Project 54-L: Lubricious PVD Coatings for Forging Dies

Semi-annual Fall Meeting
October 2021

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- Student: Jesus Vazquez (Mines)
- Advisors: S. Midson, A. Korenyi-Both, K. Clarke (Mines)

Project Duration

PhD: January 2021 to December 2024

- Problem: The use of conventional lubricants in forging operations is not environmentally friendly and enhances thermal fatigue, which limits the lifetime of forging dies
- Objective: Examine coating techniques and methods to modify the surface topography, to identify optimum surface conditions to reduce or eliminate the need for conventional lubricants
- Benefit: Improvements in die life, cycle time, work environment, forged parts quality and cost

Recent Progress

- Continuing literature survey
- Baseline study for uncoated dies with different surfaces roughness under unlubricated conditions
- Finalizing the redesign of the die holder to incorporate heating cartridges
- Started testing first coated dies under lubricated and unlubricated conditions

Metrics

Description	% Complete	Status
1.Perform a literature review to identify suitable thin-film lubricious coatings	40%	●
2. Improve the die holders used in the ring forging test, to provide better control of temperature	25%	●
3. Identify coatings that can provide low coefficient of friction values during unlubricated forging tests	20%	●
4. Characterize the effect of die surface morphology on friction during forging	3%	●
5. Perform trials in forging plants with the coatings & surface texturing identified in this project	0%	●

Introduction

- Forging dies usually use hardened H13 steel dies
- Lubricant is sprayed onto the die faces prior to each forging operation
  - Purpose is to decrease friction between workpiece and die
  - Minimize buildup of forged material onto die faces
  - This causes thermal fatigue of dies
- Initial FIERF funded project [1]
  - Validated the Ring Forging Test (RFT) [2] in which the best tested coatings, i-Kote, provided low levels of friction during unlubricated forging
  - Coated dies may allow a significant reduction in the use of conventional lubricants
  - Better understanding of the relationship of the coating surface morphology and the mechanism for the reduction coefficient of friction is needed
  - Pin-on-disk results do not correlate to RFT

Project Approach

- Test lubricious coatings applied to the die faces of H13 steel
  - To reduce or eliminate use of conventional lubricants used during forging
  - Examine if the use of a bonding layer will improve performance
- Current stage of this project involves performing a literature review
  - Summarize previous research on use of PVD thin-film coatings on forging dies
  - Identify different techniques to obtain lubricious coatings at forging temperatures
- RFT of coated dies

Testing Methodology

- Use a reciprocating tribometer to down select coatings
- Perform RFT
  - Quantitatively distinguish coefficient of friction (CoF) between the various coatings and test conditions
  - Simulates metal deformation conditions present in commercial forging applications
    - Correlates better than other tribological test procedures such as pin-on-disk

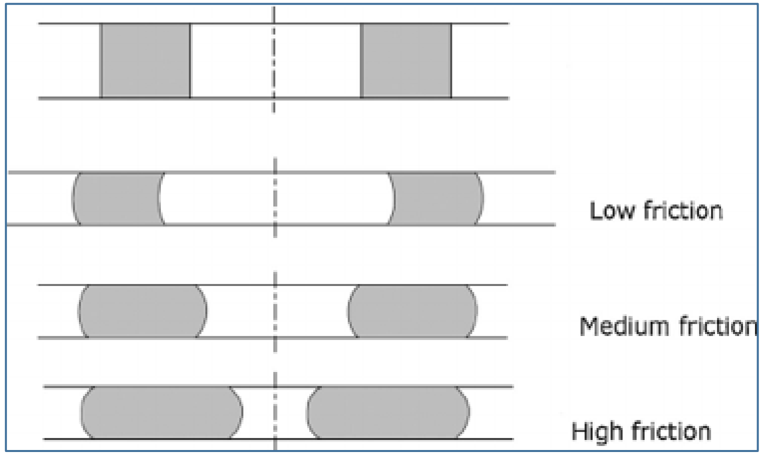
Reciprocating Tribometer

- Tests coated plates using the reciprocating tribometer and determine if has a better correlation to the RFT than the pin-on-disk.
- Capable of higher contact force on the tested surface than the available pin-on-disk
- Expect to be able to do accelerated lifetime testing of coating.

Reciprocating Tribometer

Ring Forging Test

- Test involves the compression of thin metallic rings
    - Having controlled dimensions
    - Typically: OD:ID:thickness in the ratio of 6:3:2 [2]
- Coefficient of friction can easily be estimated after forging
    - Based on change in height and change in ID



Measurement of CoF

- