Mechanochemically-Assisted Broaching of Refractory-Lined Gun Barrels

Presented by: Dr. Jason M. Davis

SEED GRANT SMART SCHOLAR PROGRAM

CAPT Duncan McKay, USN
Commanding Officer

NAVSEA
WARFARE CENTERS
CRANE

Dr. Angela Lewis, SES
Technical Director

Problem Statement

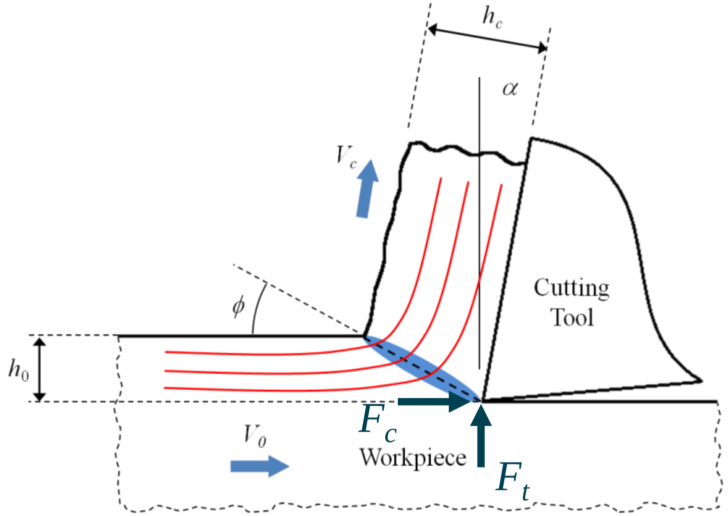
- The use of refractory metals as gun barrel liners has great potential to reduce barrel wear and permit higher rate of fire weapons, increasing reliability and sustainability.
- Machining and rifling of refractory-lined barrels has proven difficult due to the ‘gumminess’ of refractory metals, particularly for small caliber weapons – resulting in thick chip formation, large cutting forces, poor surface finish, and ultimately premature tool breakage.

Explosively Bonded Gun Tube Liner Development, Apr 2015 (ARL-CR-0771) – William de Rosset

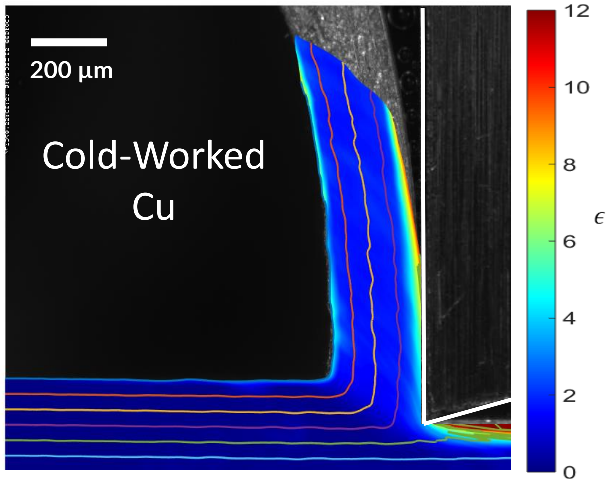
- Report recounts refractory liner development efforts – Ta10W-lined M242 barrels (25mm)
- Crown broach cutters: 60 individual cutting heads, each containing 9 pairs of teeth; each pass increases the depth of the groove by approximately 0.0004” (~ 10 µm)
  - When rifling, tooth broke on crown broach for two different barrels
  - Galling led to build-up of Ta10W on broken tooth
    - Possible causes:
      - Dull or chipped tooth
      - Inadequate cooling at tooth location
      - Chip interference with the cutting process
      - Broach moving off axis
      - Radial misalignment of the broach

      - Maybe something else…

Laminar Plastic Flow – "Well-Behaved" Flow

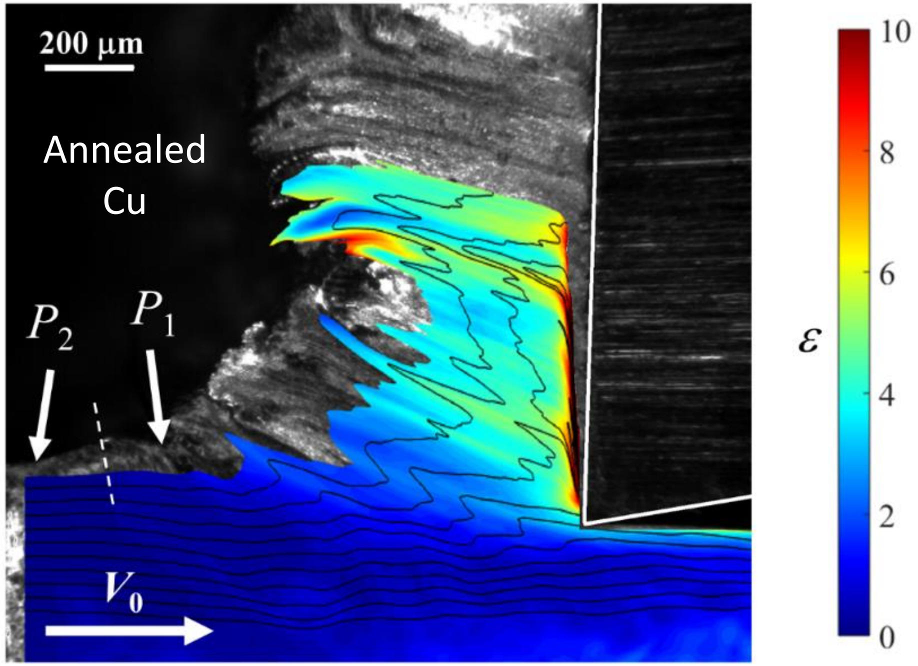


- Merchant model (1940s)
- Plane-strain orthogonal cutting
- Predicts laminar flow



