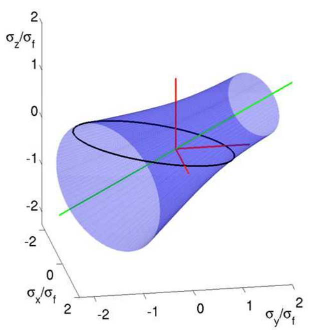
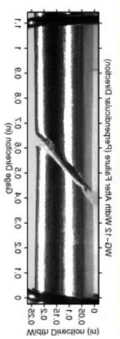
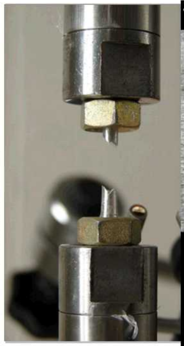
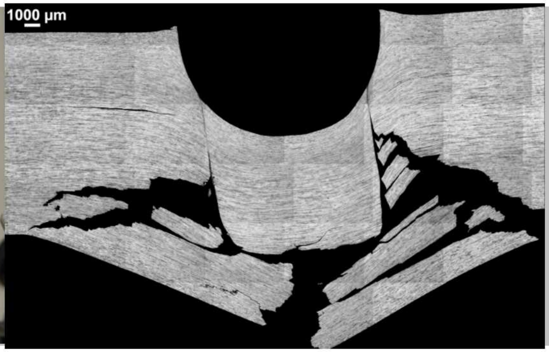
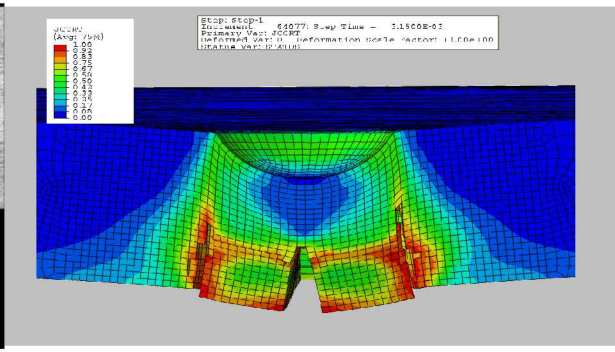
SAND2014-20333C











Calibration and Evaluation of the Johnson-Cook Strength and Failure Models for Puncture Simulations of Aluminum Plates

Edmundo Corona, Matthew A. Spletzer, Theresa E. Córdova, George E. Orient and Lisa A. Deibler

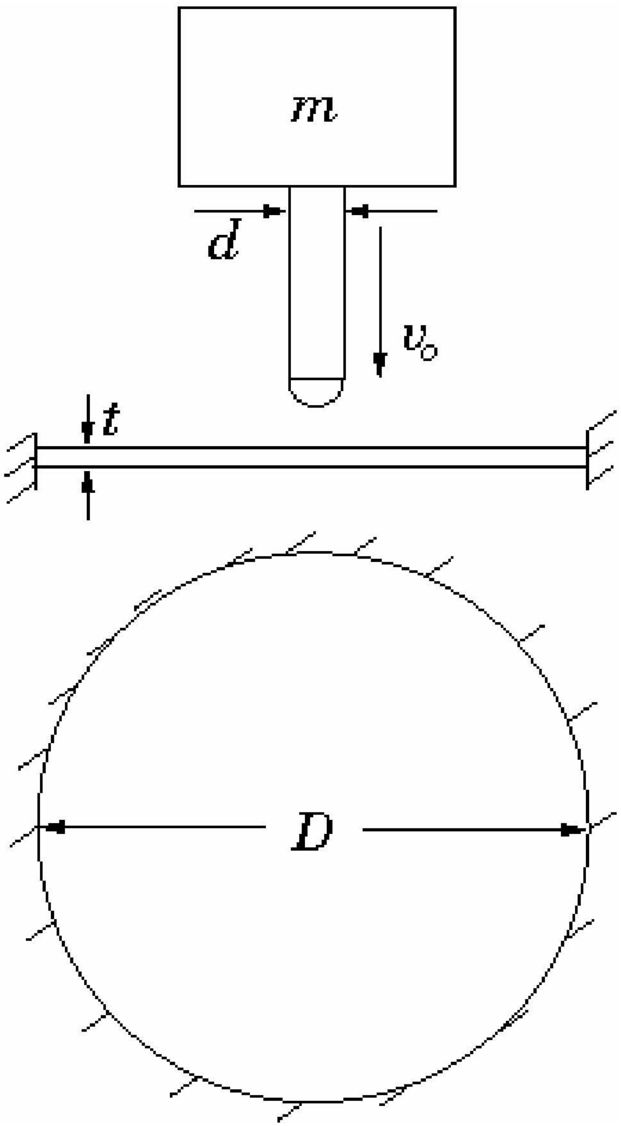
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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.

Problem Schematic

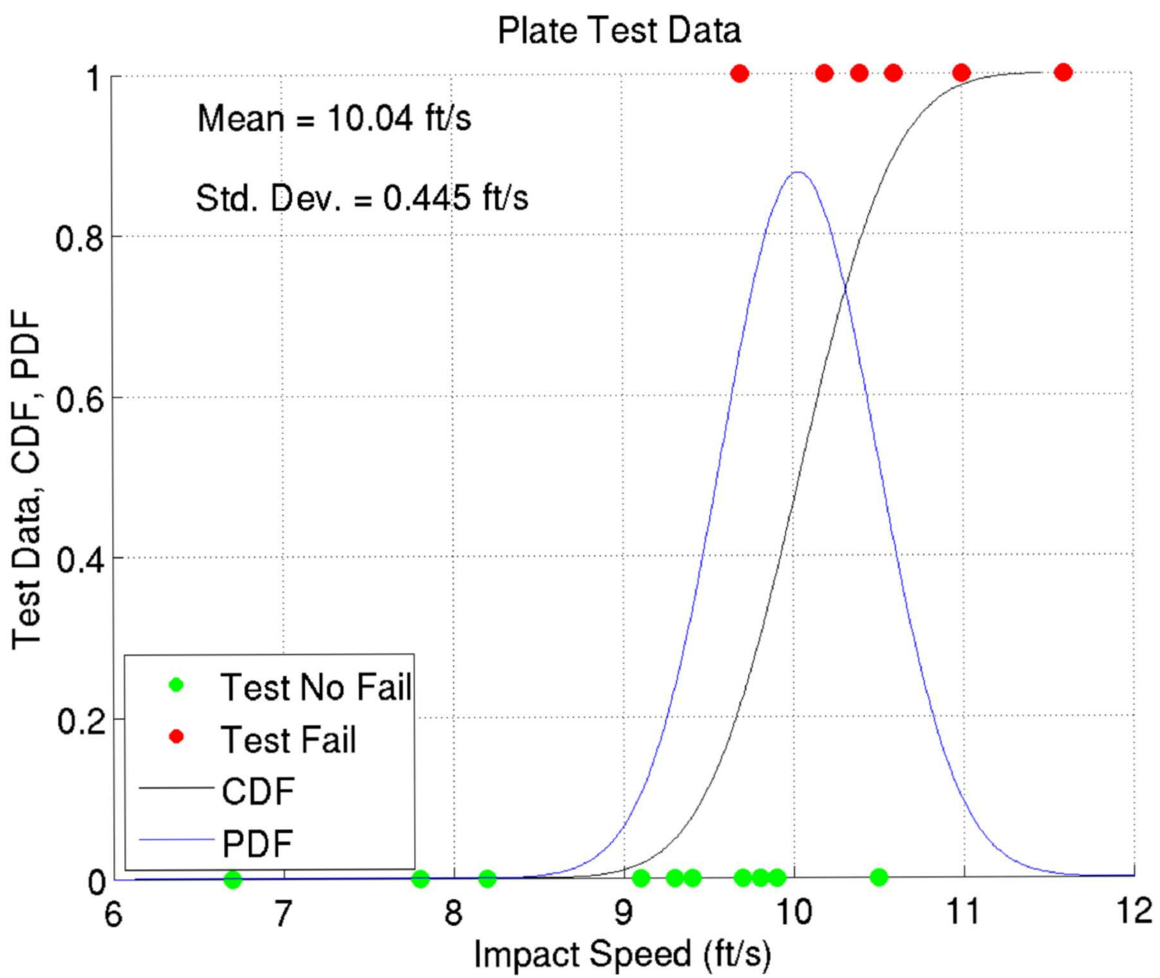
$$m = 306 \text{ lb}$$
$$d = 0.5 \text{ in}$$
$$t = 0.5 \text{ in}$$
$$D = 6.75 \text{ in}$$

Al 7075-T651



- Determine threshold velocity
- Observe failure mode

Experimental Results



Threshold velocity: [9.7,10.5] ft/s

Puncture Video Record

Johnson-Cook Material Choice

- Initial results overestimated threshold puncture velocity by 60%

- Searched for a model that:
  - Accounts for temperature and strain rate effects on material response/failure
  - Triaxiality dependence of failure strain can be adjusted
  - Has been implemented in a finite element code

- Johnson-Cook model met all the criteria.

- It has also been used by others in puncture applications (Borvik, Weirzbicki) and reported good results.

Johnson-Cook Material Characterization

J_2 Isotropic hardening, "Strength" Model:

$$\sigma_e = \left[A + B\left(\varepsilon_e^p\right)^n\right]\left[1 + C\ln\left(\frac{\dot{\varepsilon}_e^p}{\dot{\varepsilon}_o}\right)\right]\left[1 - \hat{T}^m\right]$$

$$\hat{T} = \frac{T - T_r}{T_m - T_r}$$

Five parameters to calibrate:

$$A, B, n, C, m$$

Auxiliary parameters that need values:

$$\dot{\varepsilon}_o, T_r, T_m$$

Johnson-Cook Material Characterization

Failure Model:

$$\varepsilon_{ef}^{p} = \left[d_1 + d_2 e^{d_3 \eta}\right]\left[1 + d_4 \ln\left(\frac{\dot{\varepsilon}_e^{p}}{\dot{\varepsilon}_o}\right)\right]\left[1 + d_5 \hat{T}\right]$$

$$\eta = \frac{\sigma_m}{\sigma_e}$$

Five parameters to calibrate:

$$d_1, d_2, d_3, d_4, d_5$$

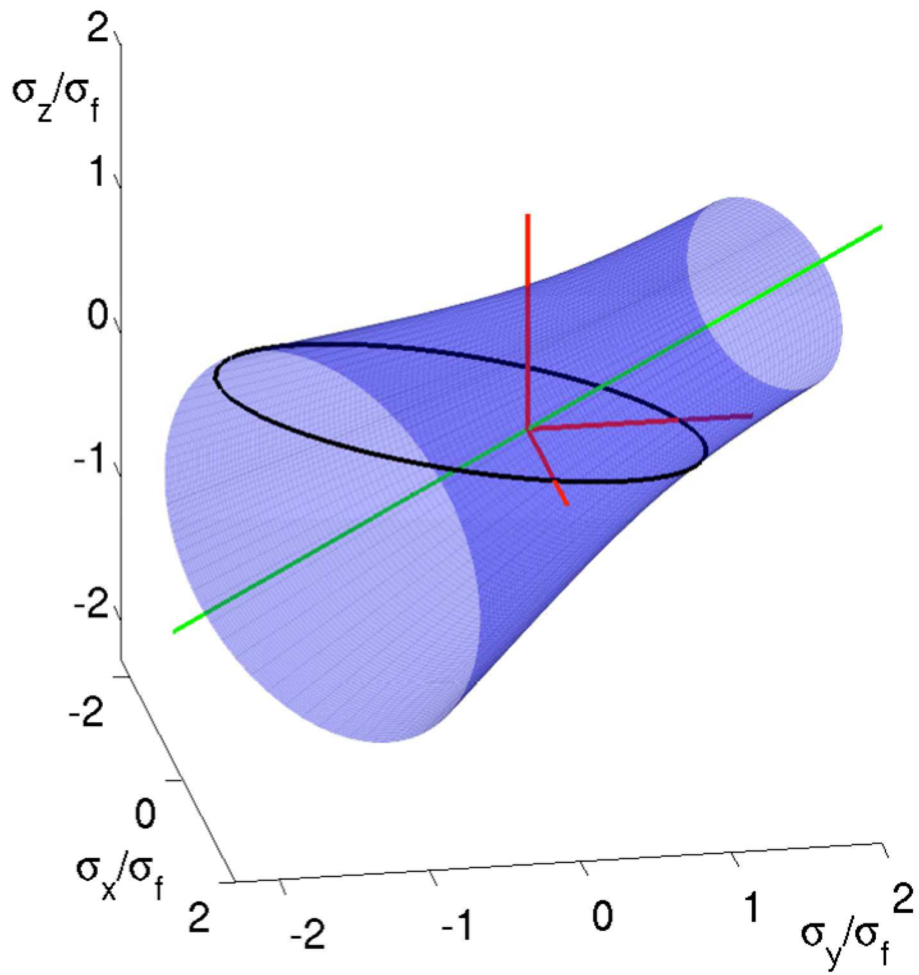
Damage accumulation:

$$\bar{D} = \int \frac{d\hat{\varepsilon}_e^p}{\varepsilon_{ef}^p(\eta, \dot{\varepsilon}/\dot{\varepsilon}_o, \hat{T})}$$

Failure when $\bar{D} = 1$

Johnson-Cook Failure in Principal Stress

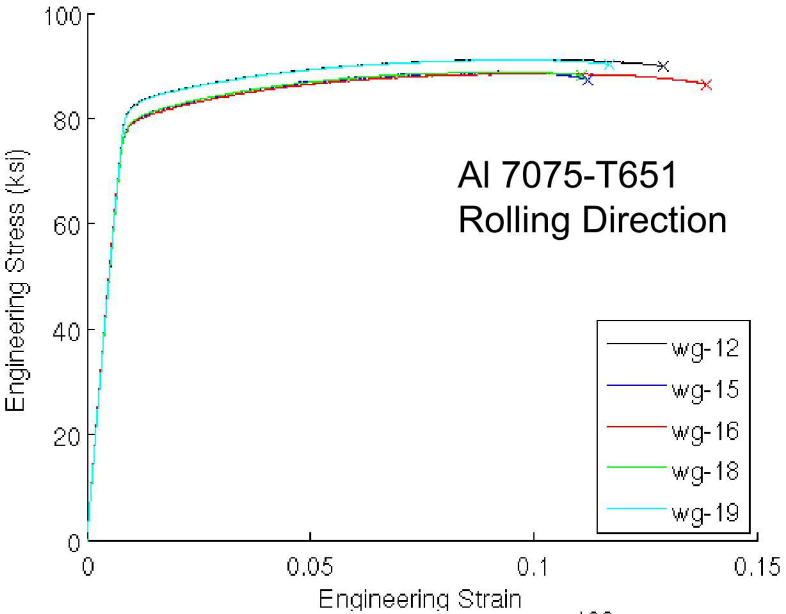
$$d_1 = 0.005$$
$$d_2 = 0.34$$
$$d_3 = -1.5$$

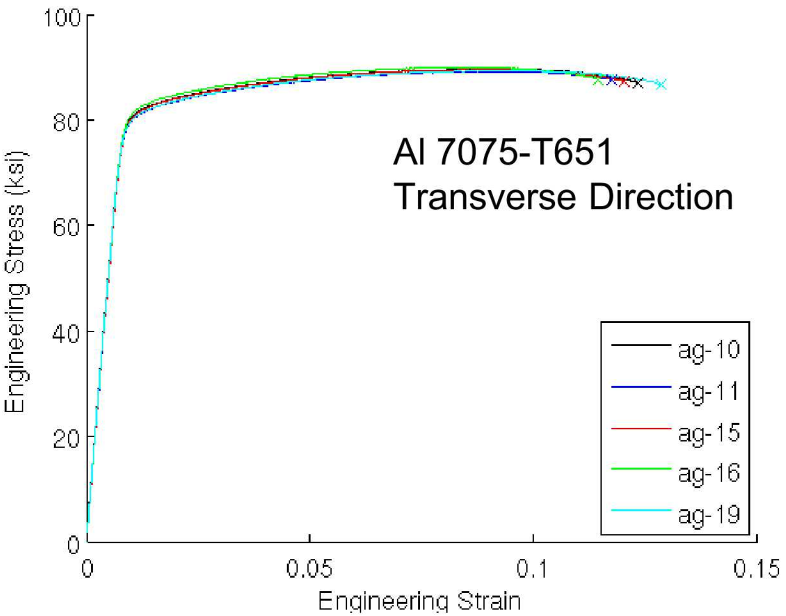


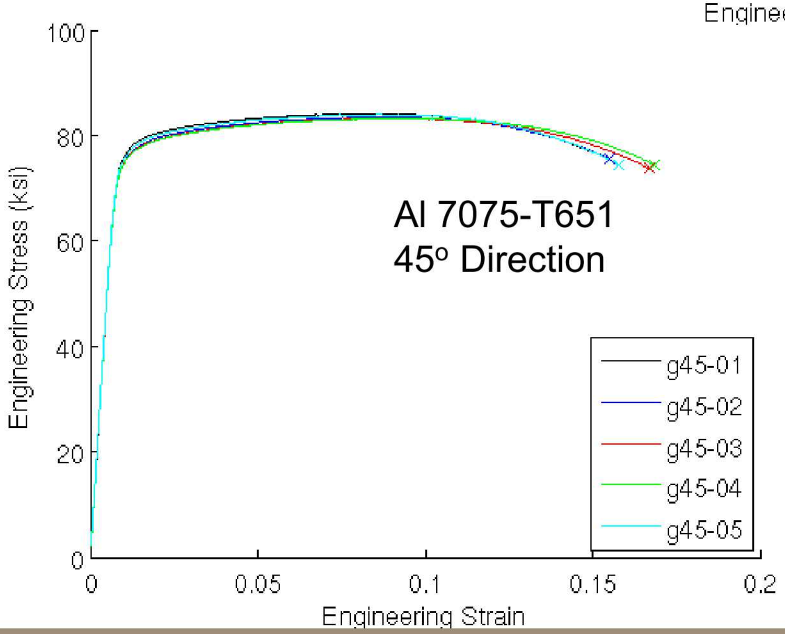
Special case:

$$T = T_r$$
$$\dot{\varepsilon}_e^p = \dot{\varepsilon}_o$$
$$\dot{\eta} = 0$$

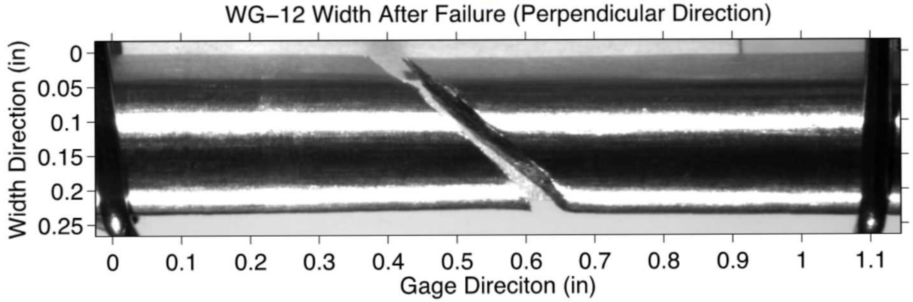
Uniaxial Tension Test Data

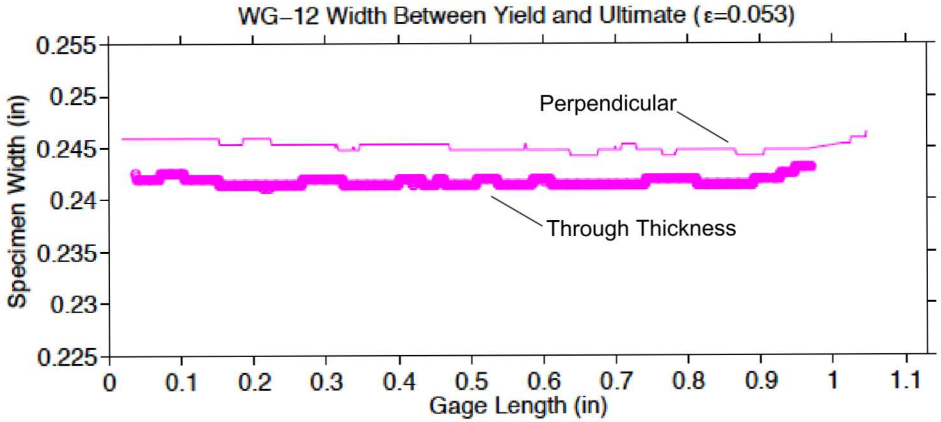


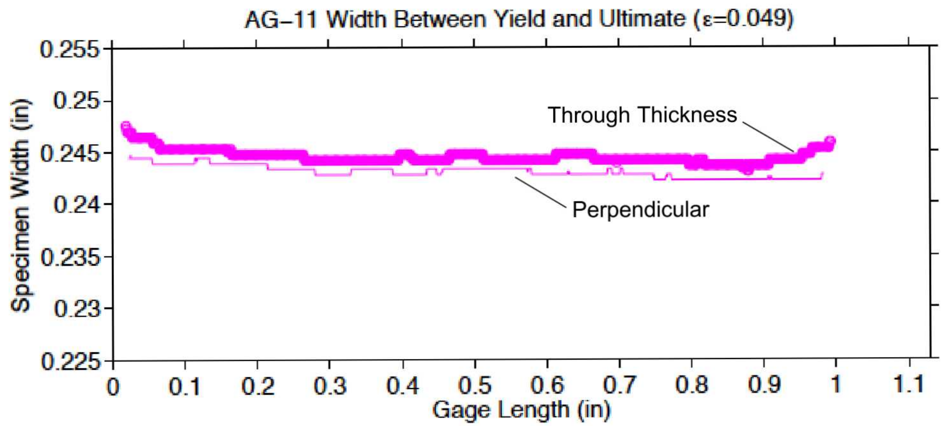




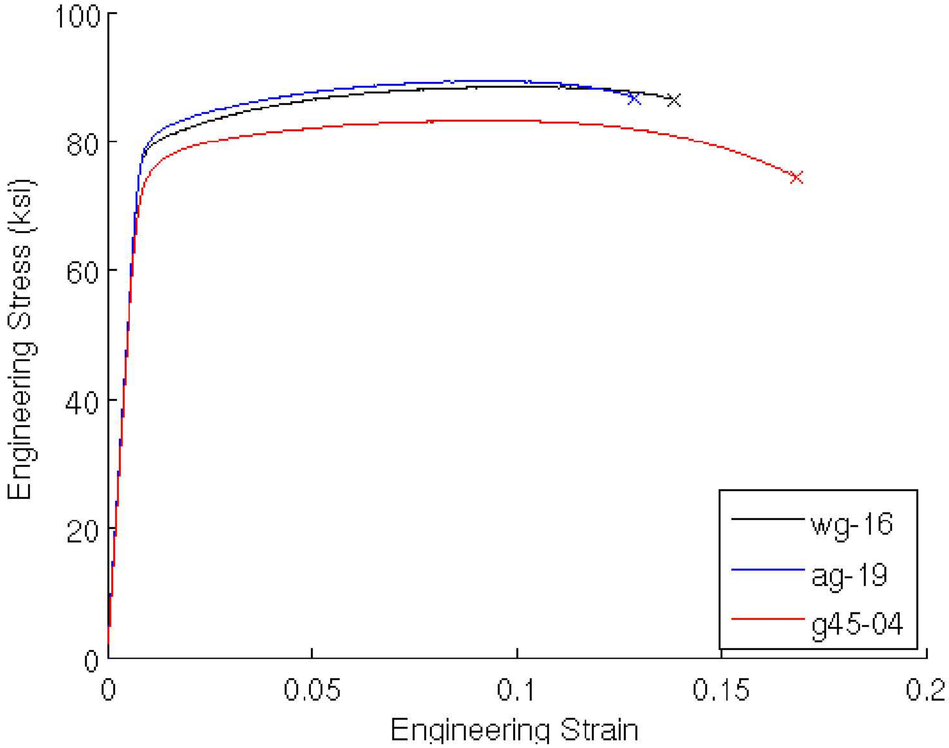
Uniaxial Tension Edge Detection Data







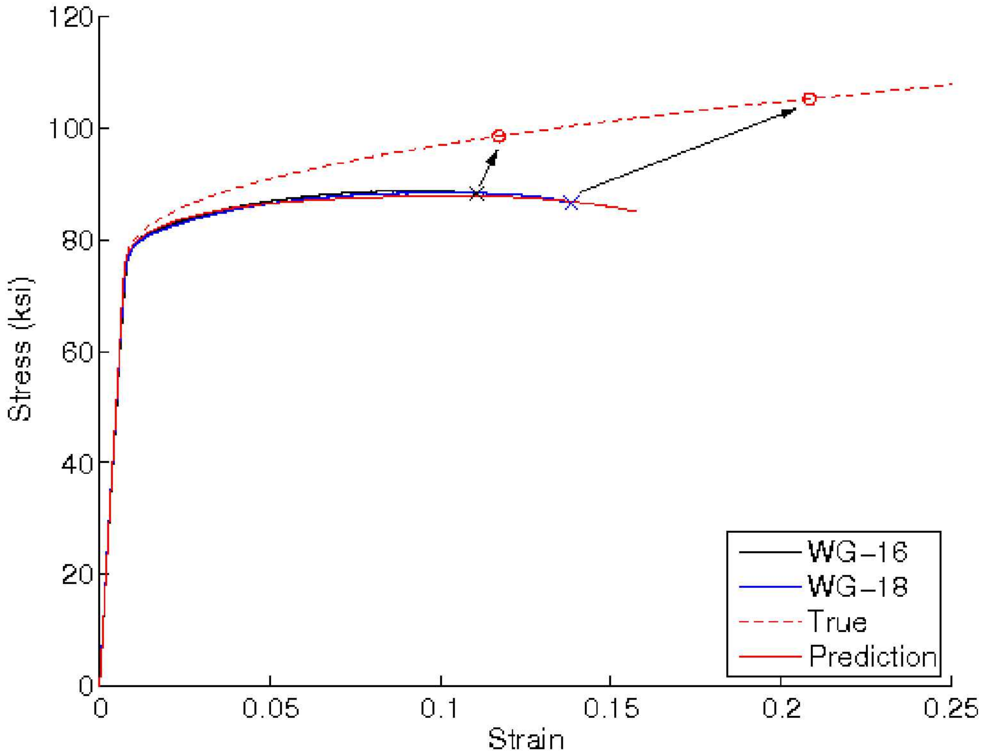
Uniaxial Tension Test Data Summary



Choice of stress-strain curve to fit: Highest strain to failure

Fitting Procedure

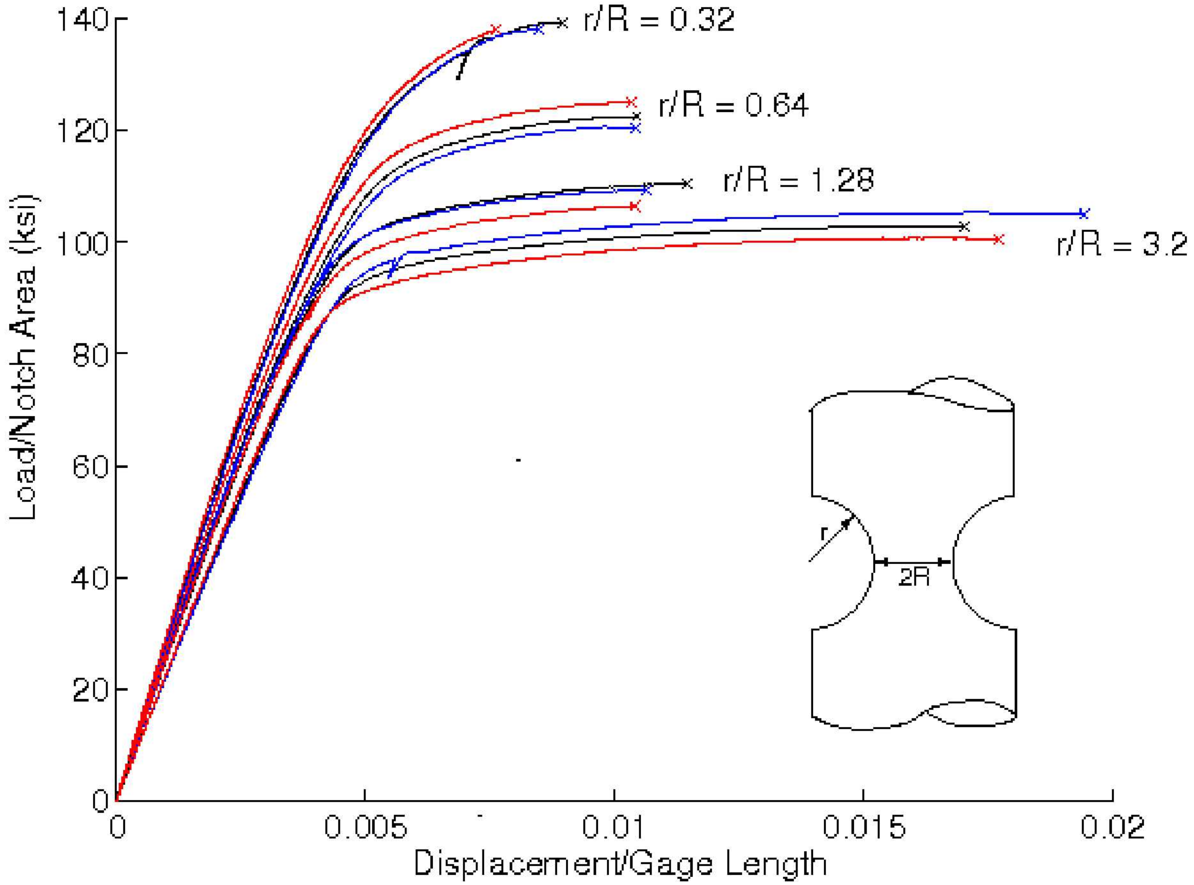
- Make finite element model of tension test specimen
- Guess values for A, B, n
- Simulate the tension test
- Compare the predicted engineering stress-strain curve to measured one
- Iterate as necessary
- Note the true plastic strain at failure



