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Title: Characterization of Shocked Beryllium

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Characterization of Shocked Beryllium

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Abstract

Beryllium metal has many excellent structural properties in addition to its unique radiation characteristics, including: high elastic modulus, low Poisson's ratio, low density, and high melting point. However, it suffers from several major mechanical drawbacks: 1) high anisotropy - due to its hexagonal lattice structure and its susceptibility to crystallographic texturing; 2) susceptibility to impurity-induced fracture - due to grain boundary segregation; and 3) low intrinsic ductility at ambient temperatures thereby limiting fabricability. While large ductility results from deformation under the conditions of compression, the material can exhibit a brittle behavior under tension. Furthermore, there is a brittle to ductile transition at approximately 200 C under tensile conditions.

While numerous studies have investigated the low-strain-rate constitutive response of beryllium, the combined influence of high strain rate and temperature on the mechanical behavior and microstructure of beryllium has received limited attention over the last 40 years. Prior studies have focused on tensile loading behavior, or limited conditions of dynamic strain rate and/or temperature. The beryllium used in this study was Grade S200-F (Brush Wellman, Inc., Elmore, OH) material.

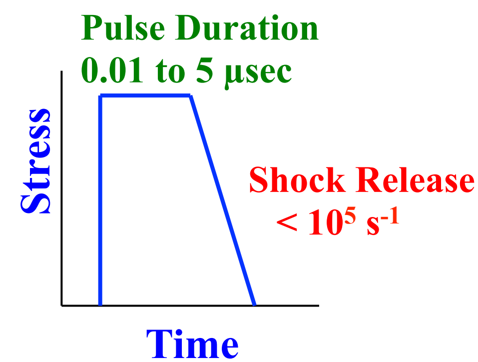
The work focused on high strain rate deformation and examine the validity of constitutive models in deformation rate regimes, including shock, the experiments were modeled using a Lagrangian hydrocode. Two constitutive strength (plasticity) models, the Preston-Tonks-Wallace (PTW) and Mechanical Threshold Stress (MTS) models, were calibrated using the same set of quasi-static and Hopkinson bar data taken at temperatures from 77K to 873K and strain rates from 0.001/sec to 4300/sec. In spite of being calibrated on the same data, the two models give noticeably different results when compared with the measured wave profiles. These high strain rate tests were conducted using both explosive drive and a gas gun to accelerate the material. Preliminary analysis of the results appears to indicate that, if fractured by the initial shock loading, the S200F Be remains sufficiently intact to support a shear stress following partial release and subsequent shock re-loading of the material. Additional "arrested" drive shots were designed and tested to minimize the reflected tensile pulse in the sample. These tests were done to both validate the model and to put large shock induced compressive loads into the beryllium sample.

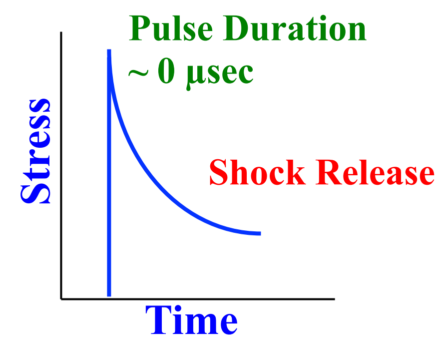
LA UR 11-06178

Outline

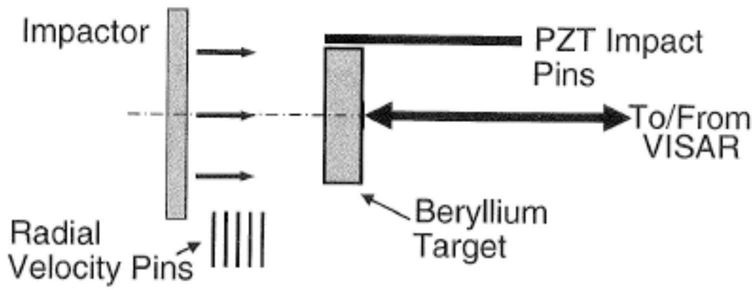
- The material characterized in this study is S-200 F Be manufactured by Brush Wellman Inc..
- By weight it is 99.02% Be, 0.72% BeO, 0.9% Fe, 0.072% C, 0.038% Al, 0.025% Si, and 0.038% other.
- The average grain size is 11.4μm and the density is ρ = 1.85g/cc

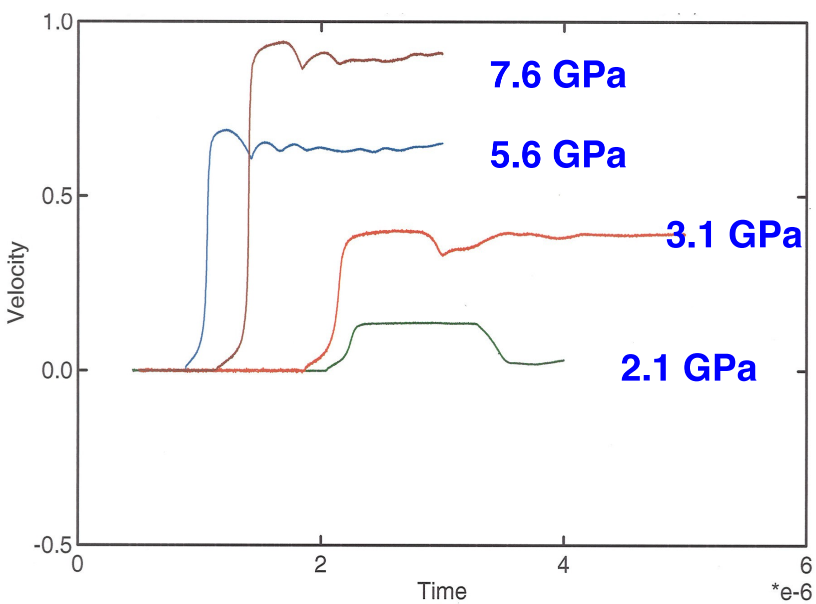
- Background
  - Flyer Plate Shock Image
  - Explosively Driven Shock
- Explosively Driven Arrested Shock
  - Design
  - Results
- Conclusions





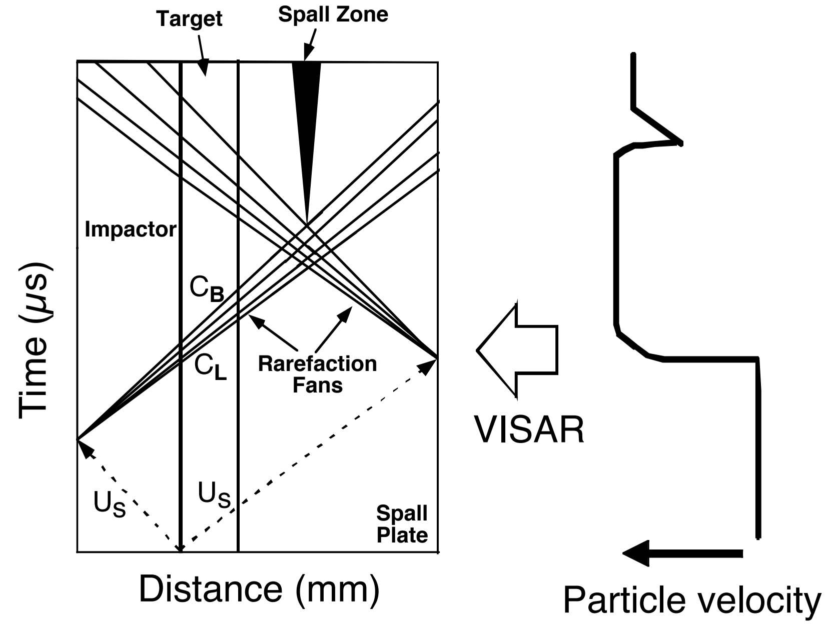
Introduction to Shock and Low Pressure Shock Data on Be