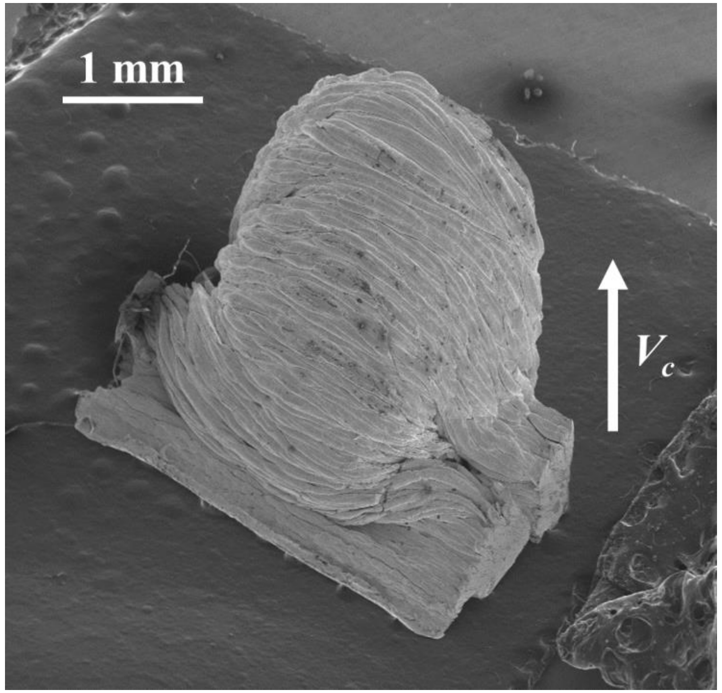
- Moderately pre-hardened Cu (cold-worked)
- Homogeneous strain
- Follows shear plane/zone model

Sinuous Flow Explains Gumminess



- Unsteady, highly redundant (mesoscale) mode of large-strain plastic deformation
- Plastic buckling and large-amplitude folding
- Heterogeneous strain distribution in the chip

