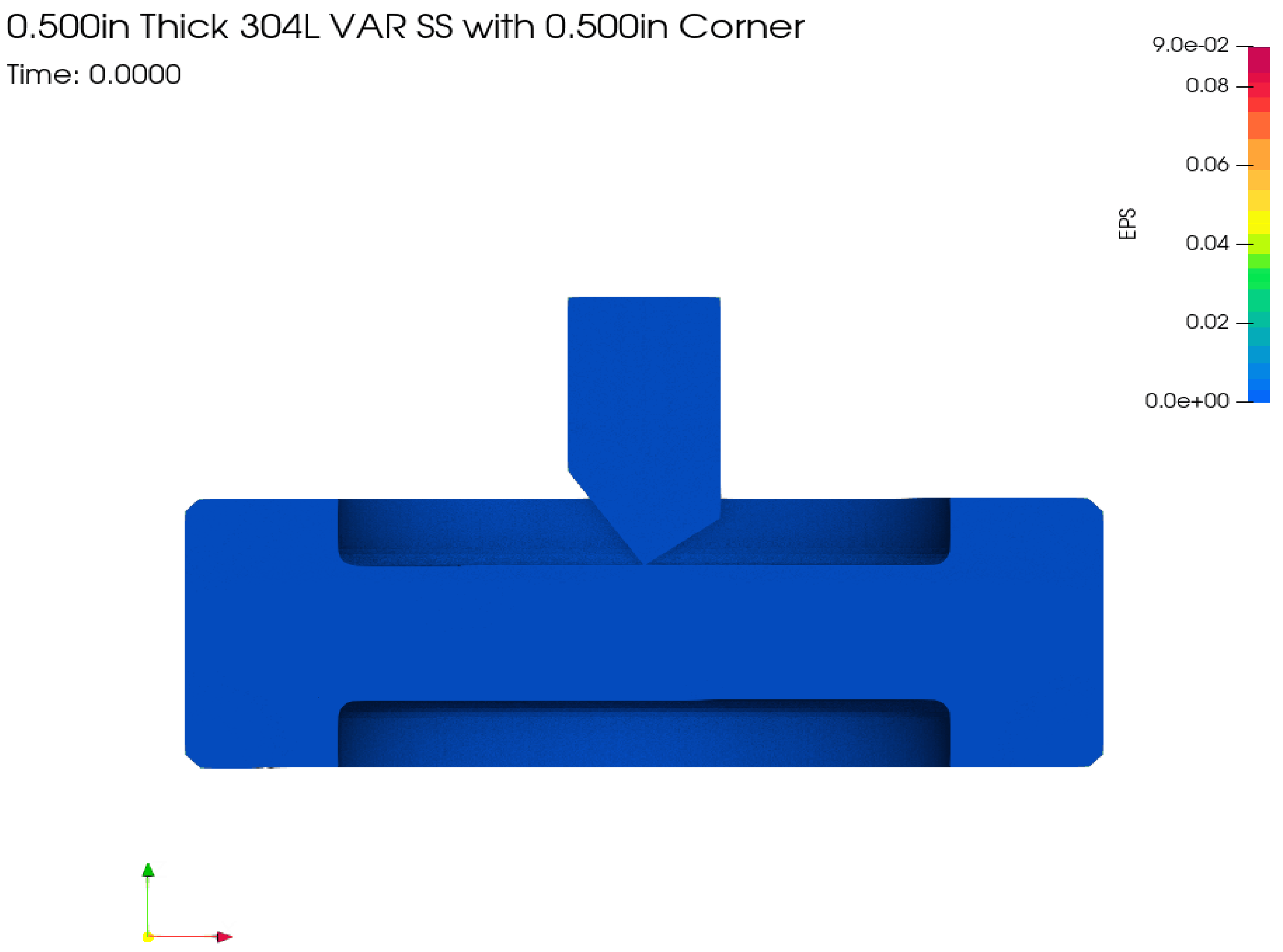


Flat : 0.50in Probe Through 0.50in 304L SS

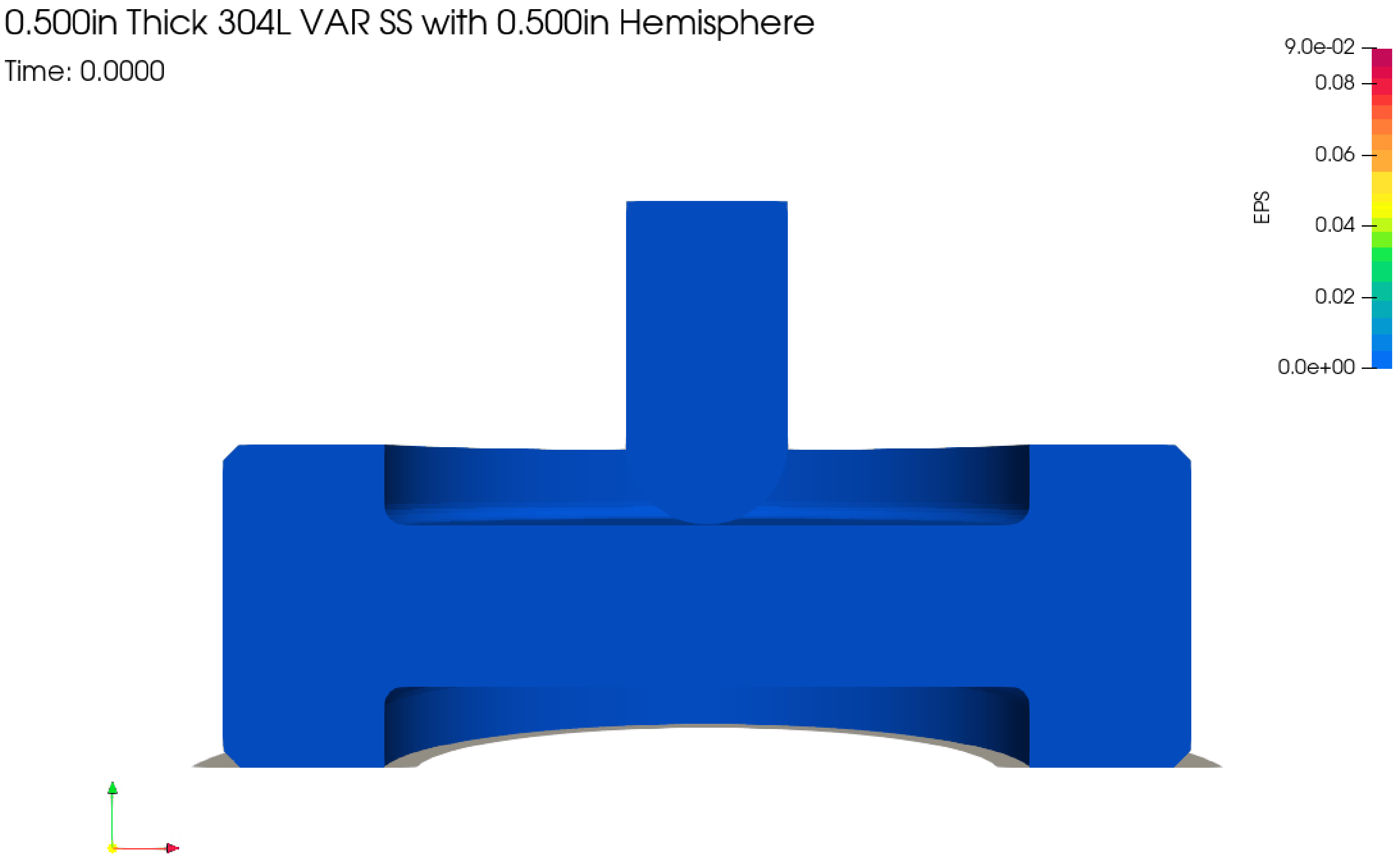


Note: The probe model was set to elastic and therefore does not show elastic plastic strain (EPS).

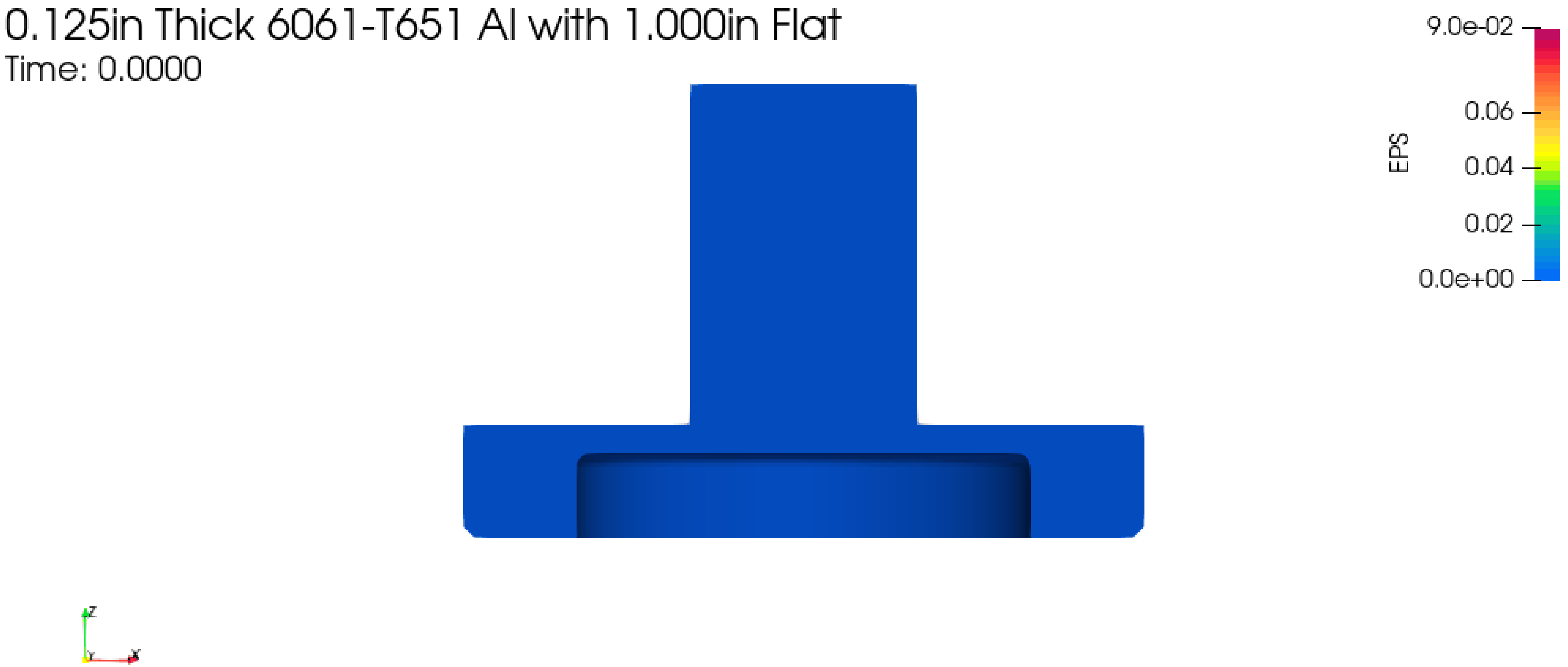
Corner : 0.50in Probe Through 0.50in 304L SS



Hemisphere : 0.50in Probe Through 0.50in 304L SS



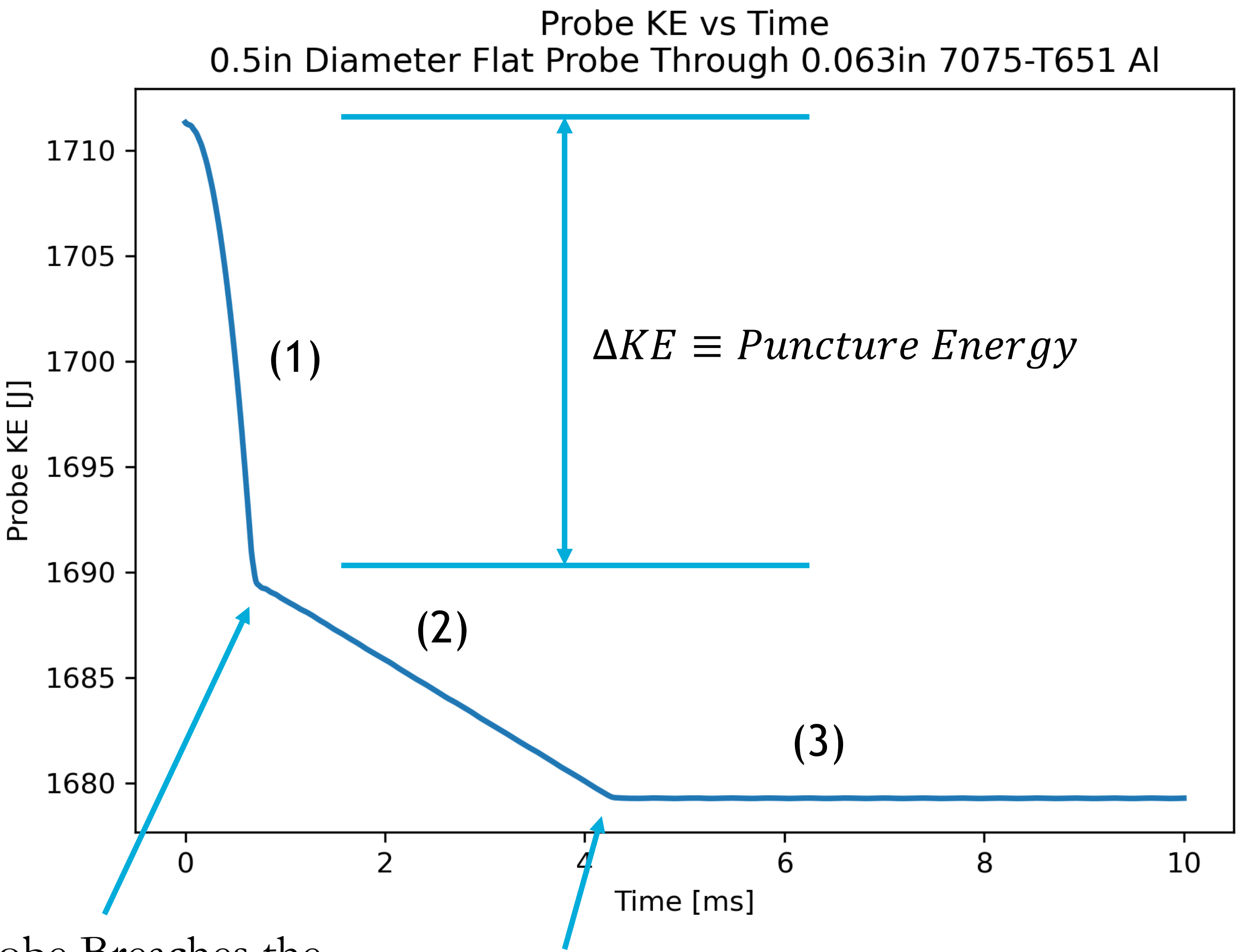
The 6061 Material Model Can Fail Easily



Probe Unique Aspects

- Flat : localizes stress at the circumference of the contact area
- Corner : acts like a wedge, cutting and spreading the coupon
- Hemispherical : the “smooth” probe shape induces the most plastic strain

Puncture Stages and Puncture Energy Determination



Probe Breaches the Coupon

Probe-Coupon Contact Ends

Stages of Puncture:

1. Probe contacts and deforms the coupon.
2. Probe scrapes the edge of the puncture hole.
3. Probe no longer in contact with the coupon.

Empirical Fit Equation by *Corona (2020)*

$$E = K\sigma_u \epsilon_f t^3 \left(\frac{d}{t}\right)^c$$

Puncture Energy [J]

Constant 1

Ultimate Engineering Stress [Pa]

Ultimate Engineering Strain at Failure

Coupon Thickness [m]

Probe Diameter [m]

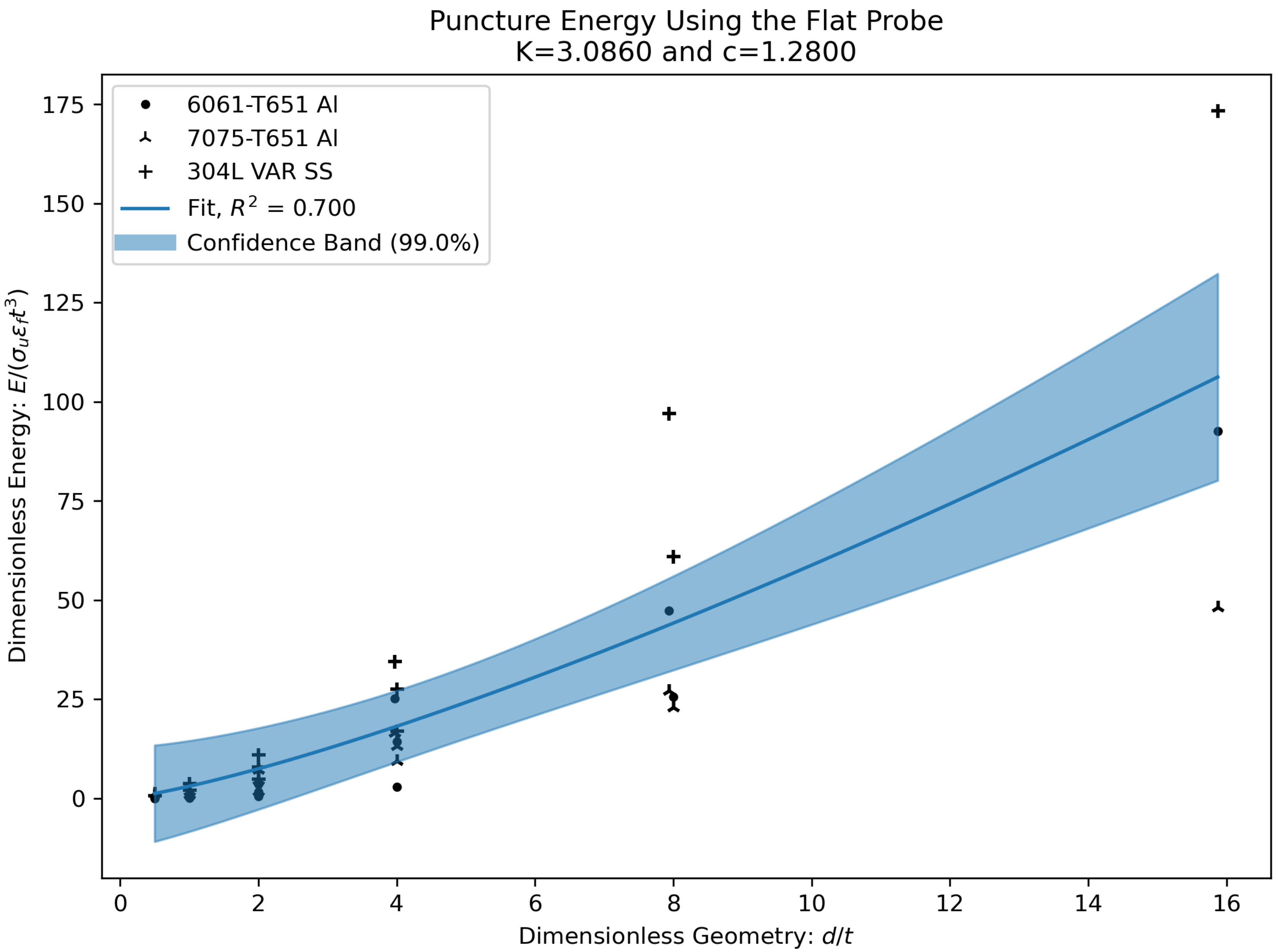
Constant 2

$$\rightarrow \frac{E}{\sigma_u \epsilon_f t^3} = K\left(\frac{d}{t}\right)^c$$

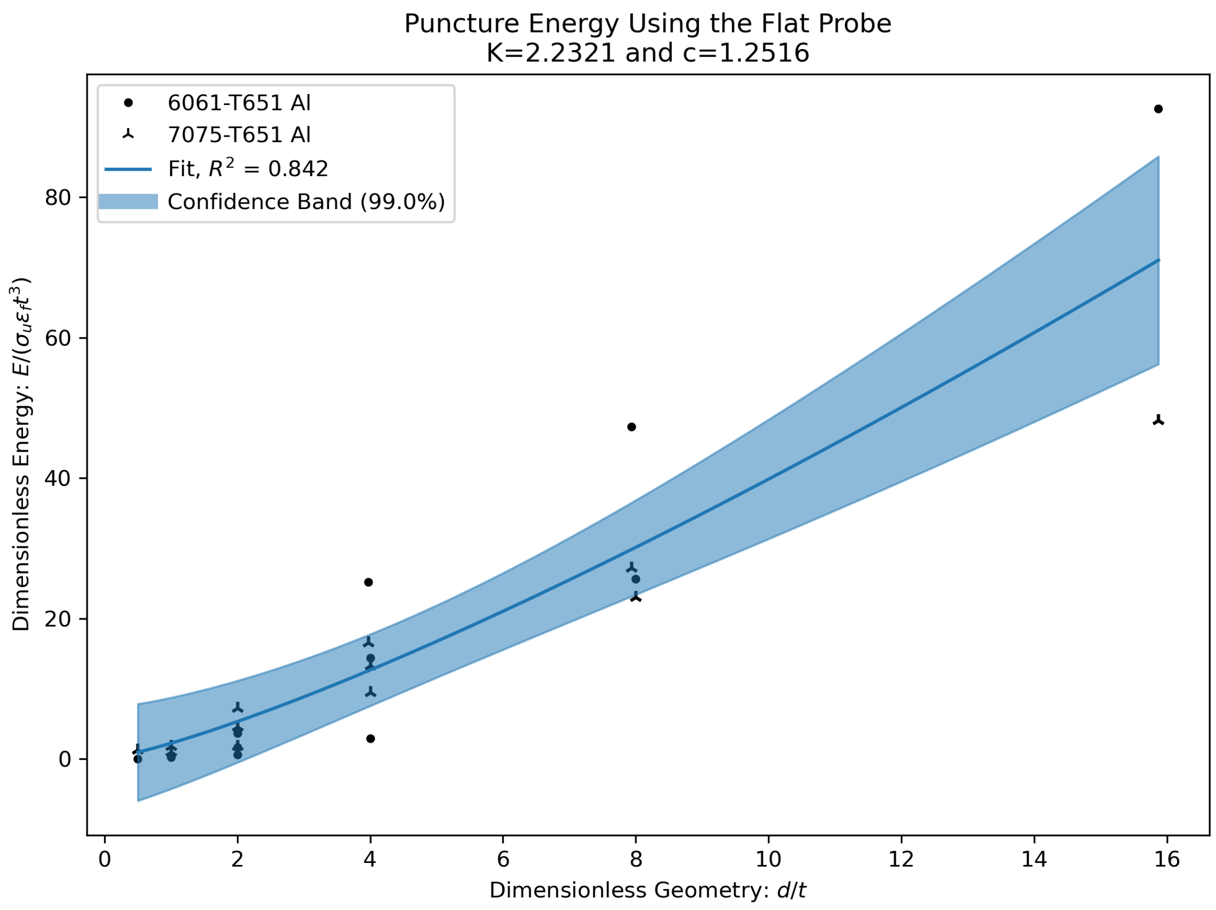
dimensionless energy = dimensionless geometry