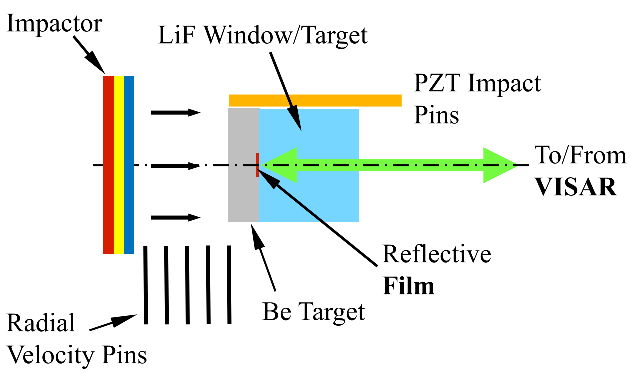
HEL appears consistent w/ prev. 6 mm thick Be target data

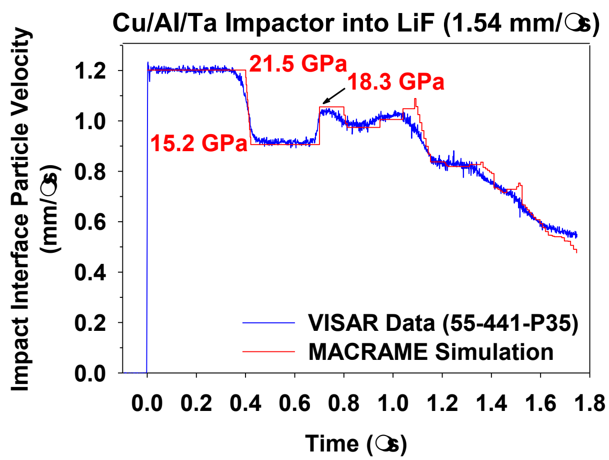
Same "rampy" wave profile as previously observed

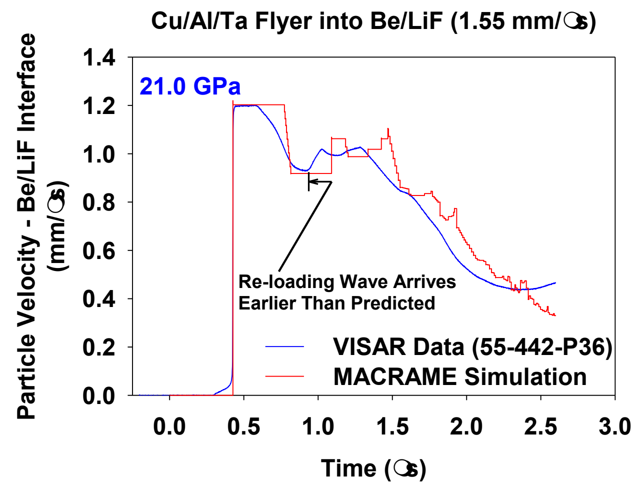


40 mm gun in glove box

Be Shock/Partial Release/Re-shock Experiments

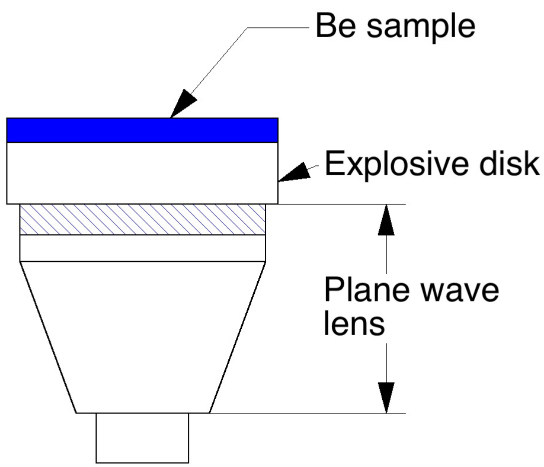




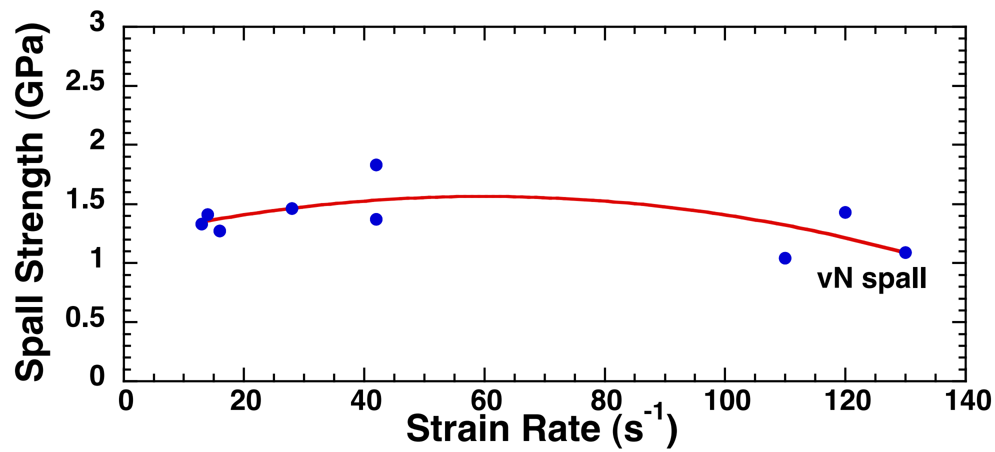


- Goal: Measure composite impactor shock loading profile
  - Configuration:0.98 mm annealed OFHC Cu, 0.95 mm 6061-T6 Al, 0.80 mm annealed Ta
- Front surface impact geometry with LiF window target at 1.54 mm/ms
- Successful experiment
  - Achieved initial shocked state pressure in excess of 20 Gpa, partial release of ~5 GPa, and re-shocked ~ 3 Gpa. Excellent Agreement with 1-D MACRAME Wave propagation code Prediction (See Graphic) which gives no consideration to elastic waves
- Questions addressed:
  - Is Be turned to rubble by the passage of an initial 20+ GPa shock?
  - Does this Be support a shear stress (retain strength) after partial release and shock re-loading?
- Early arrival of re-loading wave suggests elastic (shear strength) as opposed to bulk wave re-loading