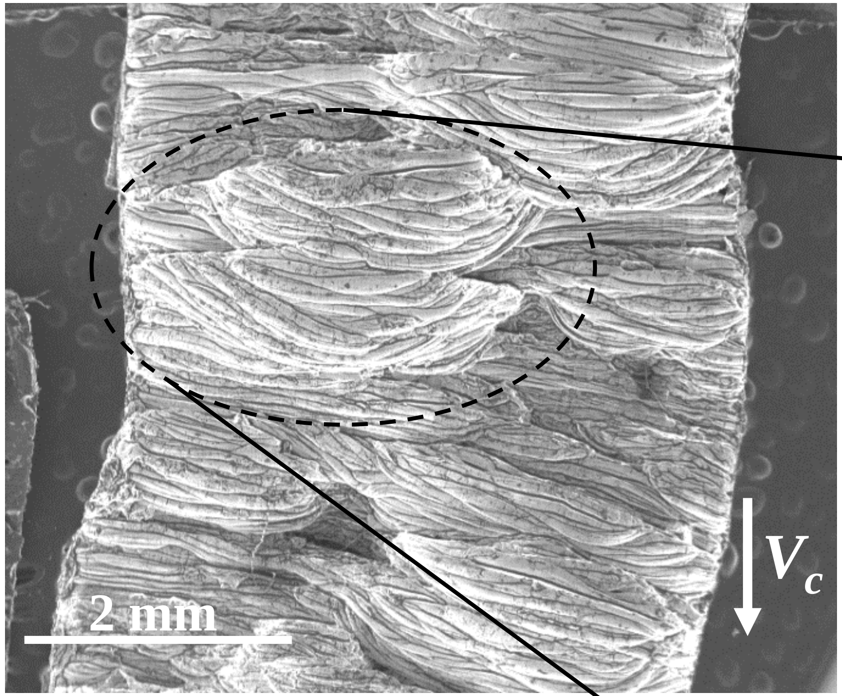
Tantalum Chip Morphology



$\alpha = 10°$
V_0 = 2 mm/s
h_0 = 40 μm

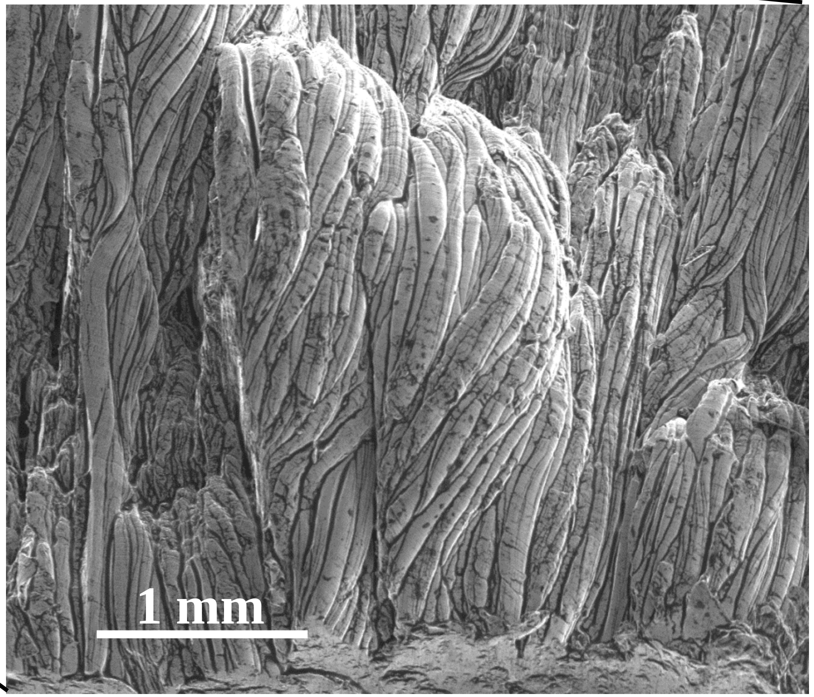
Low Speed Cutting

Top view of chip free-surface



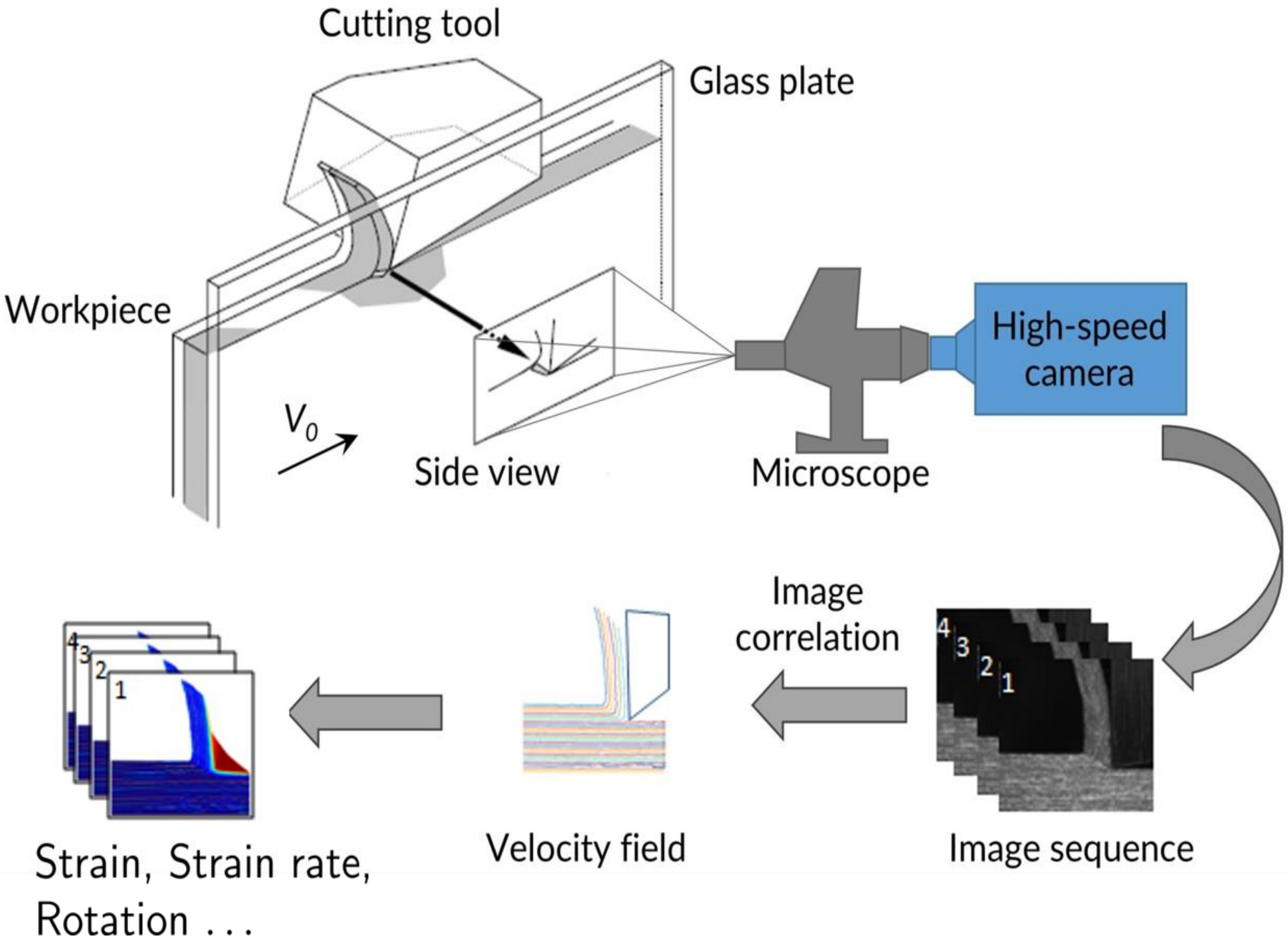
$\alpha = 0°$
V_0 = 625 mm/s
h_0 = 50 μm