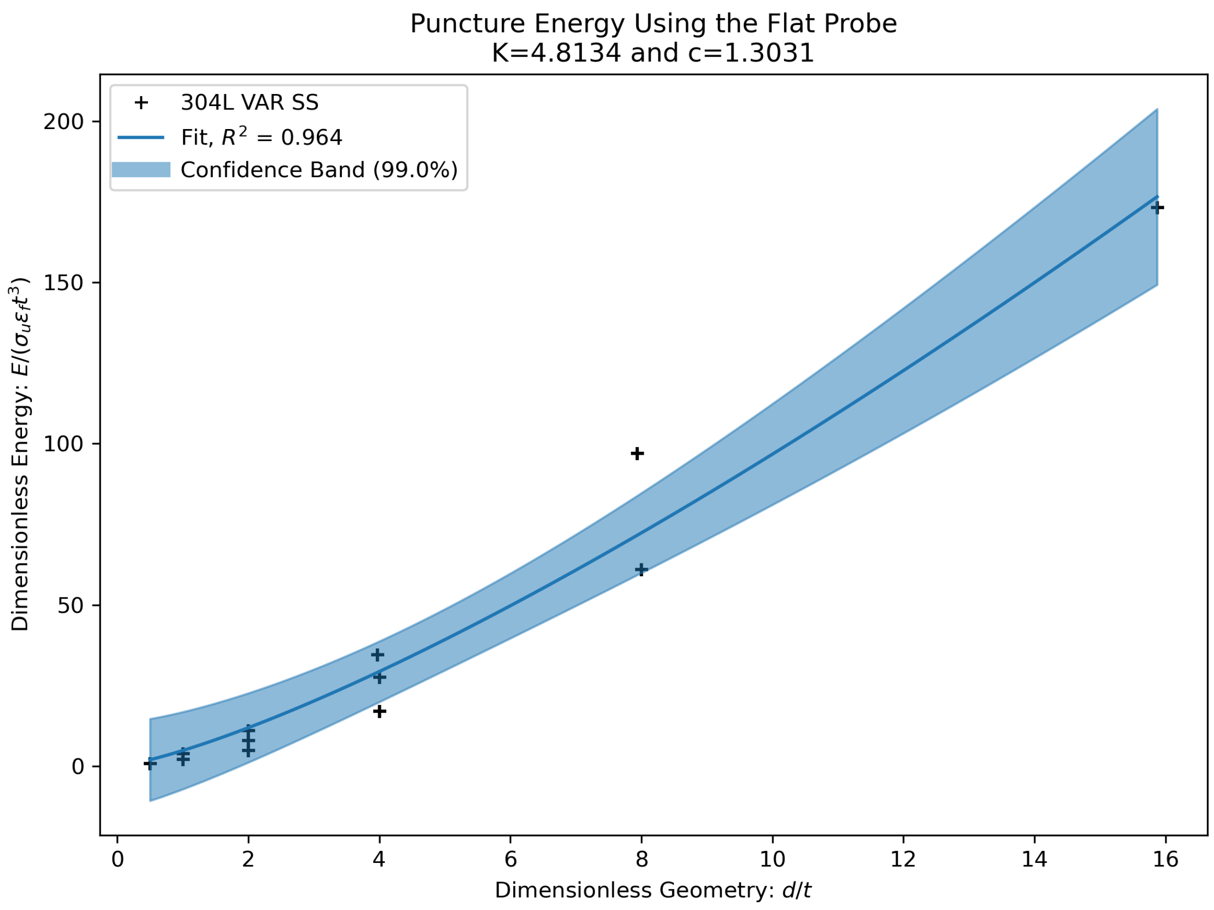
Corona, E., “Empirical Formula for Puncture Energy of Flat Metal Plates by a Cylindrical Flat Punch,” Sandia National Laboratories, 6 November 2020.