Explosively Driven Spall Strength Measurements



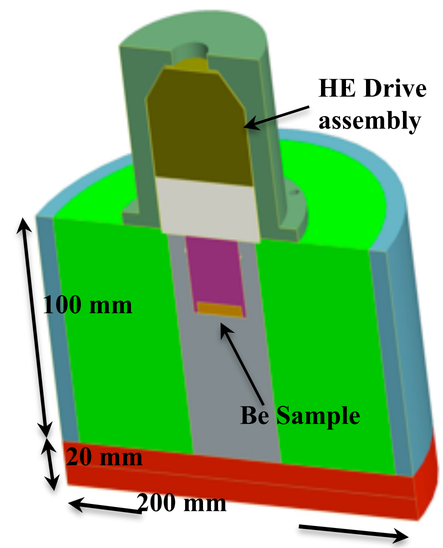
Shot Probe	Be mm	Explosive	du_{fs}/dt m/s^2	$\dot{\varepsilon}$ s^{-1}	Δu_{fs} m/s	σ GPa
B1	1.0	TNT	-3.4e9	1.3e5	89.8	1.09
B2	1.0	TNT	-3.0e9	1.2e5	117.7	1.43
B3	1.0	TNT	-3.0e9	1.1e5	85.5	1.04
X1	5.0	9501	-1.1e9	4.2e4	112.6	1.37
X2	5.0	9501	-1.1e9	4.2e4	150.0	1.83
X3	5.0	9501	-7.4e8	2.8e4	120.5	1.46
C1	5.0	TNT	-4.1e8	1.6e4	104.6	1.27
C2	5.0	TNT	-3.3e8	1.3e4	110.2	1.33
C3	5.0	TNT	-3.7e8	1.4e4	116.5	1.41

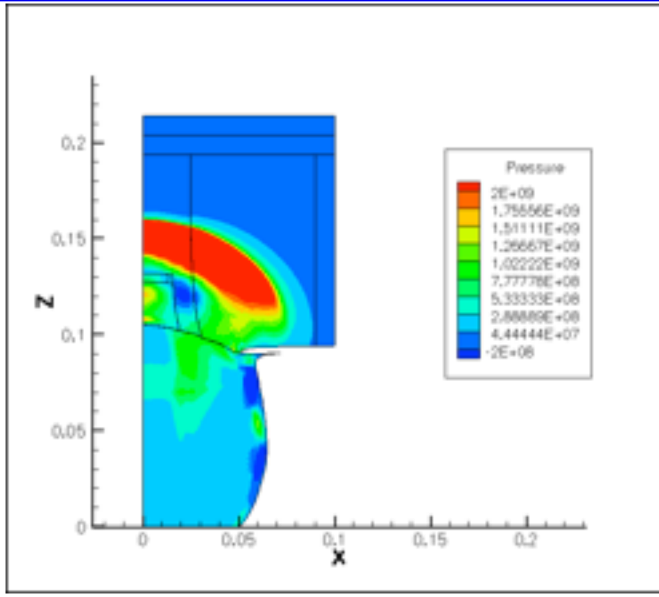


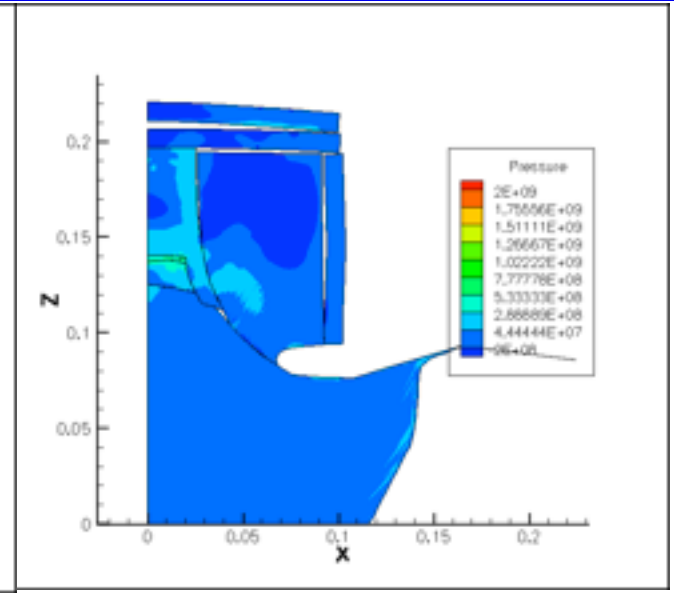
- **The spall strength for explosively driven shock does not strongly depend on strain rate.**
- **The observation of spall on the von Neumann spike indicates that Be fails under vary short-lived unloading (very narrow triangle waves) (Similar results were seen by Meyers(1))**
- **The spall strength beryllium does not appear to be dependent on either strain rate or the shape of the incident wave indicating that the kinetics of the failure mechanism is quite fast.**

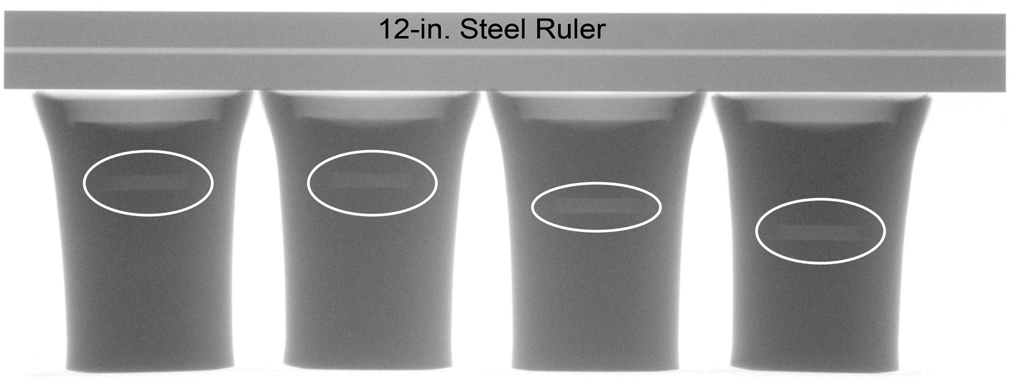
(1) M.A. Meyers and C.T. Aimone "Dynamic Fracture (Spalling) of Metals" *Progress in Materials Science*, Vol 28, pp 1-96, 1983