"High" Speed Cutting

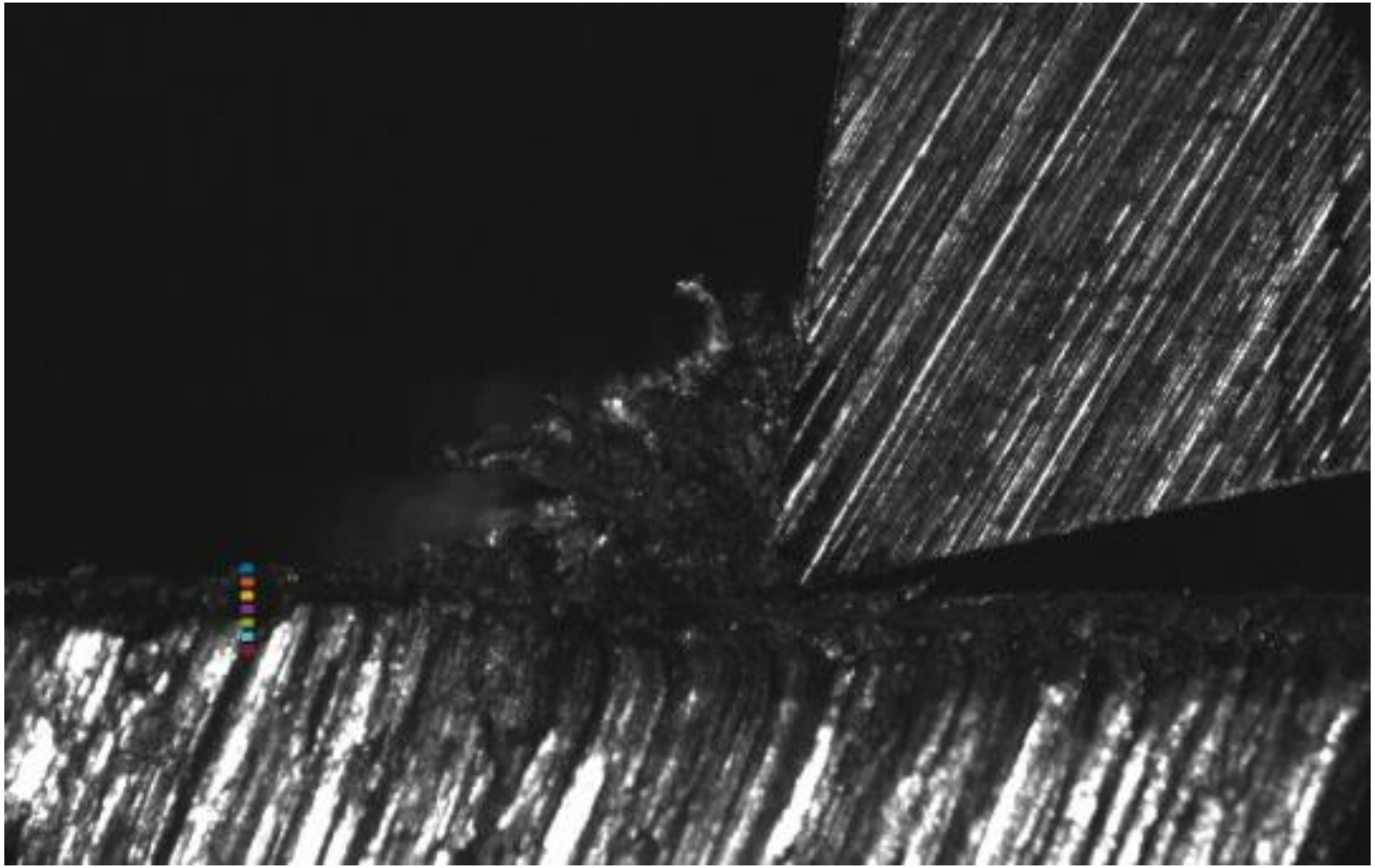


Side view of chip free-surface

In situ Analysis of Flow

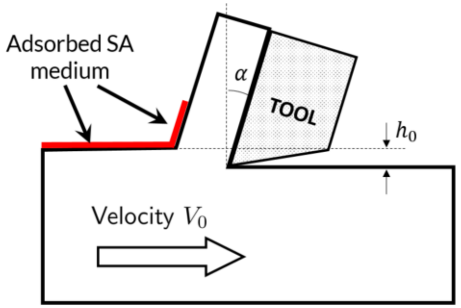


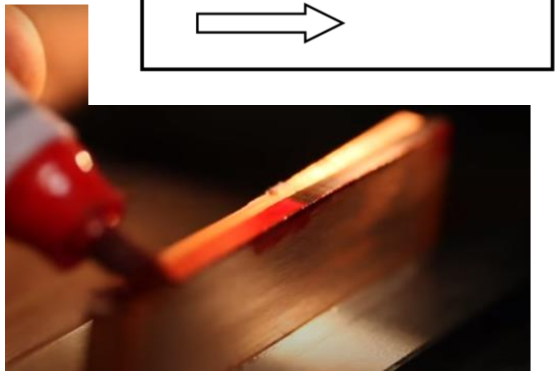
Sinuous Flow in Tantalum

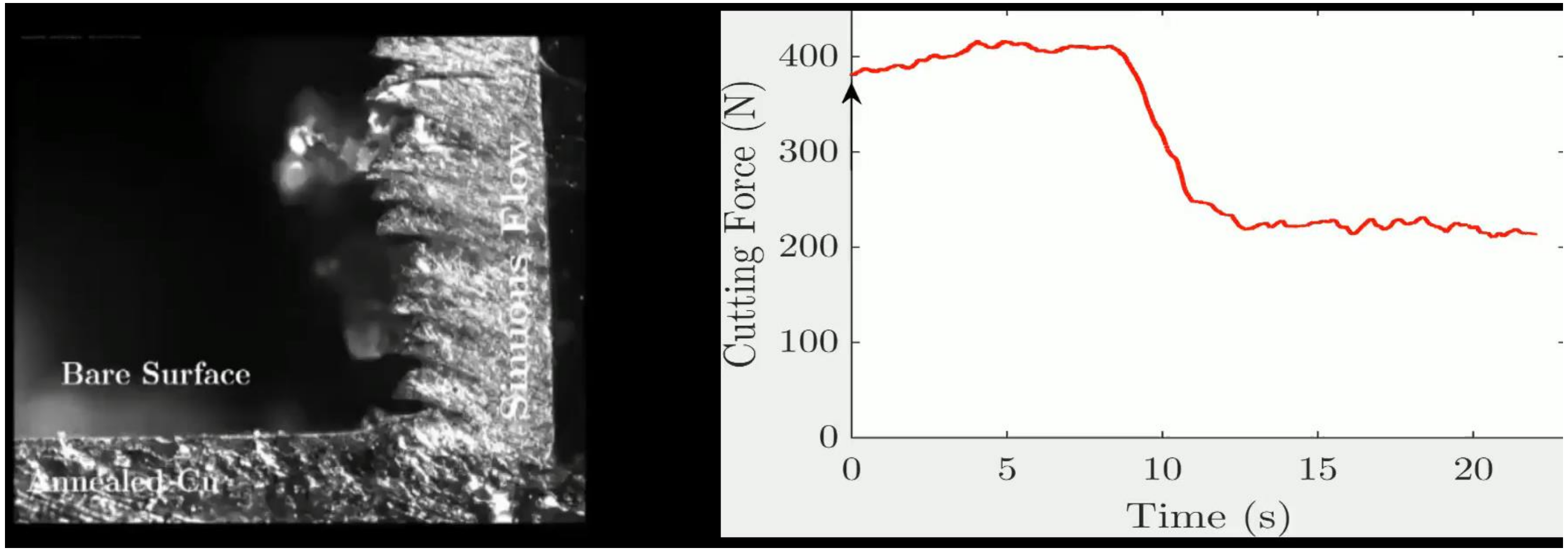


Mechanochemical Effect

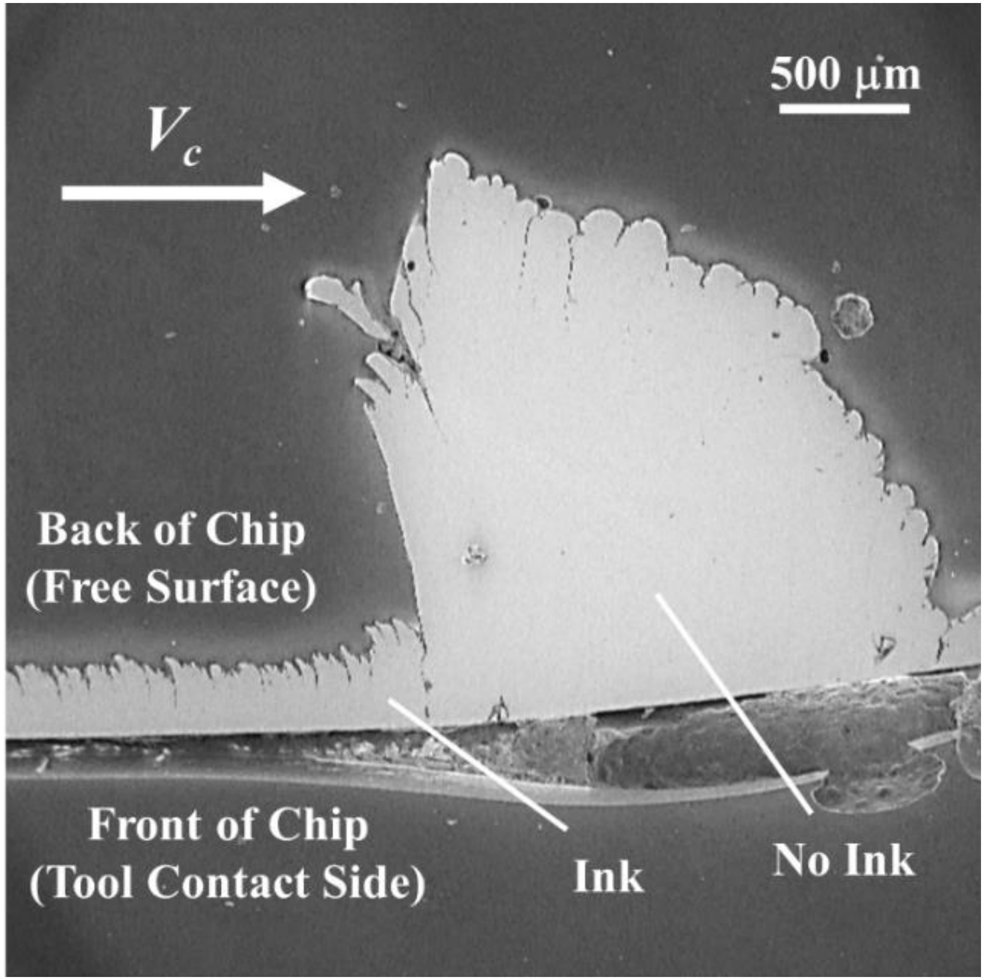
- Mechanochemical effect – changes in plastic deformation response of a material due to presence of a chemical medium; closely tied to adsorption properties, initial mechanical state of material, defect structure, conditions of fracture and deformation