$$\boxed{A, B, n}, C, m$$

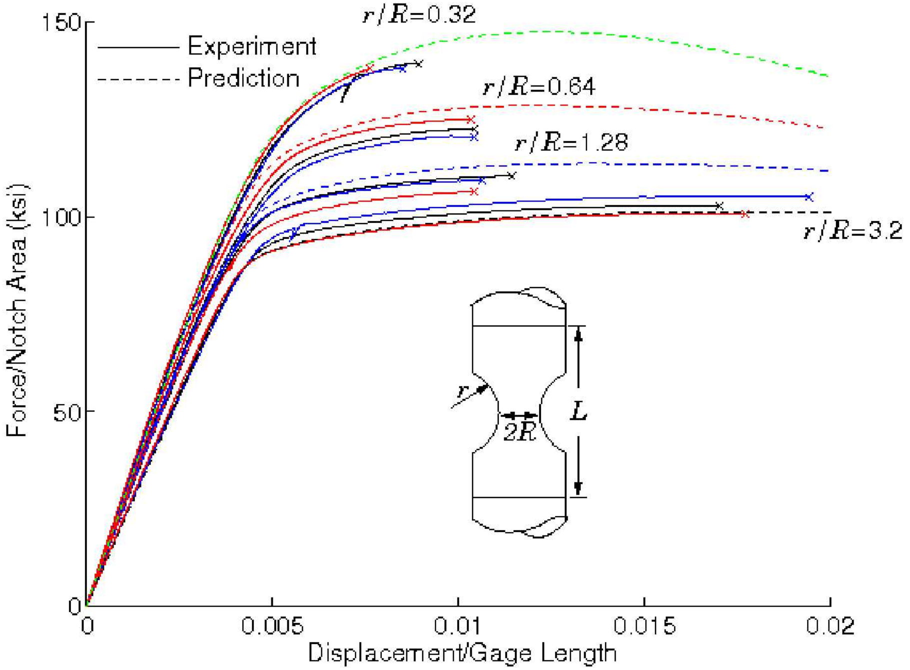
$$d_1, d_2, d_3, d_4, d_5$$

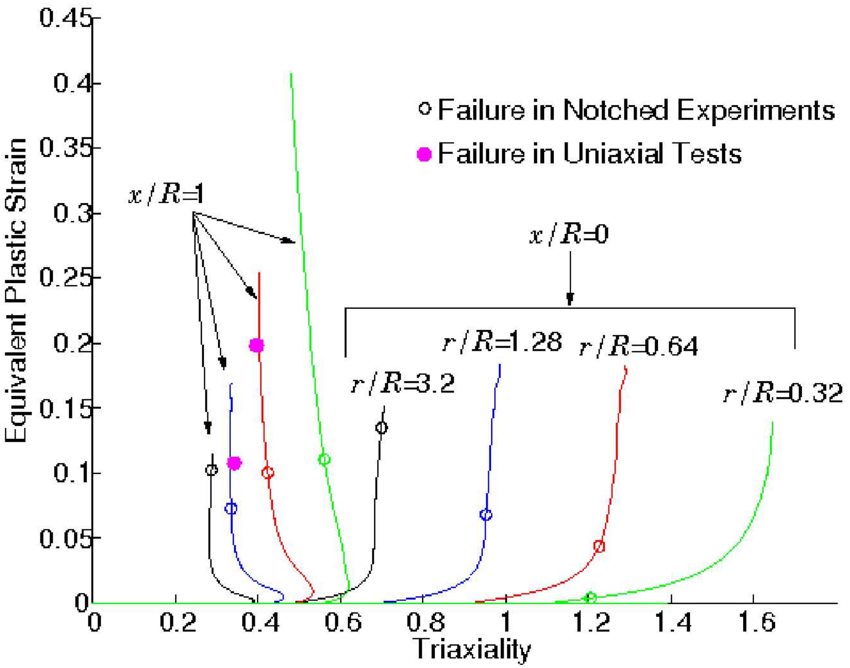
Notched Specimen Tension Test Data



Notched Specimen Tension Test Simulation

- Test performance of plasticity model under non-uniaxial conditions
- Obtain data to assess triaxiality dependence of the plastic strain to failure