Arrested Be Shock Assembly, Model Prediction, and Radiographs









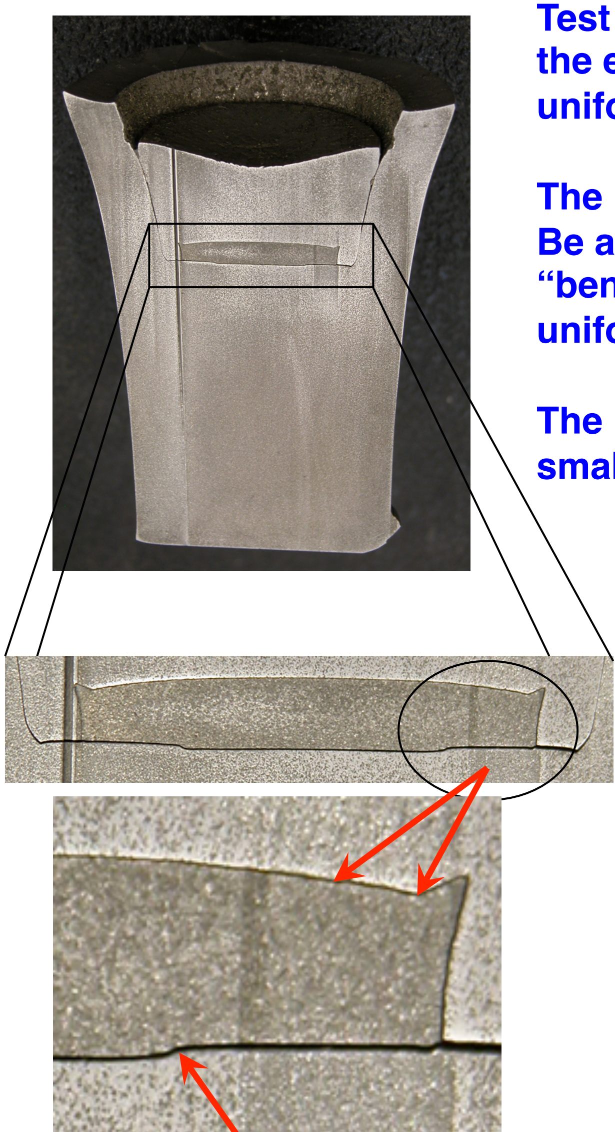
30 mm 30 mm 40 mm 50 mm

Stand-off distance from HE

The arrested Beryllium (Be) experiments are focused on validating model prediction, determining if Be fails in compression, and to observe post-shock material characteristics.

Experiment designed such that the maximum reflected tensile pressure would be < 3 kbar.

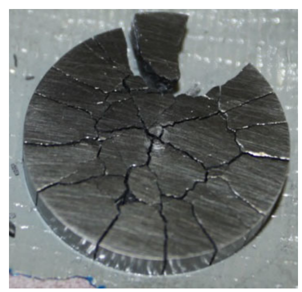
Arrested Shock loading of Mg and Be



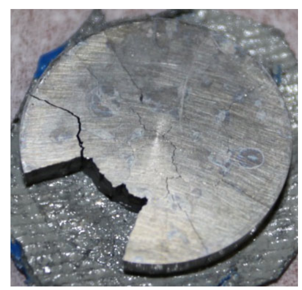
Test shot of magnesium. Note that the Mg did not deform uniformly - the edges are more compressed than the center region indicating non-uniform loading and possible "bending" moments.

The non-uniform deformation evidenced in the Mg is manifested in the Be as fairly large scale fragmentation which is believe to be caused by "bending" during the test. The post-test recovered Be disks were of uniform thickness.

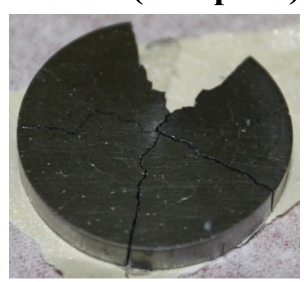
The model predictions were largely successful because there was little small scale fragmentation, an indicator of tensile stresses.



40 mm (Sample 3)



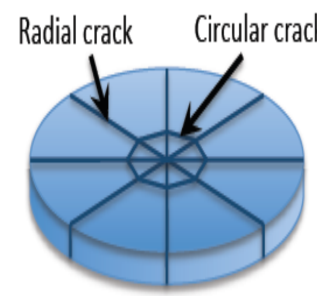
30 mm (Sample 5)



30 mm (Sample 6)

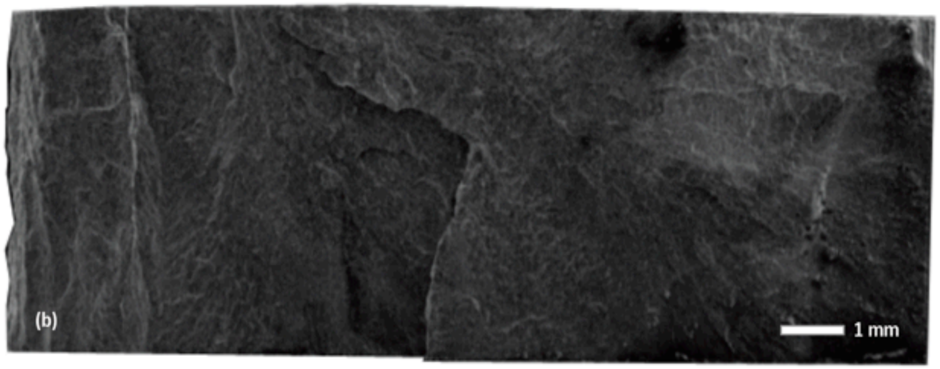
50 mm (Sample 7)

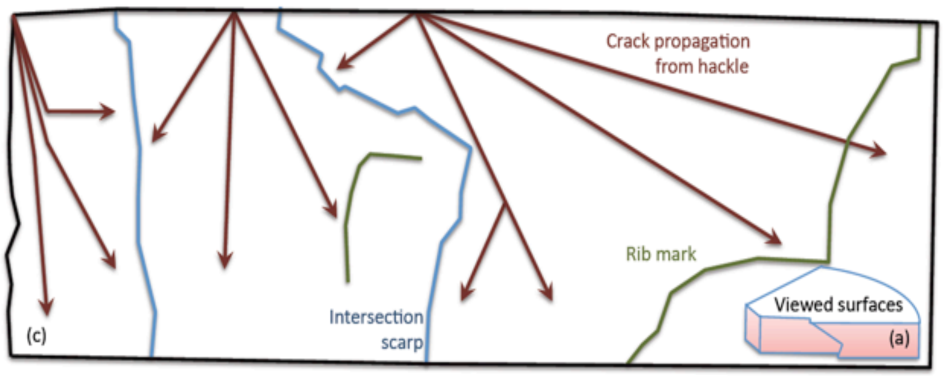
Post Test Be Disks



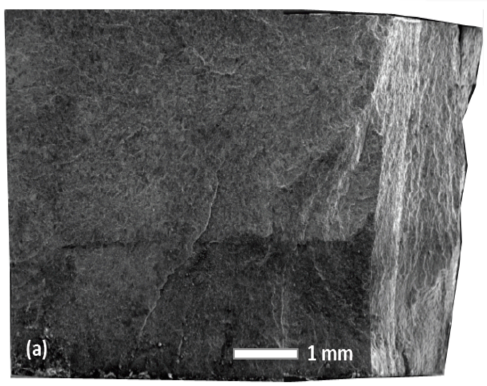
Typical Fracture Surfaces – Large Scale

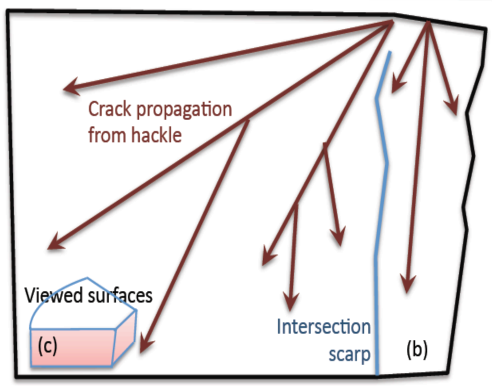
30 mm (Sample 5)