- Common media such as metal marking inks, school glue, and permanent markers have been found to transition sinuous flow to segmented flow







Comparison of Chip Morphology



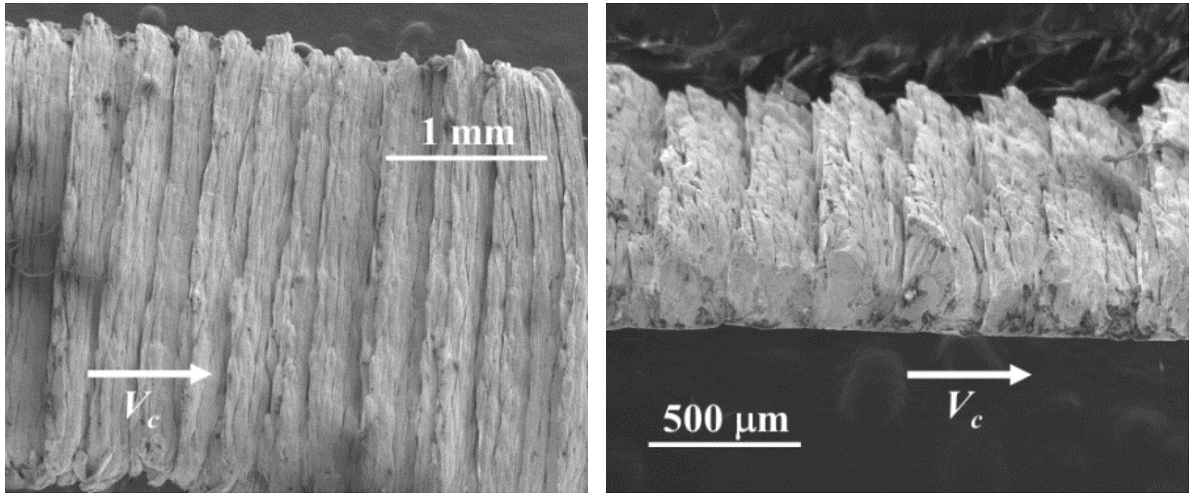
Non-inked region

- ~ 34-fold thickening in chip thickness
- Mushroom-like free surface morphology

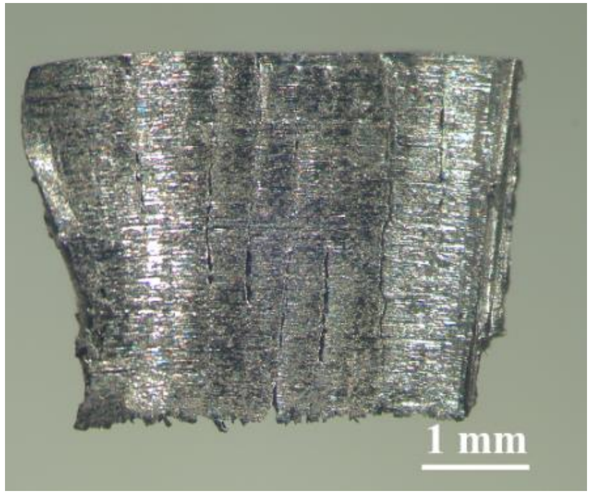
Inked region

- ~ 5-fold thickening in chip thickness
- Segmented morphology (saw-tooth)