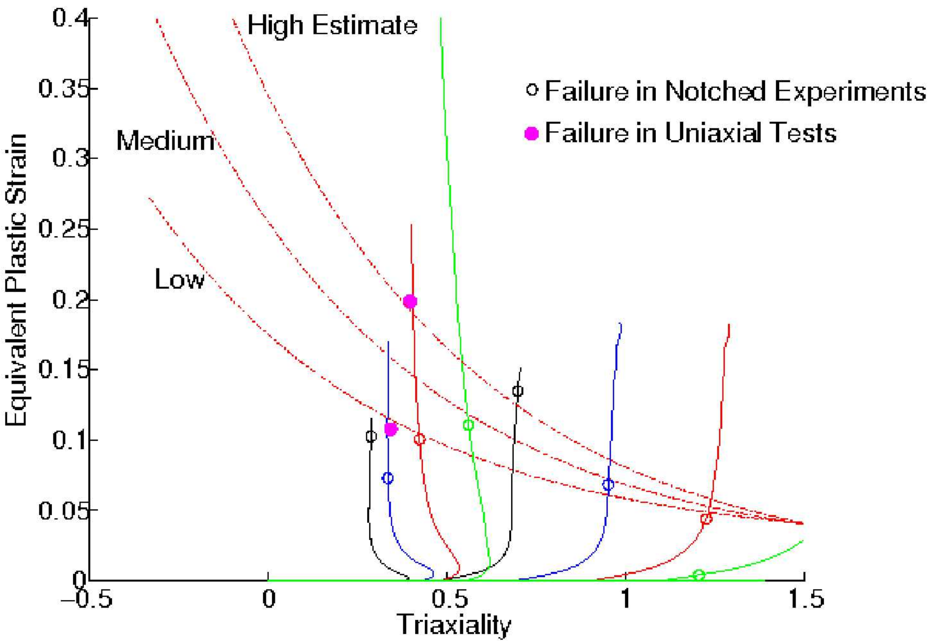


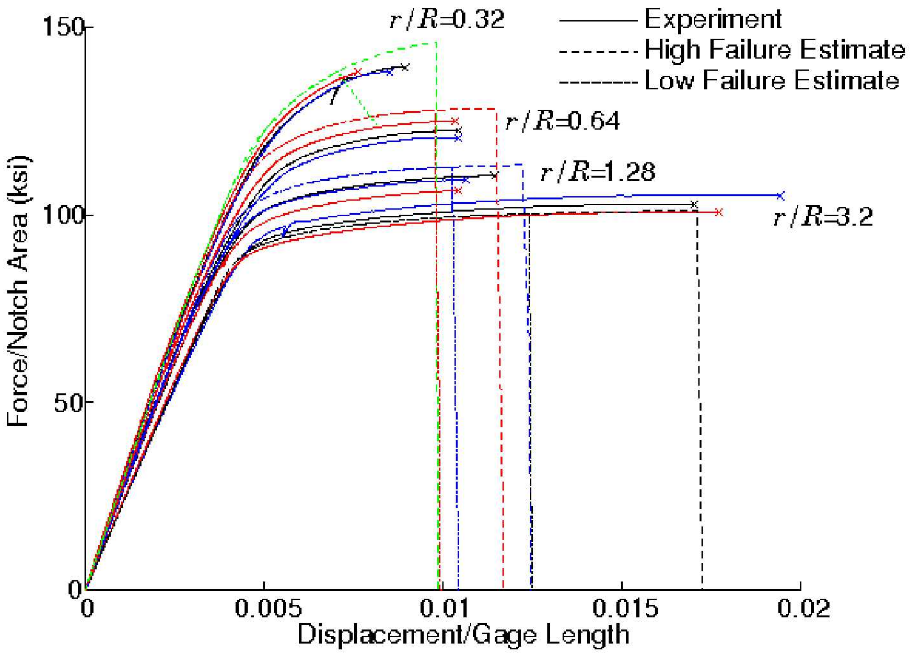


Notched Specimen Tension Test Calibration

$$\boxed{A, B, n}, C, m$$

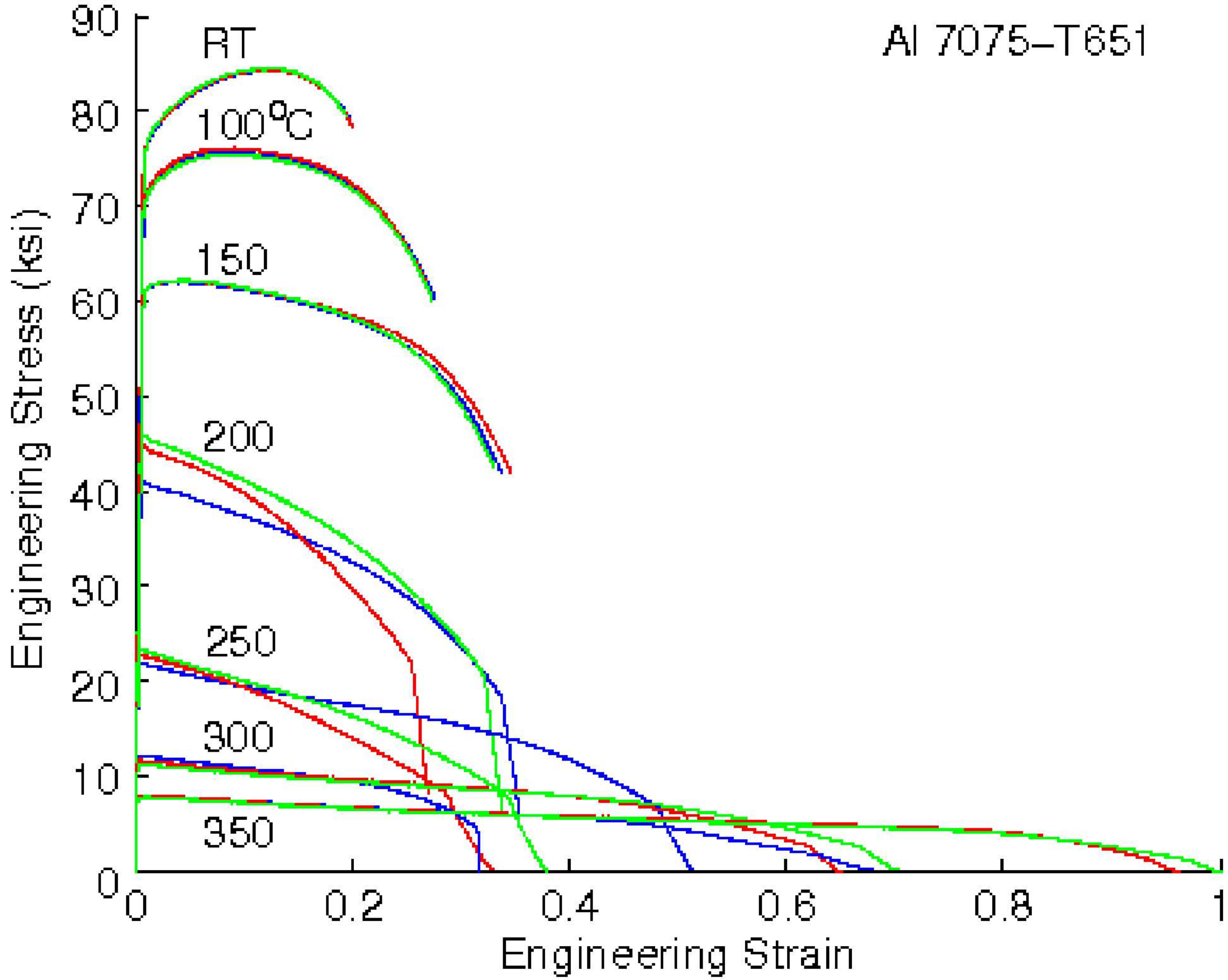
$$\boxed{d_1, d_2, d_3}, d_4, d_5$$





High Temperature Tension Test Data

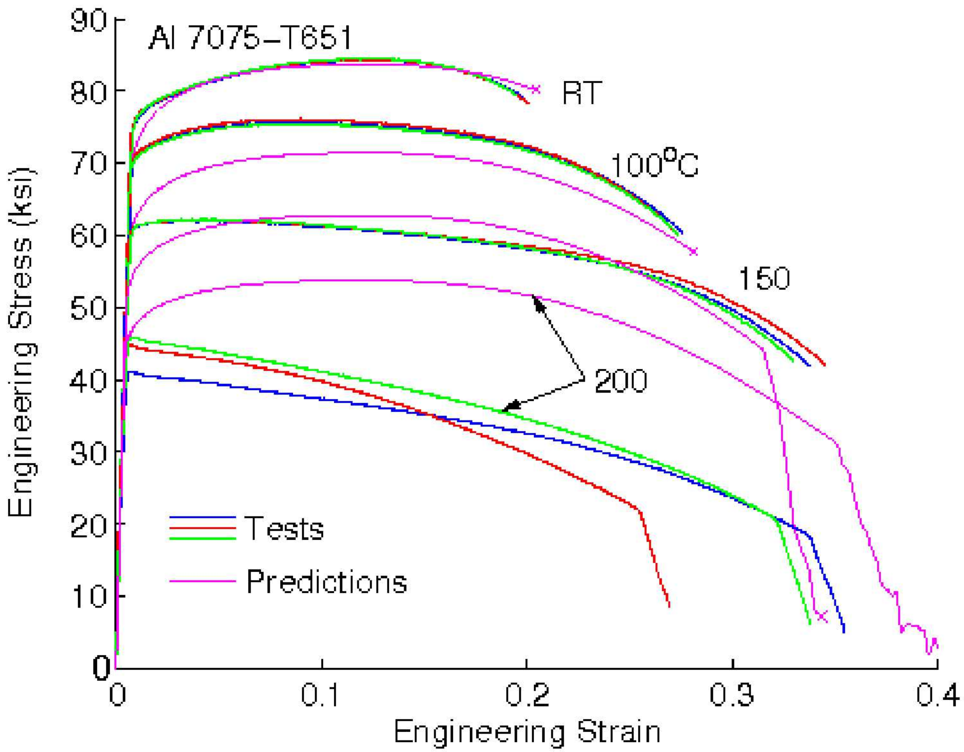
Determine values of temperature dependence parameters