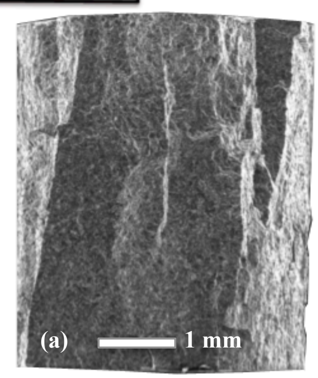


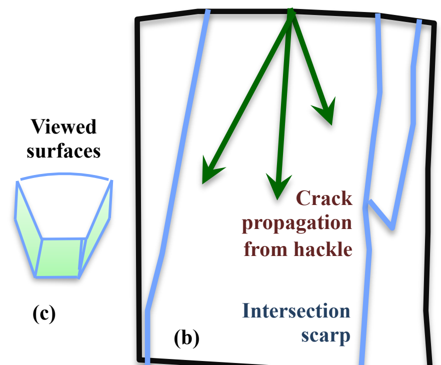


- Direction of fracture from top to bottom.
- Likely has multiple initiation sites.
- Circular and radial both initiate from side closest to HE





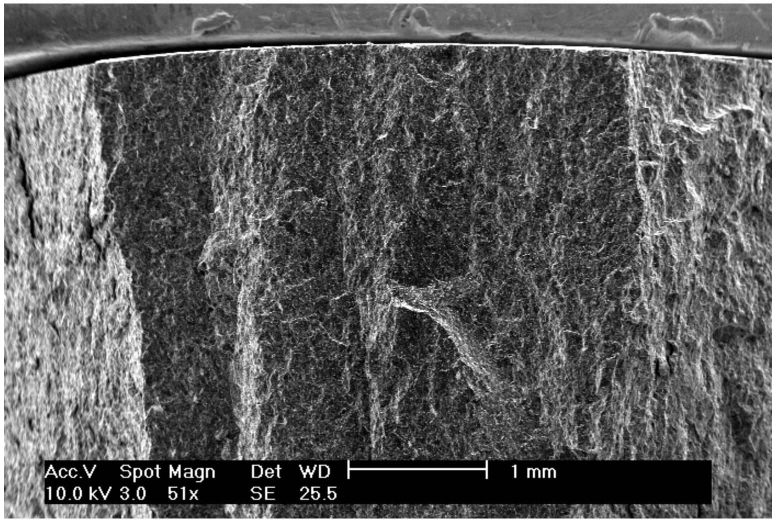


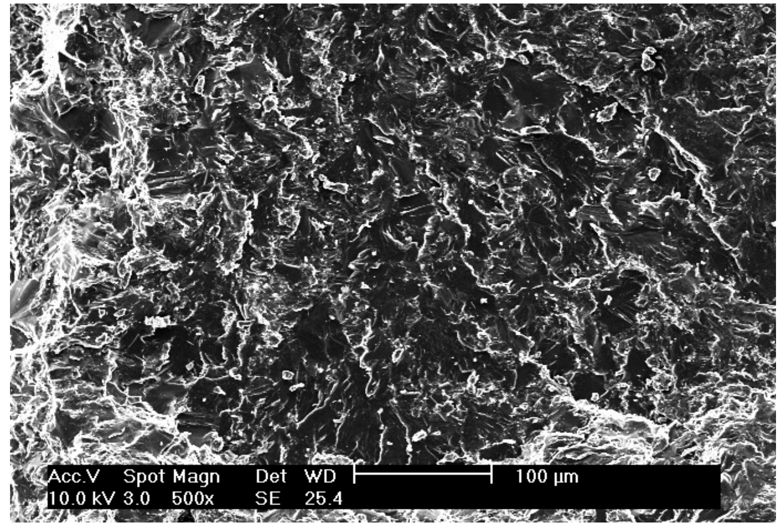


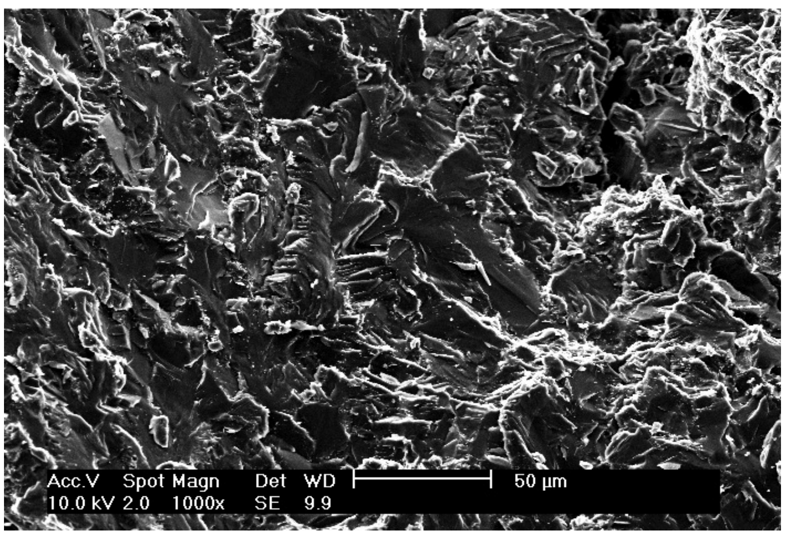
40 mm (Sample 3)

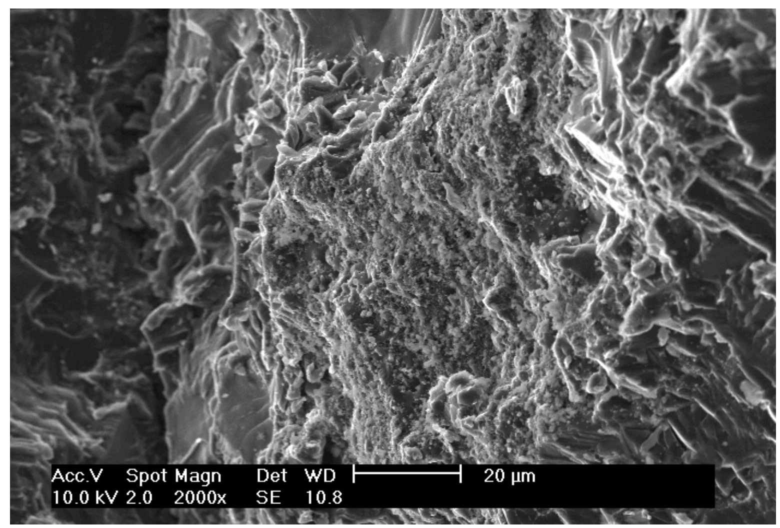
50 mm (Sample 7)