Flat Probe Fit Using All Materials

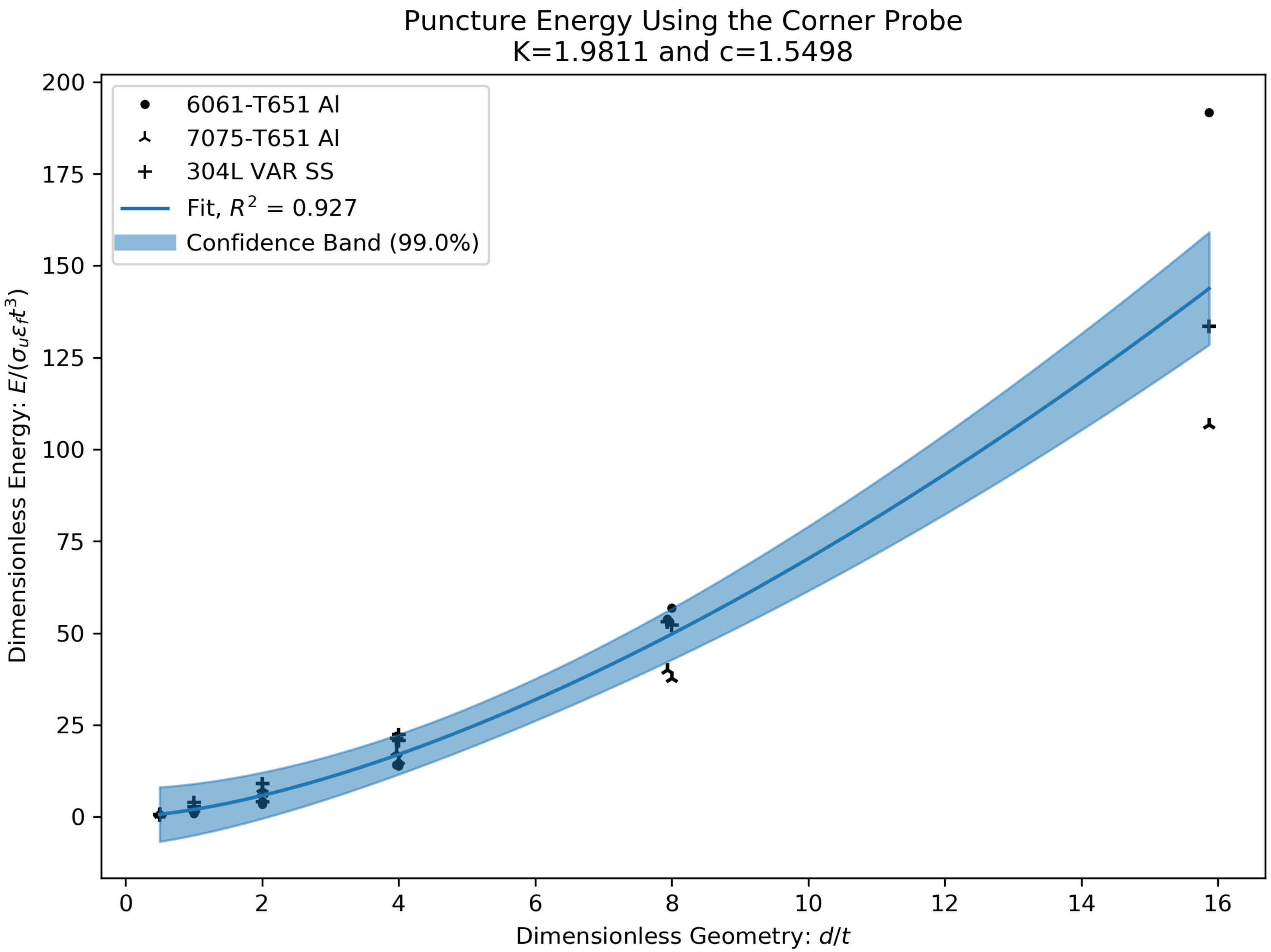


Flat Probe Fit Separating Materials

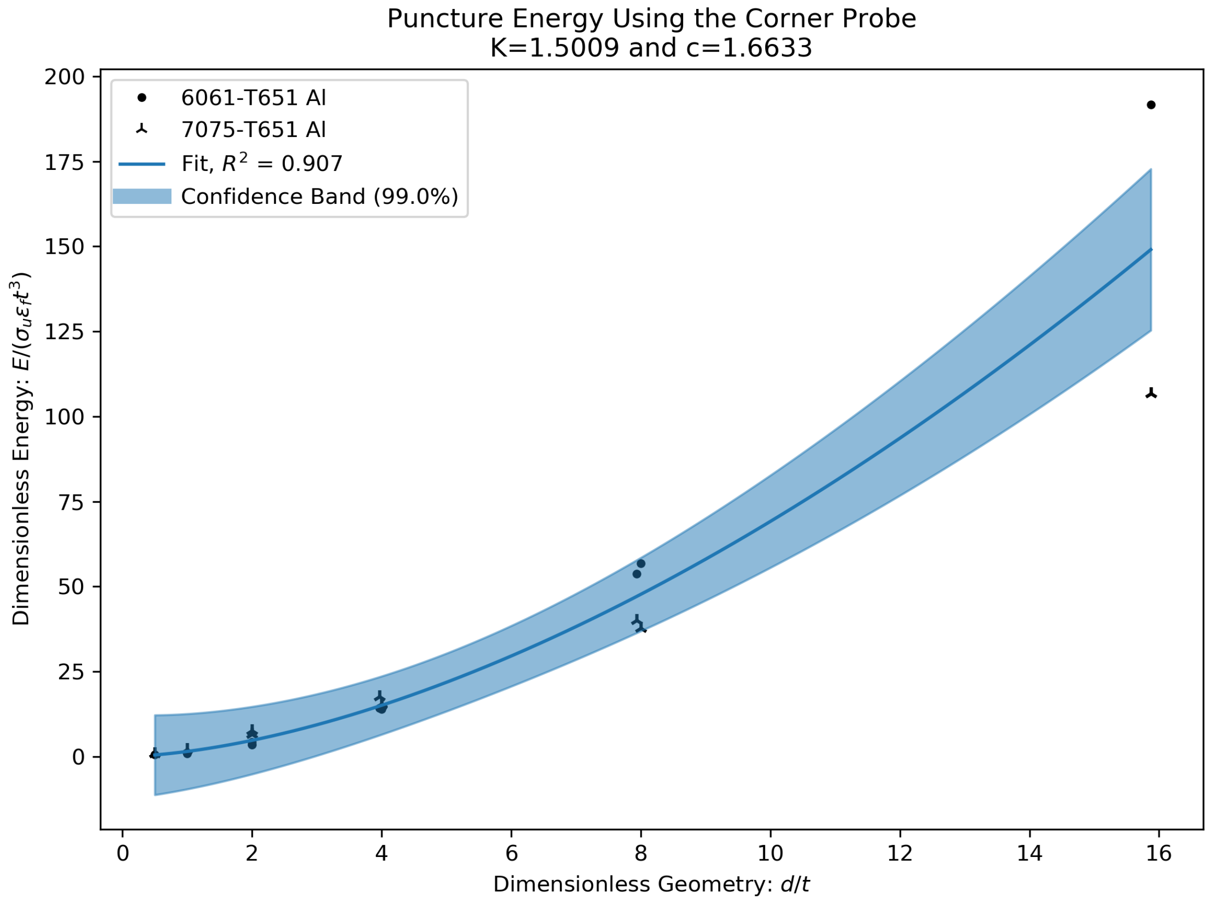


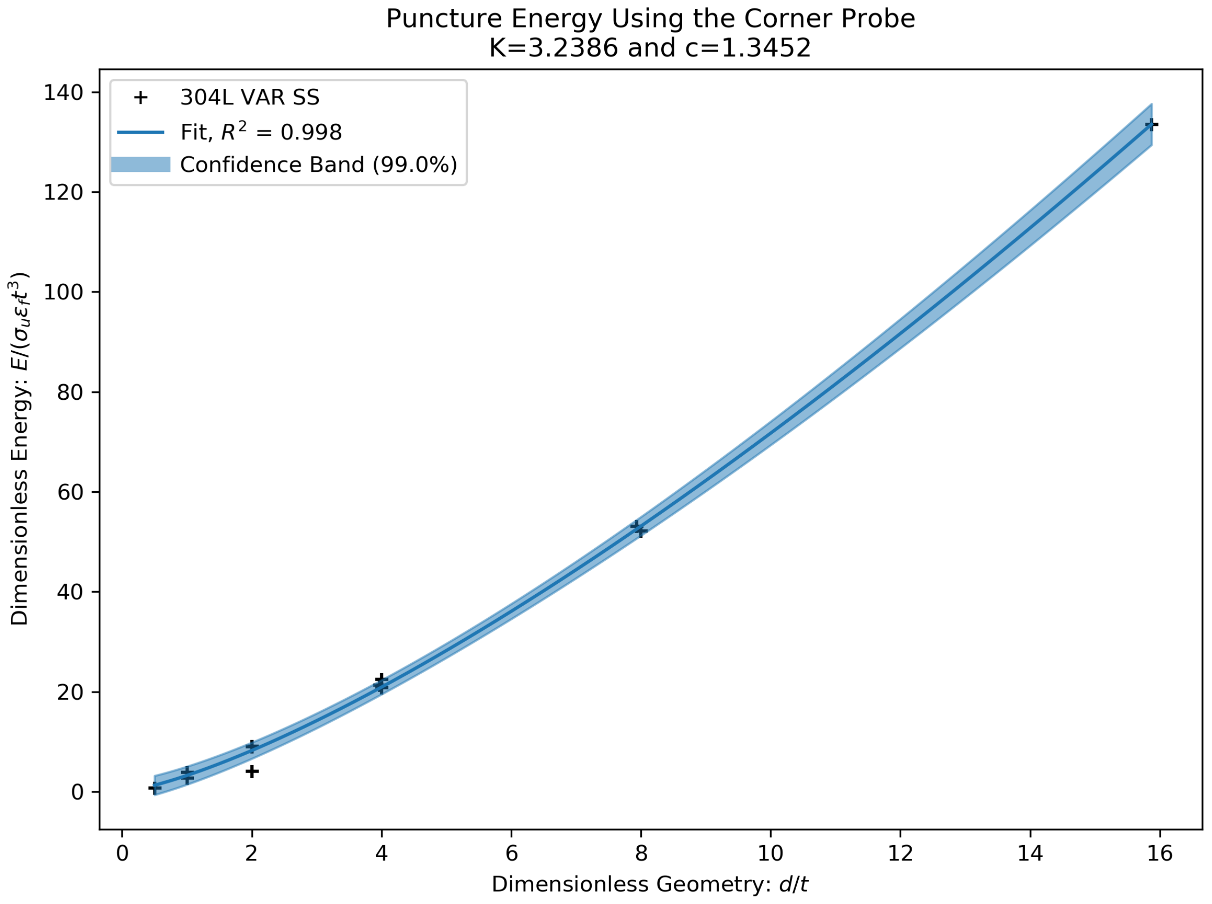


Corner Probe Fit Using All Materials

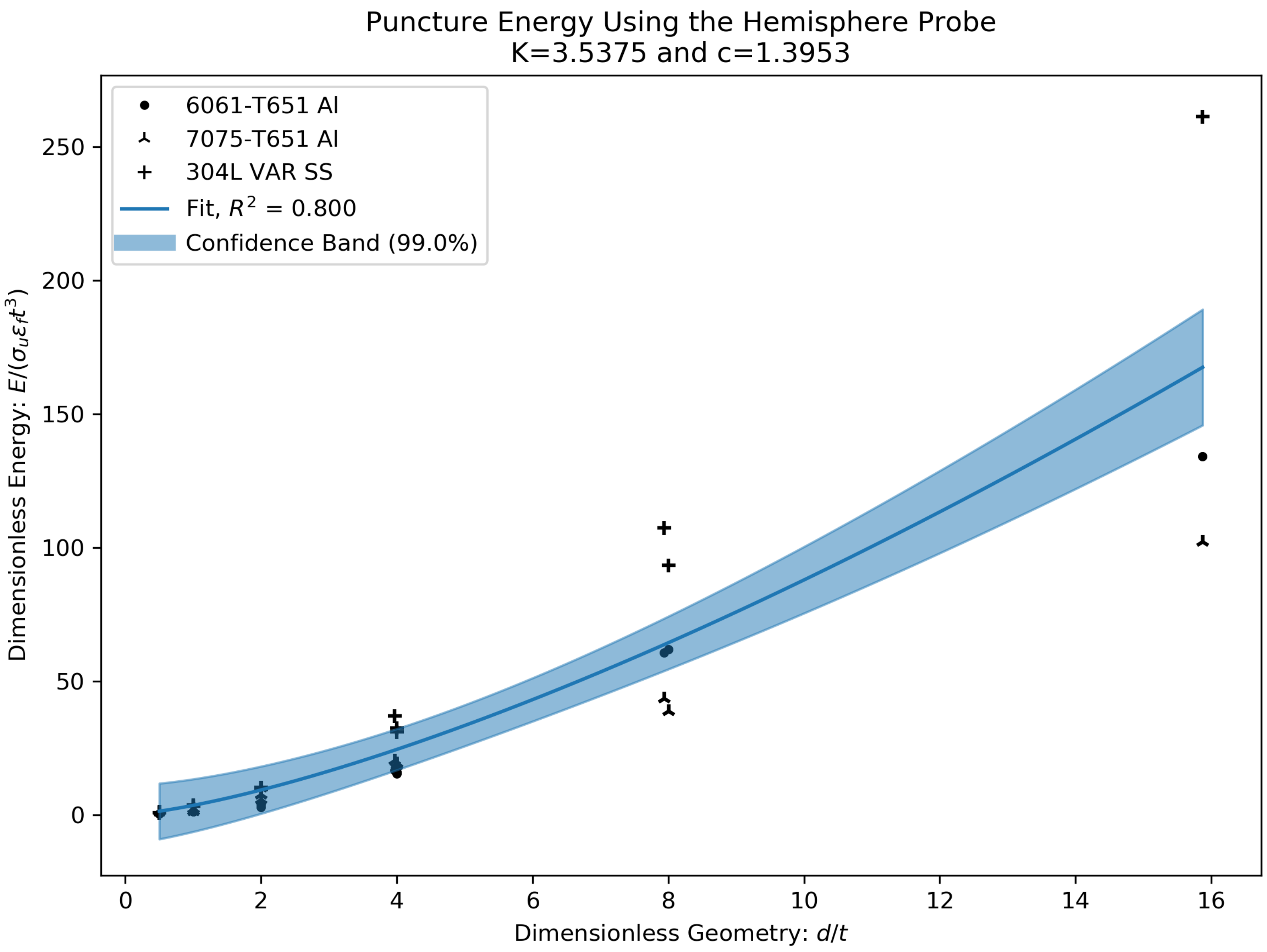


Corner Probe Fit Separating Materials

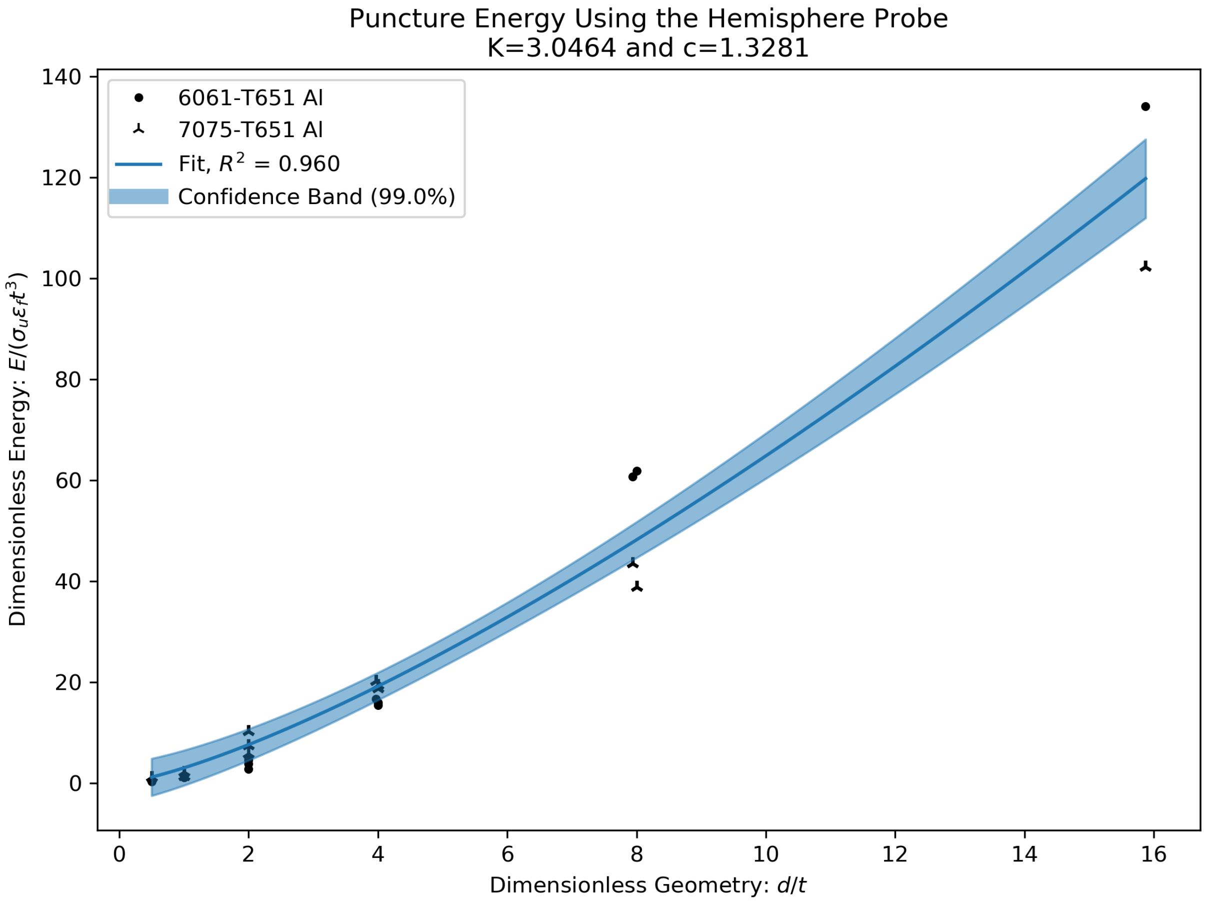


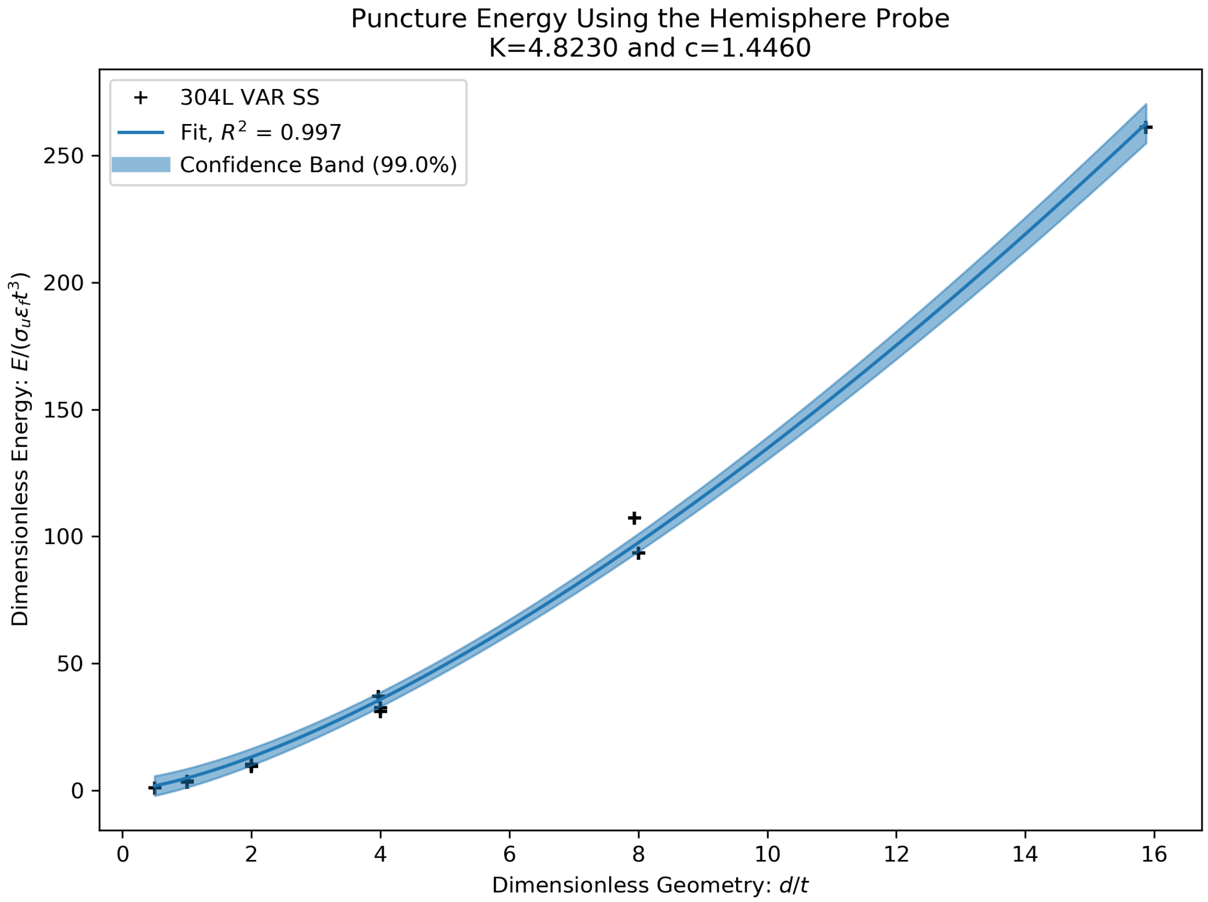


Hemisphere Probe Fit Using All Materials



Hemisphere Probe Fit Separating Materials





Conclusions

R^2 Fit Summary

	Flat	Corner	Hemispherical
All data	0.700	0.927	0.800
Aluminum	0.842	0.907	0.960
Steel	0.964	0.998	0.997

The flat probe results were very scattered.

- Consequence: **lower quality fit** than the corner and hemisphere probes

Fits should be **separated by both material and probe shape**.

Conclusions (cont.)

K and c Fit Summary

	Flat	Corner	Hemispherical
All data	K = 3.086 c = 1.280	K = 1.981 c = 1.550	K = 3.538 c = 1.395
Aluminum	K = 2.232 c = 1.252	K = 1.501 c = 1.663	K = 3.046 c = 1.328
Steel	K = 4.813 c = 1.303	K = 3.239 c = 1.345	K = 4.823 c = 1.446

Observed trend: Higher K for steel than aluminum

Future Work

- **Simulate more alloys and dimensions** to ensure the fit stays statistically significant.
- Investigate the effects of **probe velocity**.
- Add **strain rate dependency** for all materials.
- **Increase the coupon puncture-area diameter** for thinner coupons.

Acknowledgements

Thank you to Neal Hubbard for teaching and guiding us through this project and answering all of our (many) questions. Thank you to Dr. Rob Kuether, Brooke Allensworth, Dr. Debby Fowler for organizing and running this summer research opportunity. Thank you to Dr. Tariq Kharishi (UNM) asking thoughtful questions to make us consider things more deeply. Thank you to Dr. Joe Bishop for checking in with us weekly and making sure we did not have any issues.

This research was conducted at the 2021 Nonlinear Mechanics and Dynamics Research Institute hosted by Sandia National Laboratories and the University of New Mexico.

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Appendix: Confidence Band Calculation

$$\alpha \equiv signficance$$
$$t \equiv student\ t\ distribution$$
$$y_{fit} \equiv y\ as\ determined\ by\ regression$$
$$n \equiv number\ of\ independent\ variables$$
$$df \equiv degrees\ of\ freedom$$

$$s_x = (x - \bar{x})^2$$
$$SS_x = \sum_i (x - \bar{x})^2$$
$$SE = \sqrt{\frac{1}{df} \sum_i \left(y - y_{fit}\right)^2}$$
$$confidence\ interval = t \cdot SE \cdot \sqrt{\frac{1}{n} + \frac{s_x}{SS_x}}$$
$$y_{conf} = y \pm confidence\ interval$$