High Temperature Tension Test Calibration

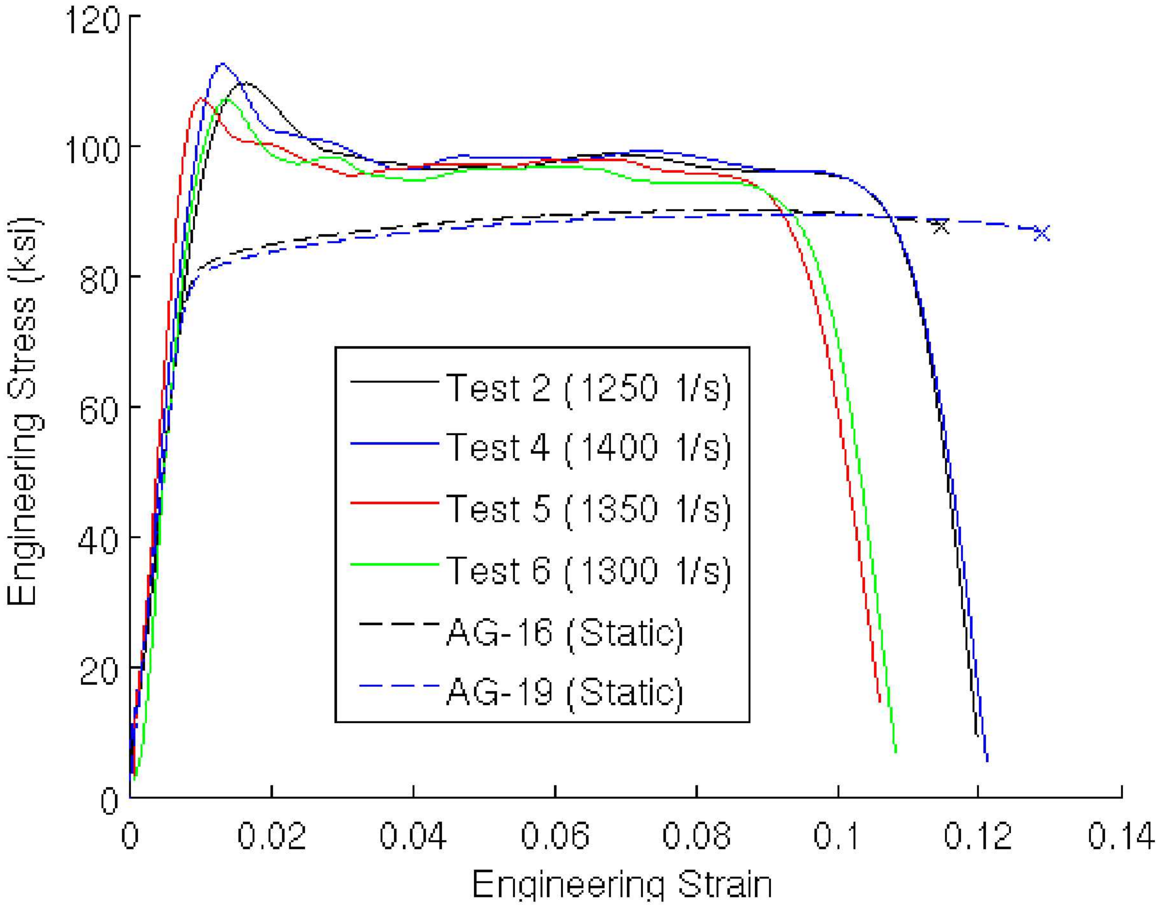
$$\boxed{A, B, n}, C, \boxed{m}$$

$$\boxed{d_1, d_2, d_3}, d_4, \boxed{d_5}$$

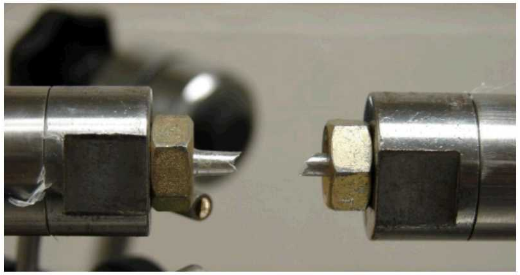


High Strain Rate Tension Test Data

Determine values of strain rate dependence parameters



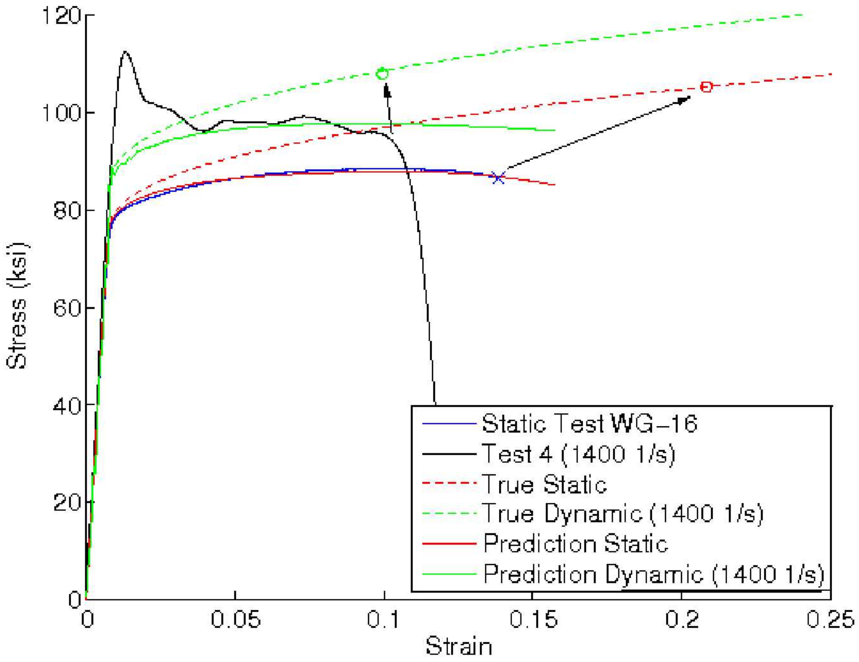
Tensile Kolsky Bar Tests



High Strain Rate Tension Test Data

$$A, B, n, \boxed{C,}\ m$$

$$d_1, d_2, d_3, \boxed{d_4,}\ d_5$$



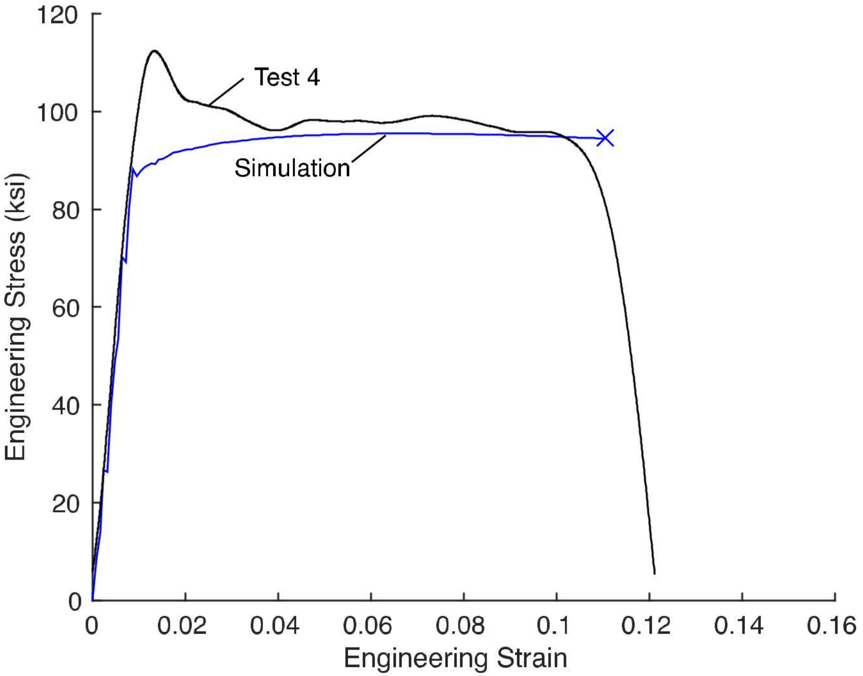


Plate Puncture Finite Element Model

- Explicit Dynamics
- Adiabatic

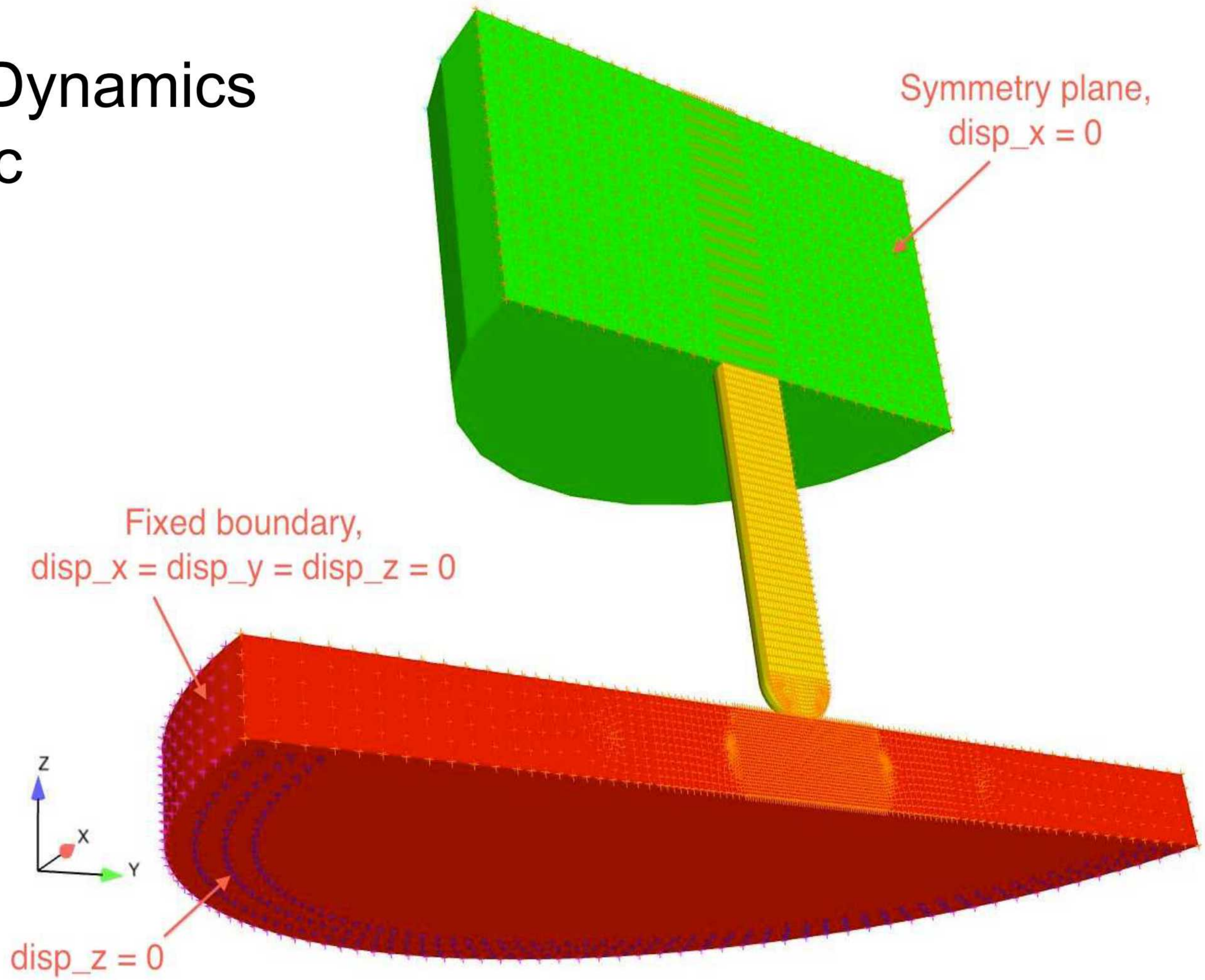
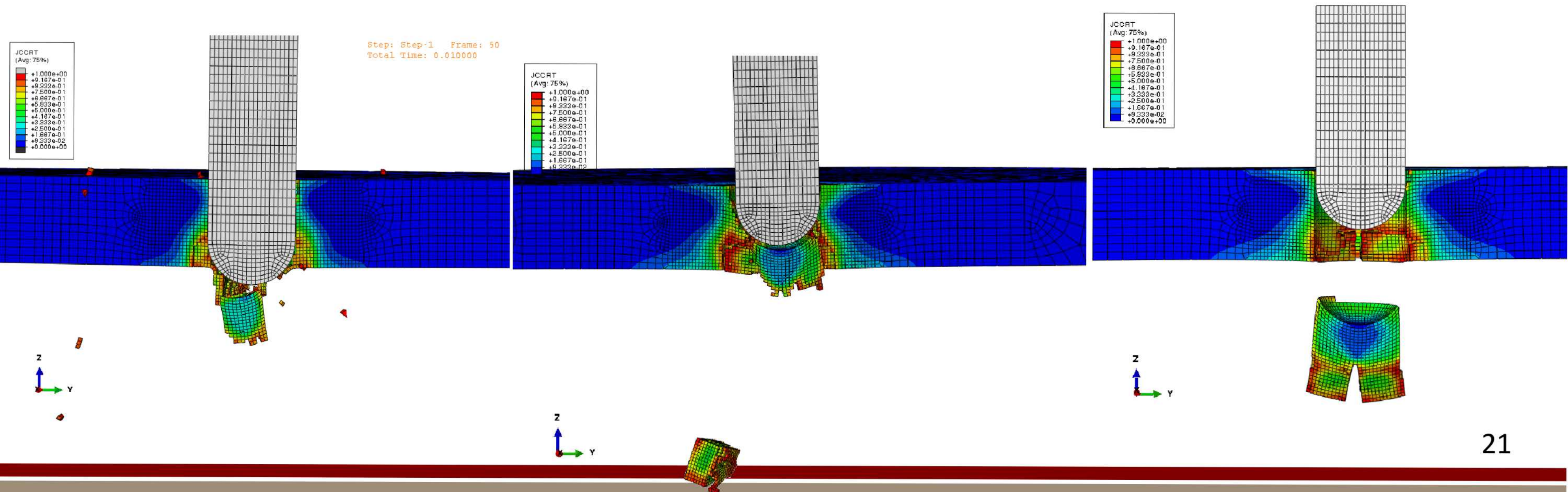


Plate Puncture Results

v_o, ft/s	Low	Medium	High
6	N		
6.5	N		
7	Y	N	
7.5	Y		
8	Y	N	
8.5	Y		N
9	Y	N	N
9.5	Y	N	N
10	Y	Y	N
10.5		Y	N
11		Y	Y
11.5		Y	Y
12			Y