Typical Fracture Surface -microscopic





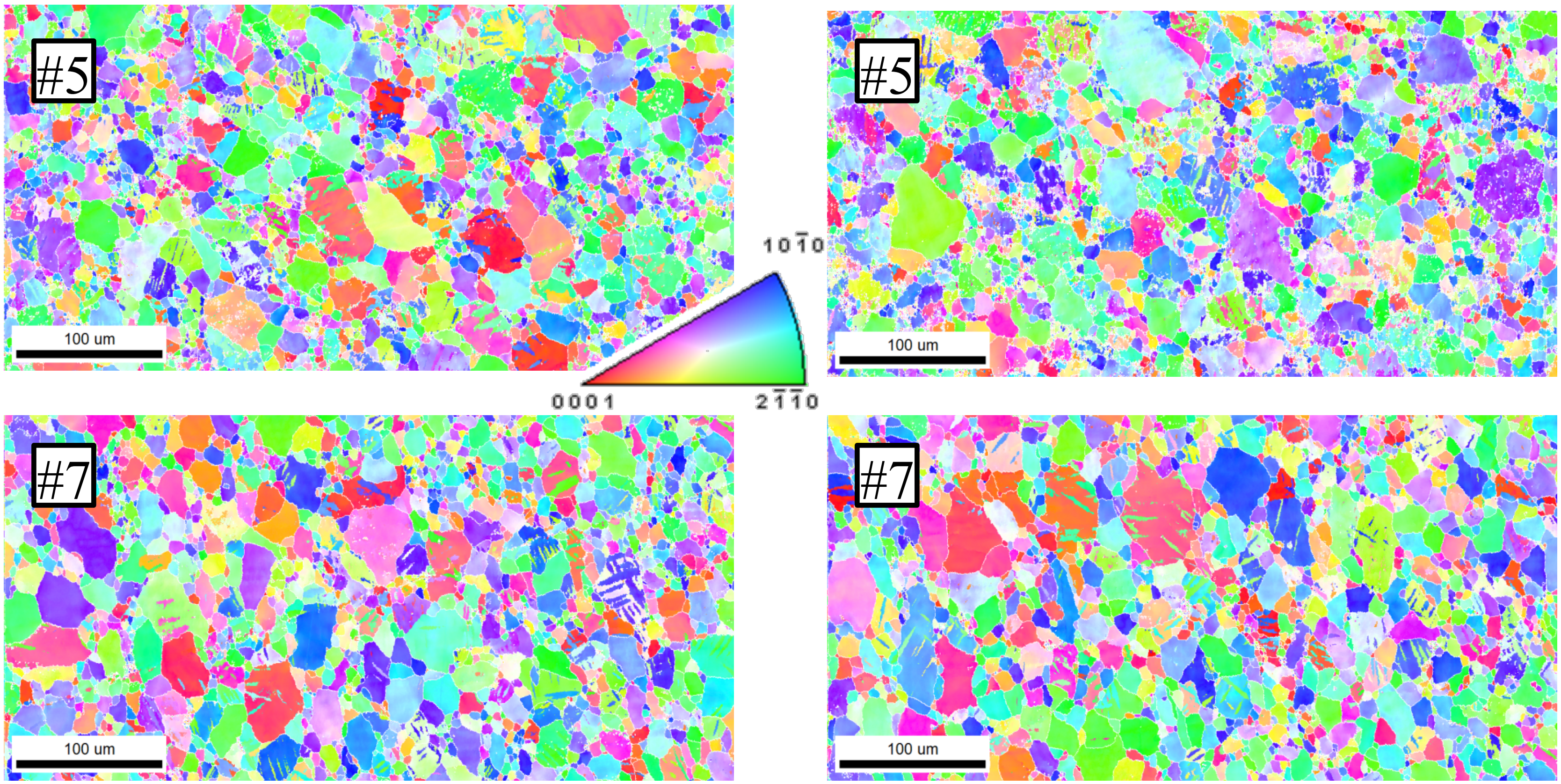




40 mm (Sample 3)

Inverse Pole Figures (Plane Normal)

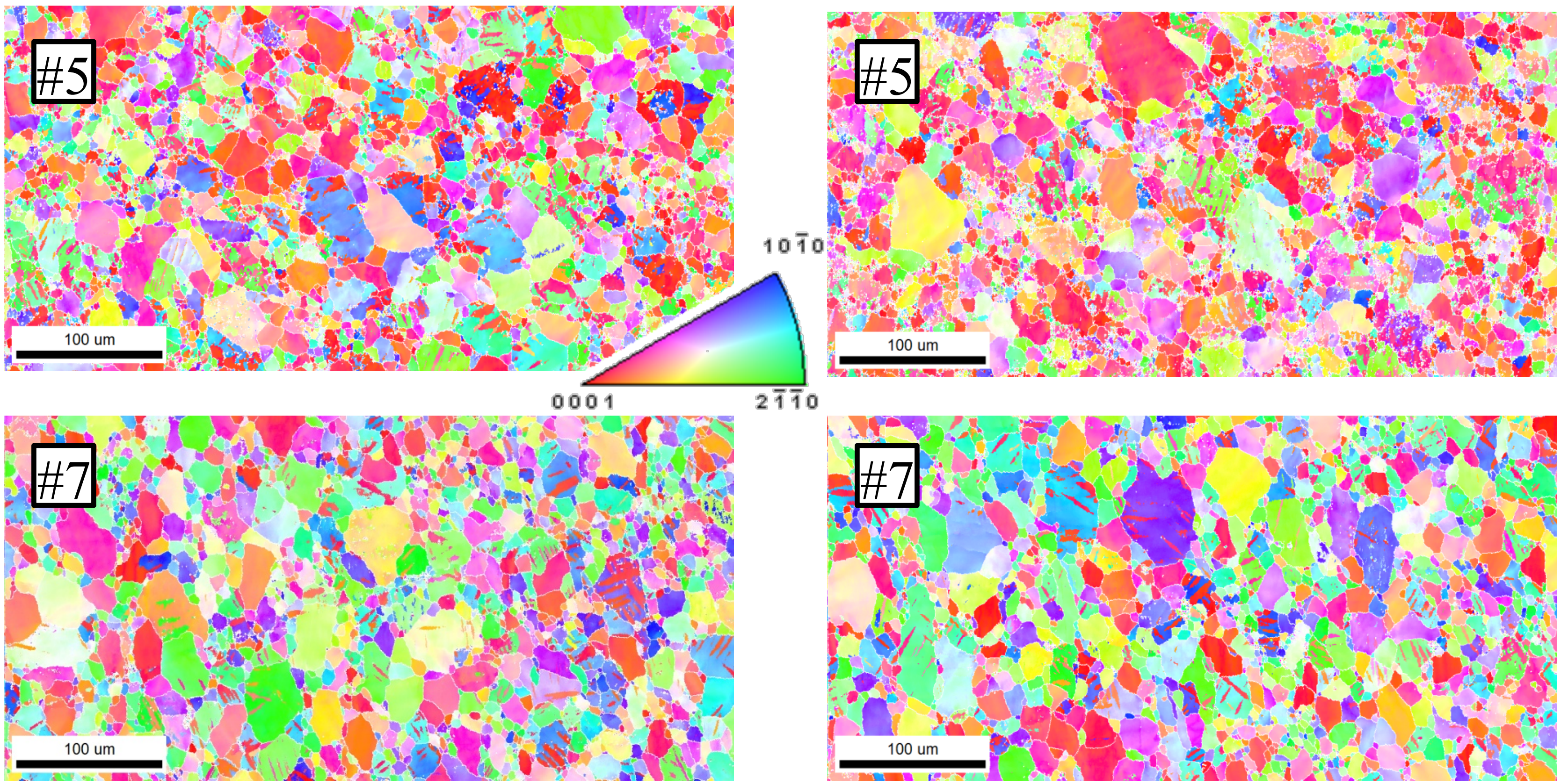
Internal | Edge



More twins may be observed qualitatively in Sample #5 IPF's. This is quantified in a following slide.
Note: All scans were performed with a step size of .5 micron.