Segmented Flow in Tantalum (with Ink)



Free-surface of chip

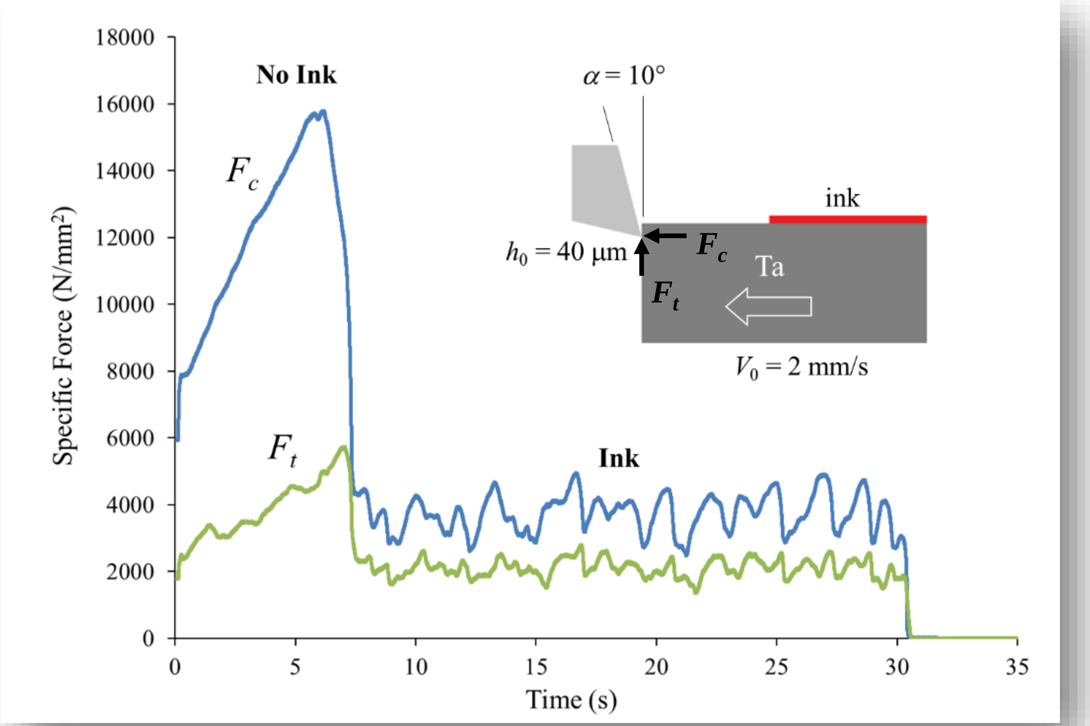


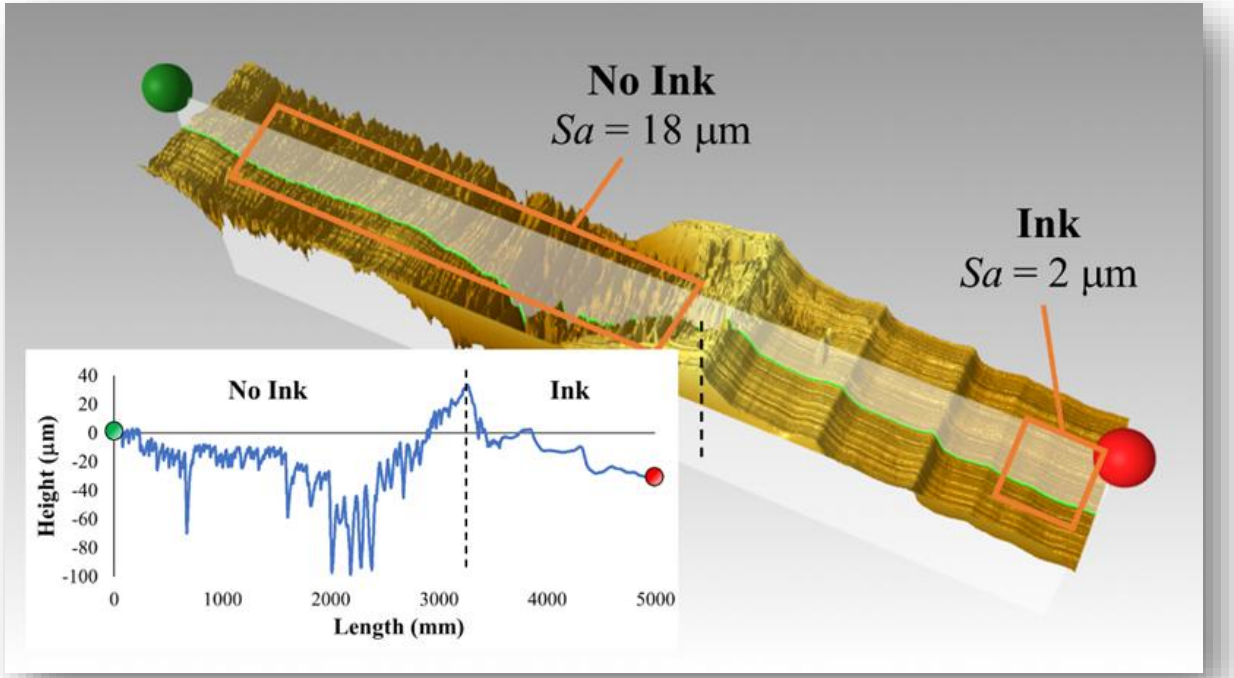
Tool contact surface of chip

α = 10°
V_0 = 2 mm/s
h_0 = 40 µm

- **Upon application of ink (~ 200 nm thick) prior to cutting, much thinner chip results with saw-tooth morphology**