Evolution of Johnson-Cook Damage

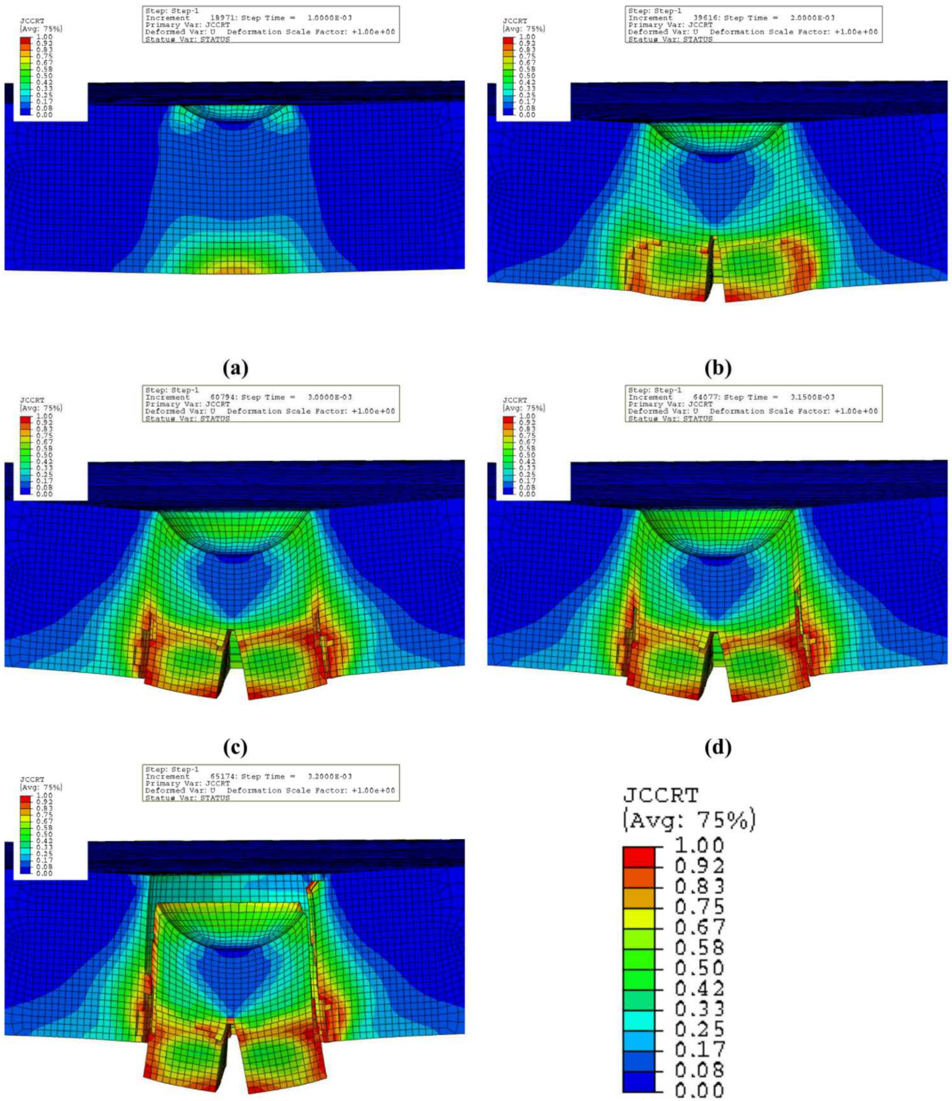
1 ms

2 ms

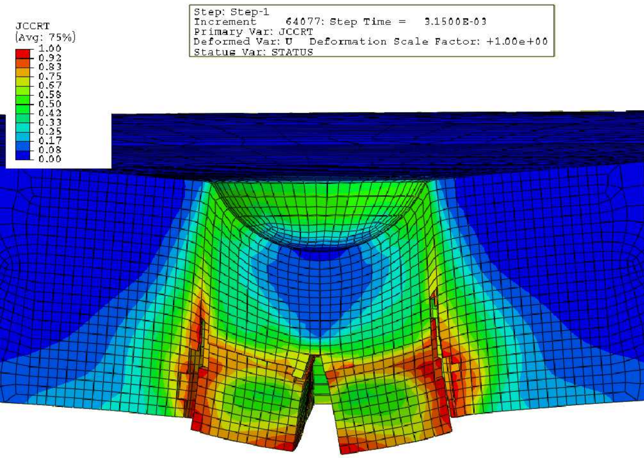
3 ms

3.15 ms

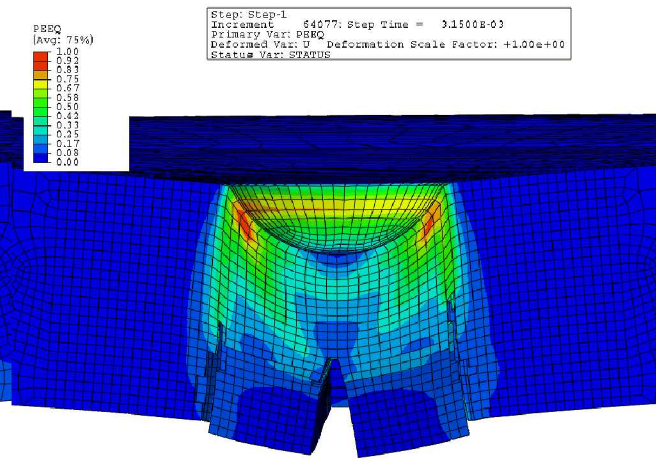
3.2 ms



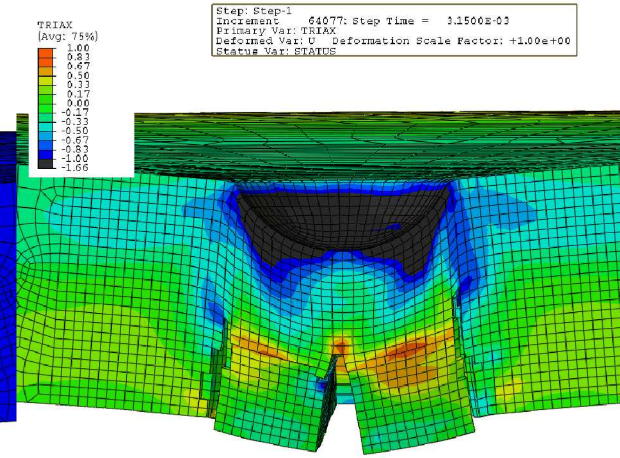
Just Prior to Plug Ejection (3.15 ms)