Inverse Pole Figures (Shocked Direction)

Internal | Edge

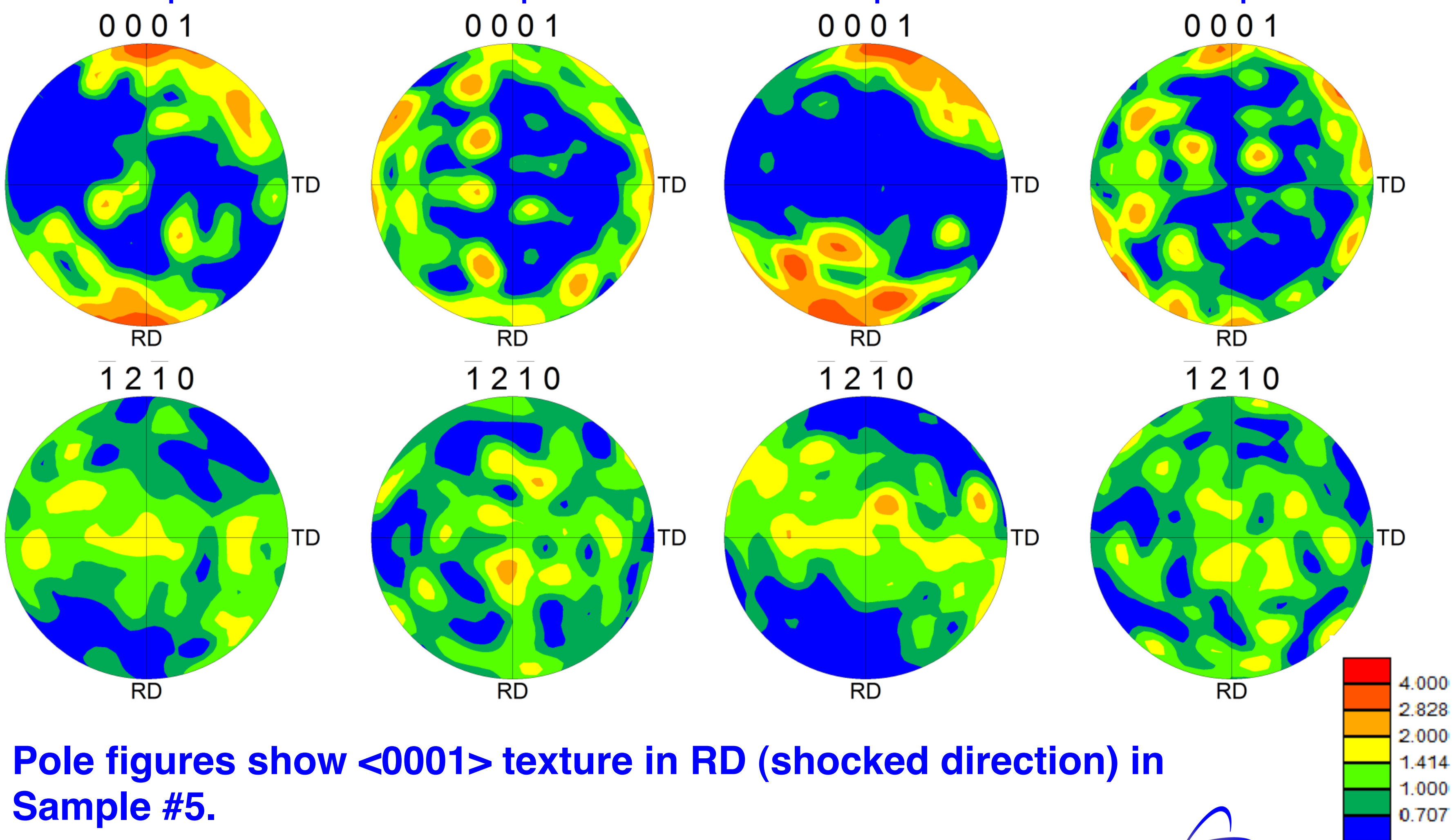


Grains in Sample #5 show a stronger <0001> texture in the shocked direction.

Pole Figures

Internal | Edge

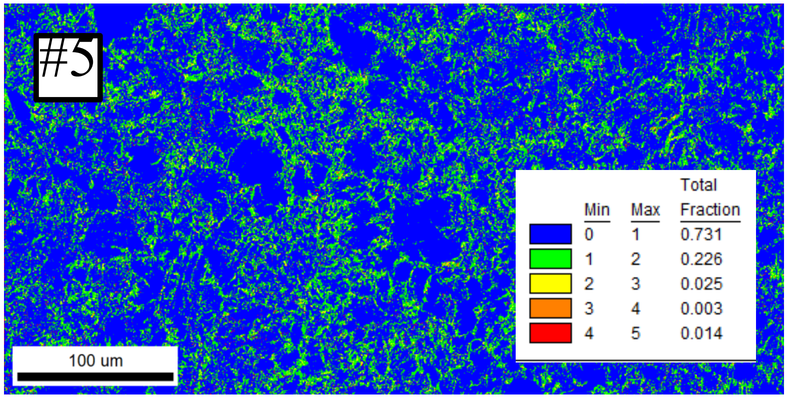
Sample 5 | Sample 7 | Sample 5 | Sample 7



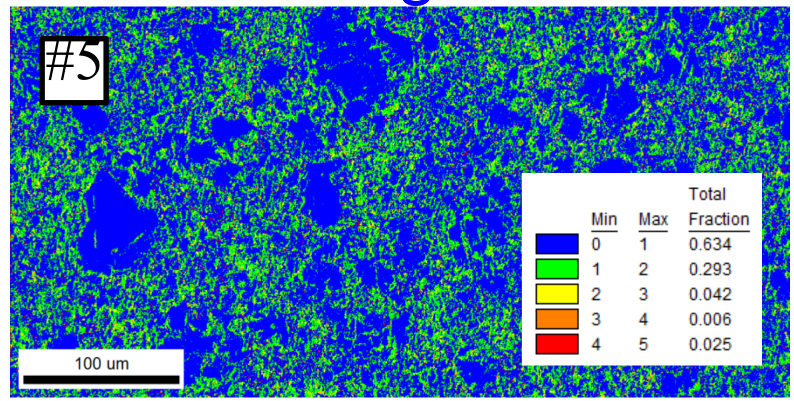
Pole figures show <0001> texture in RD (shocked direction) in Sample #5.

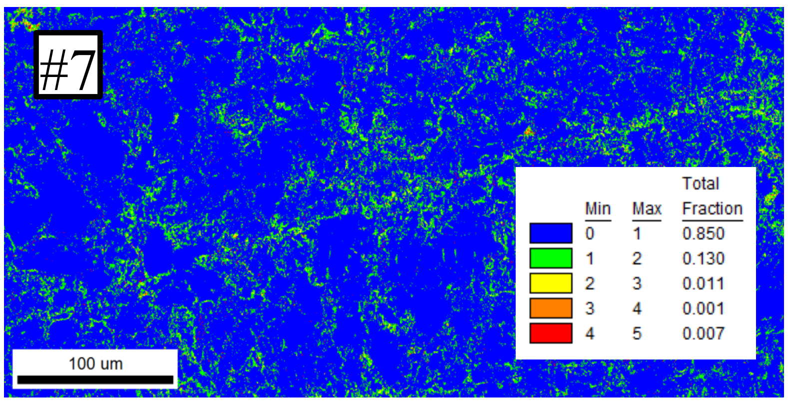
Kernel Average Misorientations (1st Neighbor)

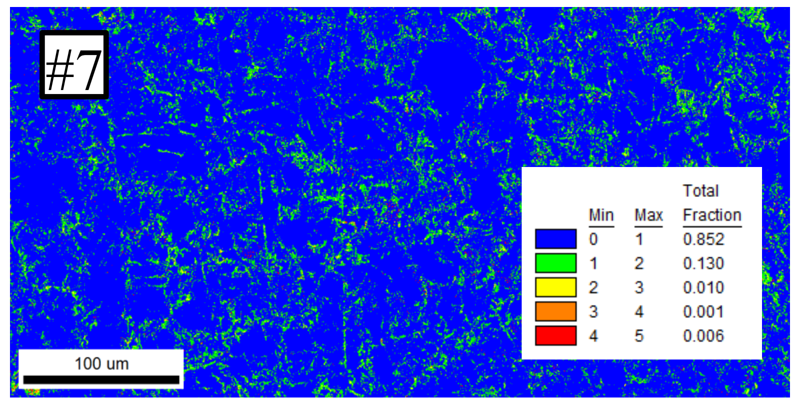
Internal



Edge





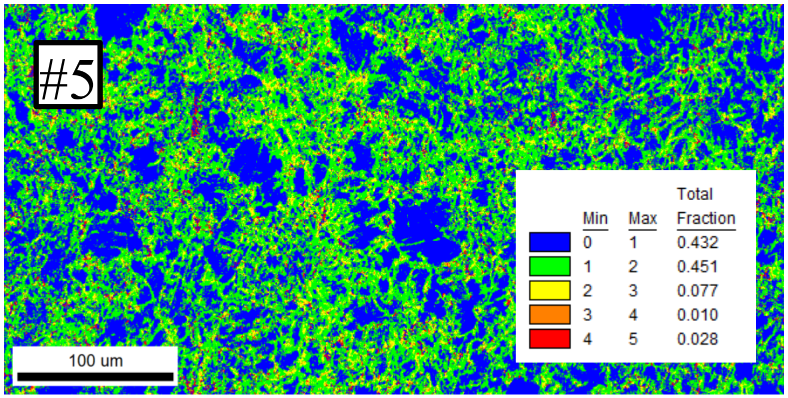


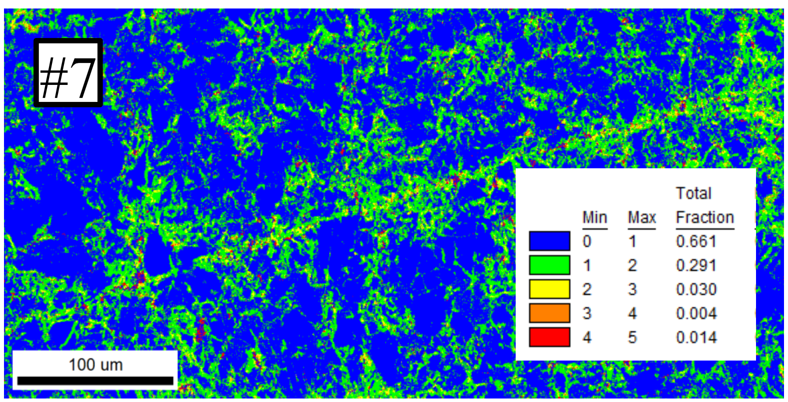
Sample #5 exhibits more localized misorientation, a sign of greater strain present within the sample.

Note: Min and Max in legend are in degrees. Maximum misorientation = 5 degrees. Step size is 0.5 μm.

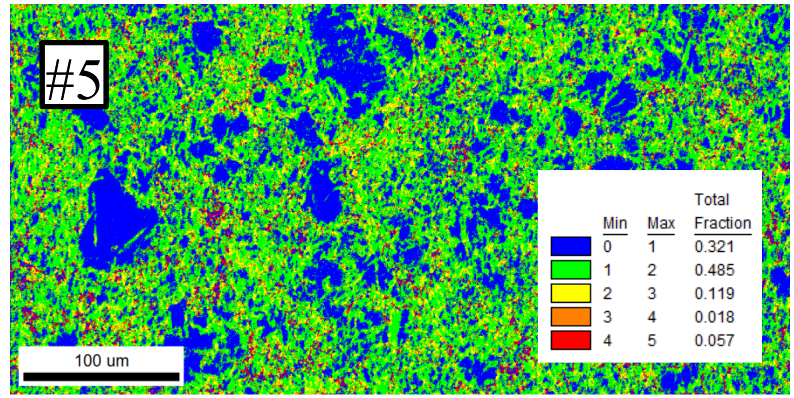
Kernel Average Misorientations (2nd Neighbor, Perimeter)

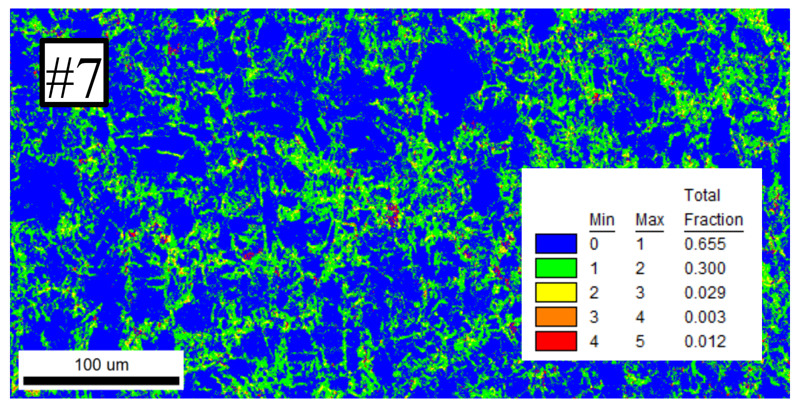
Internal





Edge





Sample #5 exhibits more misorientation. The same observations were made when KAM was performed to 3rd nearest neighbors, both perimeter and whole kernel averages.

Conclusions

- Spall strength does not strongly depend on impulse shape (□ , △ wave) for materials that exhibit brittle failure – Future work on similar material (Tungsten heavy alloy) is planned to see if this result is material independent.
- Bending stresses likely lead to the failure of the Be in Arrested tests.
- Failure typically propagated from center to edge and from HE side downward.
- Evidence of Damage relative to position
  - Sample closer to HE contains a higher area fraction of twins and twinned grains; twinning is a primary damage mechanism in Be.

	Internal	Edge
Sample #5	0.129	0.136
Sample #7	0.080	0.076

  - More residual strain is seen in the sample closer to the HE detonation.
  - Maps show more Kernel average misorientation for samples located closer to HE detonation.