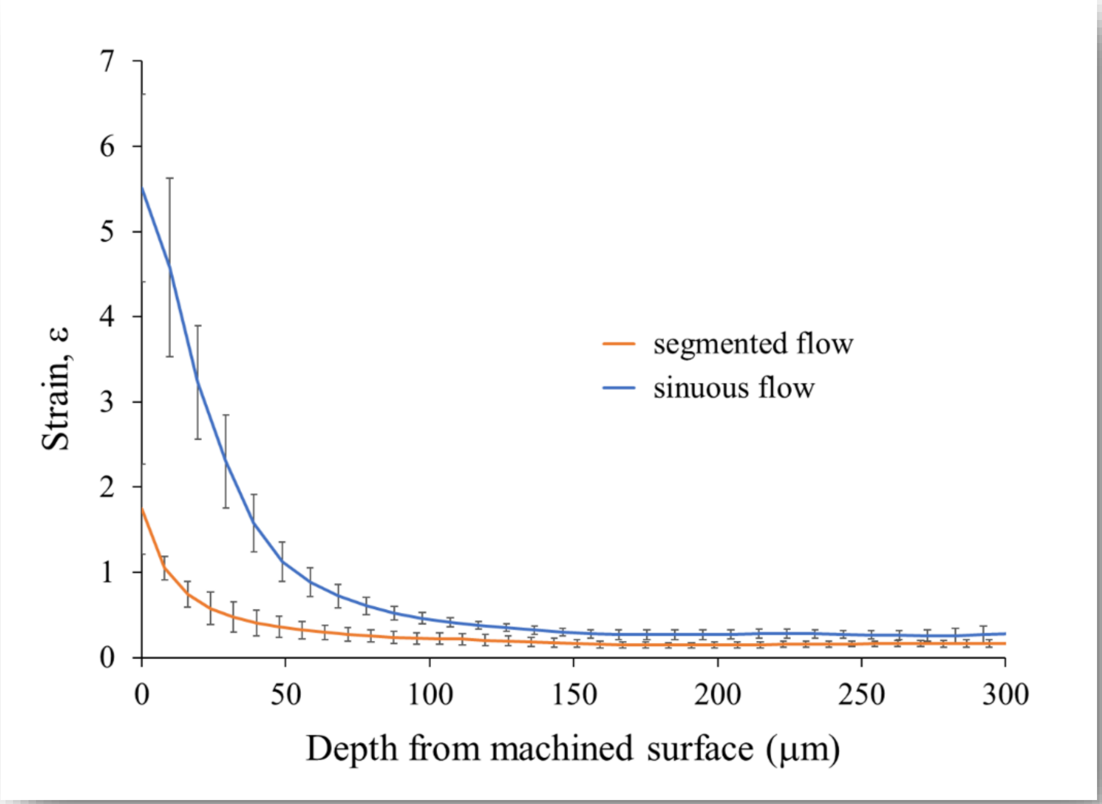
Specific Force & Surface Roughness

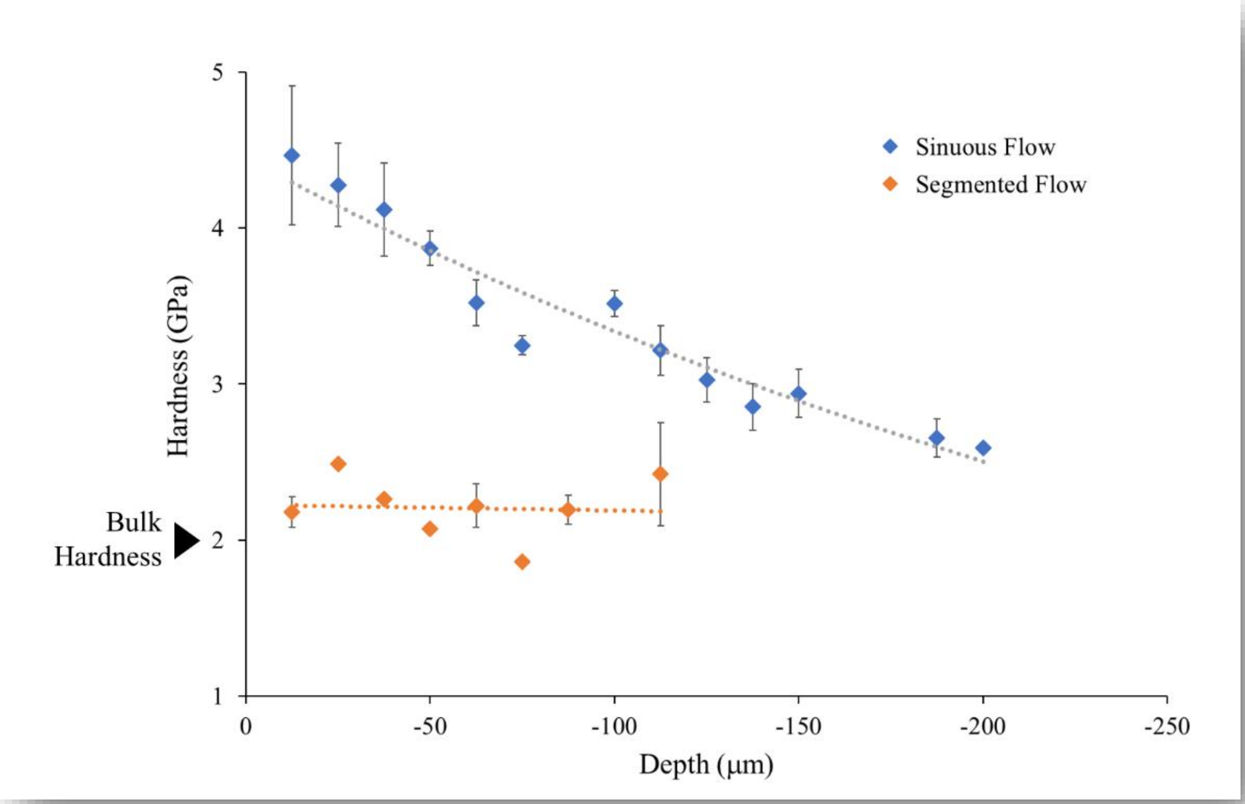




- **Lower forces decrease tool breakage and increase active cutting**

Surface Strain & Surface Hardness





Why Does Phenomenon Occur?

- Folding creates notches which are natural stress concentrators
- Surface adsorbing media induces tensile surface stress
- Additional surface stress triggers cracking at the notch tips
- Transitions deformation from plastic to brittle

- Near-surface effect (< 150 µm)

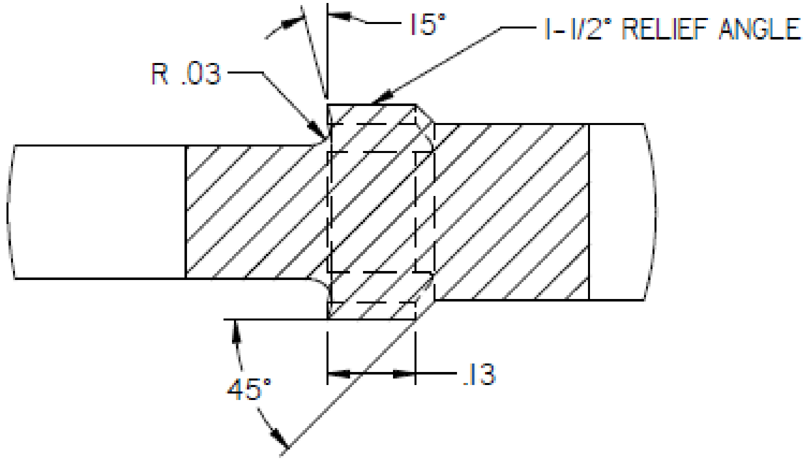
Research Approach

- Leverage basic research conducted as a Phase I SMART Scholar
  - Underlying mechanism that makes some metals ‘gummy’ when cut
  - Use of a mechanochemical effect to alleviate ‘gumminess’
- Apply basic research to the broaching/rifling of representative refractory tubes
- Success will be measured through force/torque and surface quality measurements

Basic Research vs. Broaching

How applicable is the basic research to broaching/rifling?
Or restated, does it fall within the parameters over which sinuous flow occurs?

Parameter	Basic Research	Broaching
Tool Rake Angle (α)	0 – 20°	0 – 15°
Cutting Speed (V_0)	< 4 m/s	0.05 – 0.1 m/s
Undeformed Chip Thickness (h_0)	< 150 µm	10 µm



Project Plan Overview

Phase I

Media screening FY21

Identify effective cutting media through controlled experiments – force measurements, chip morphology, surface quality, and/or high speed video.

- Drilling
- Linear cutting

Metals of Interest:

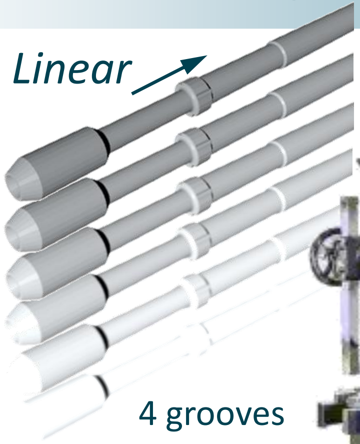
- Nb, Ta

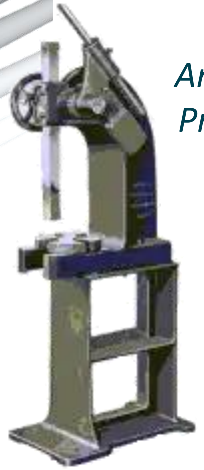
Phase II

Straight push broaching FY22

Series of Broaches

Increasing cutting diameter





Arbor Press

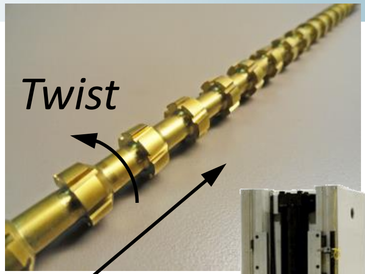
Metals of Interest:

- Cu 101, Nb
  (ID 0.300”/OD 1”, 6” length)

Phase III

Spiral pull broaching FY23

Gang Broach



Increasing cutting diameter

Vertical Broaching Machine

Metals of Interest:

- Nb, Ta
  (ID 0.300”/OD 1”, 6” & 18” length)

Next Steps – FY22

- Complete media screening and measuring of surface stress
- Finish fixture design for arbor press
- Conduct straight push broaching of 6” Cu and Nb
  - Broaches and Nb tubes in-hand
- Characterize surface quality of broached tubes
- Finish design and procure spiral pull broaches
- Procure 6” and 18” Ta tubes

Acknowledgements

Science, Mathematics & Research for Transformation (SMART) Scholar SEED Grant Program

Center for Materials Processing & Tribology – Purdue University

American Broach & Machine Co.

NAVSEA WARFARE CENTERS CRANE

Thank You!

Jason M. Davis, Ph.D.

Naval Surface Warfare Center, Crane Division (NSWC Crane)

300 Hwy 361 - Bldg 3422

Crane, IN 47552-5001

Ph: 812-854-6855

e-mail: jason.m.davis3.civ@us.navy.mil

References

- De Rosset W. (2015). Explosively bonded gun tube liner development (ARL-CR-0771).
- Davis, J. M., Saei, M., Mohanty, D., Udupa, A., Sugihara, T. & Chandrasekar, S. (2020). Cutting of tantalum: Why it so difficult and what can be done about it. *Int. J. Mach. Tools Manuf*, *157*, 103607.
- Sugihara, T., Udupa, A., Viswanathan, K., Davis, J. M. & Chandrasekar, S. (2020). Long-chain monolayers disrupt plastic flow in metals. *Science Advances*, *6*(51), 1-7.
- Udupa, A., Viswanathan, K., Davis, J. M., Saei, M., Mann, J. B., & Chandrasekar, S. (2019). A mechanochemical route to cutting highly strain-hardening metals. *Tribology Letters*, *67*(4), 1-12.