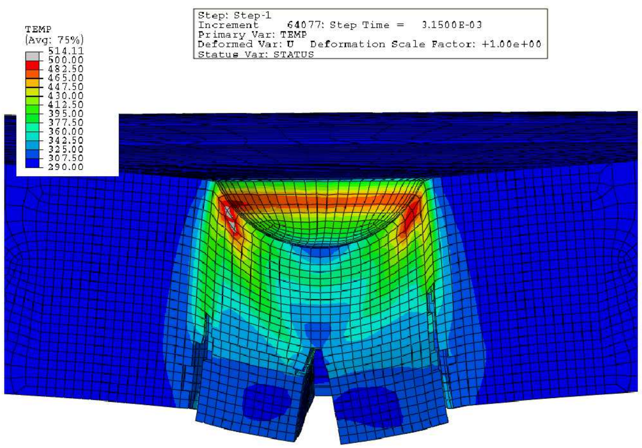
Damage



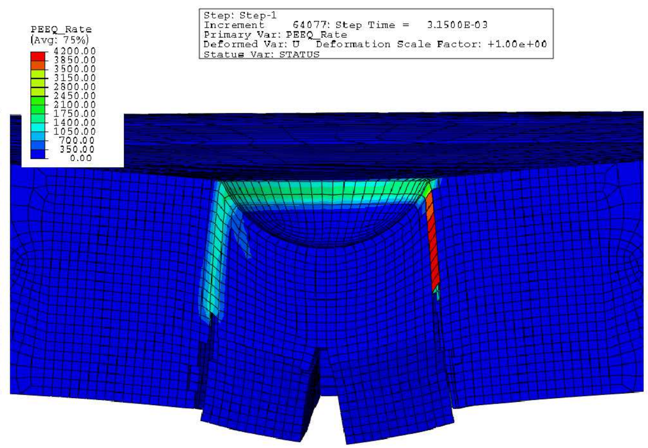
Equivalent Plastic Strain



Triaxiality



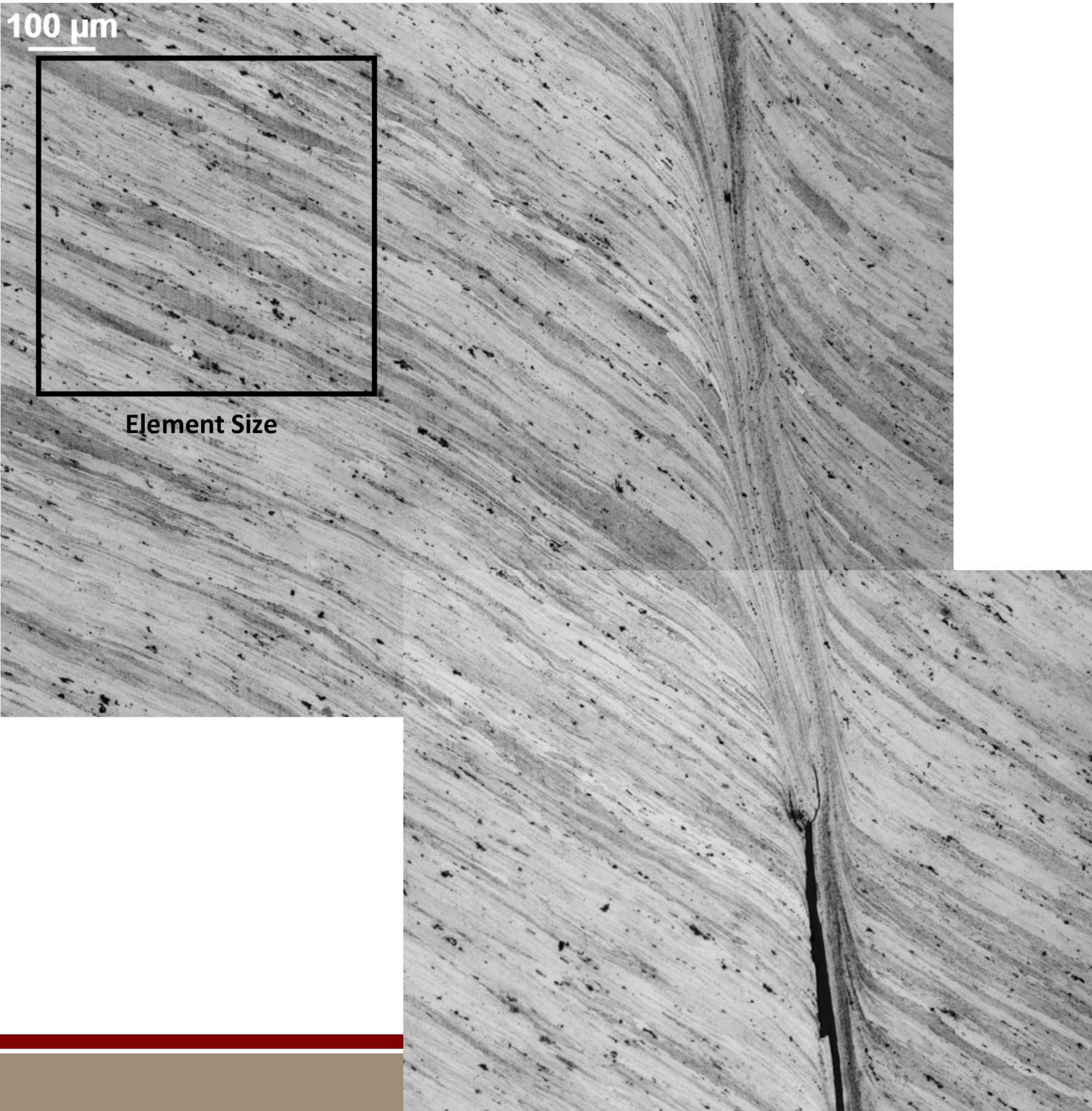
Temperature



Equivalent Plastic Strain Rate

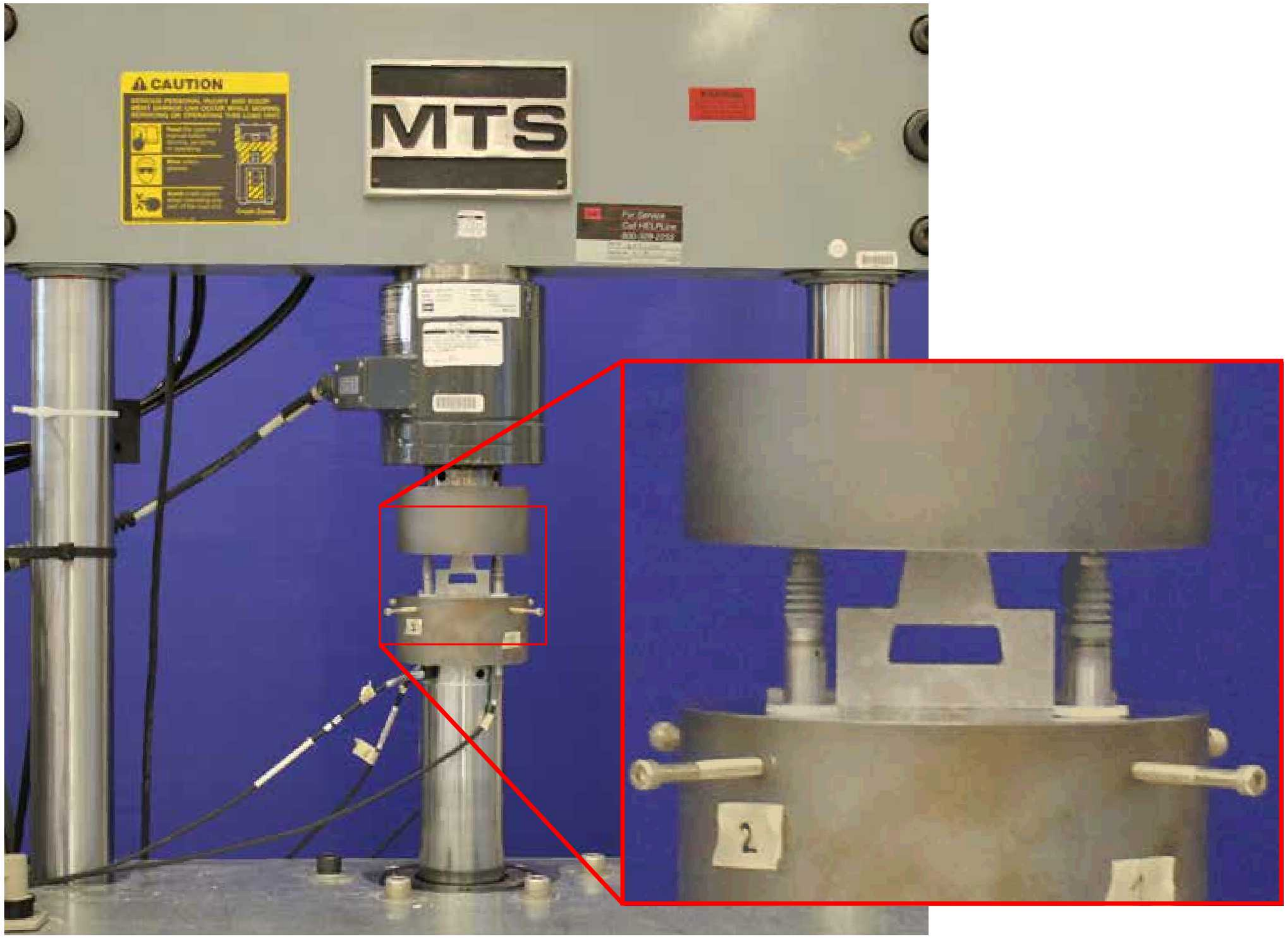
10.5 ft/s, No Failure

Microstructure of Plug Formation

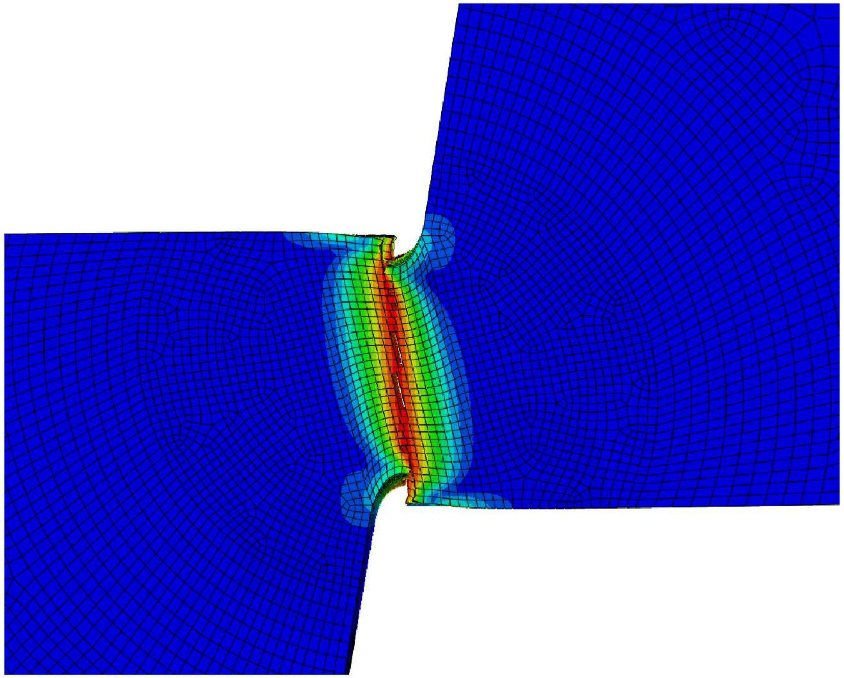


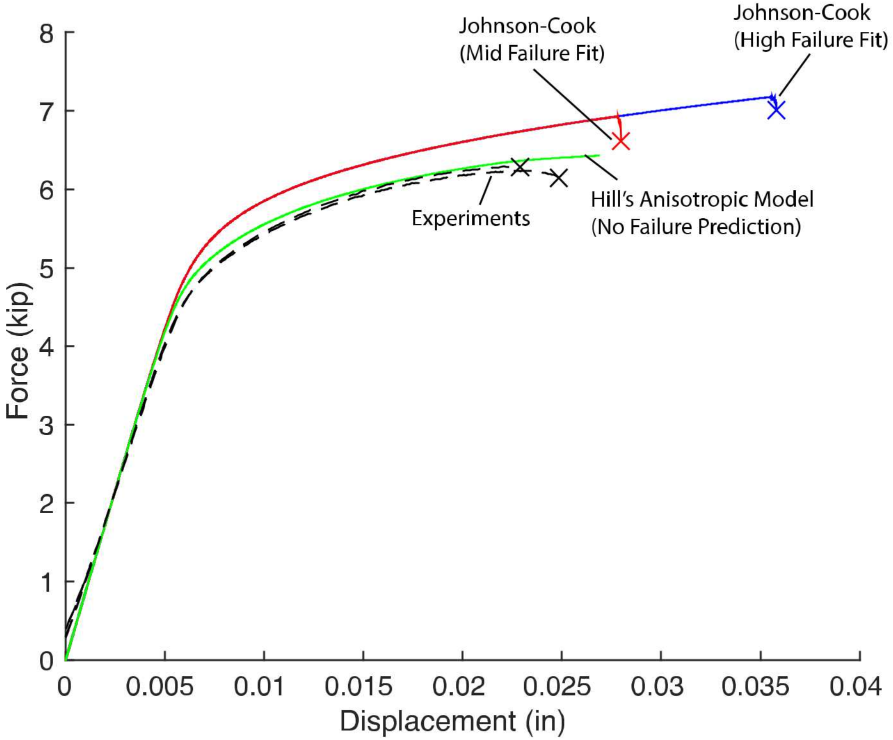
High Shear Test

Test predictions against test in high shear regime



High Shear Test Results and Predictions





Conclusions

Positive Outcomes:

- Accomplished full calibration of Johnson-Cook strength and failure model
- Puncture predictions have high resemblance to experimental observations
  - Accurate prediction of threshold puncture velocity
  - Failure sequence leading to plugging reasonably reproduced

Deficiencies:

- Model neglects observed material anisotropy
- Model captures response at high temperature to a first order only
- High shear failure information is scarce
- Material properties in the thickness direction have not been measured
- The element size used in the puncture calculations is way too big compared to the observed shear bands. (Clearly, however, the model predicts the onset of a shear instability)
- We are still uncertain whether the very reasonable predictions by the model are due to good modeling or good luck.

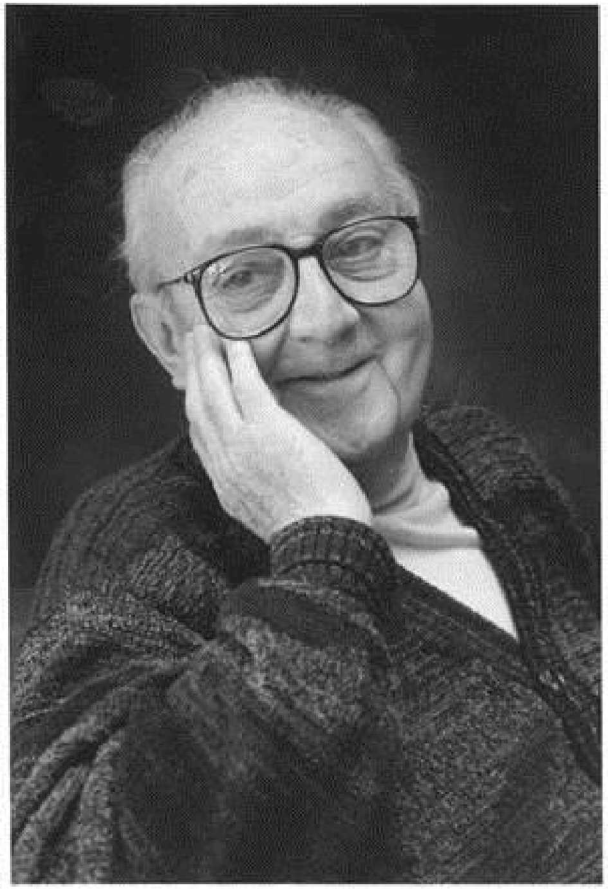
Observations and Recommendations:

- The Johnson-Cook model provided a reasonable first-order representation of the observed material behavior, both for response and failure

- The puncture predictions were reasonable

- It is reasonable to use a properly calibrated Johnson-Cook model as an initial step in the simulation of similar problems.

- Use of the methods considered here in other problems will provide further experience and evidence of the soundness of the approach.



George E. P. Box (1919-2013)

British mathematician
Statistics professor at Univ. of WI

"Essentially, all models are wrong, but some are useful."

"Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful."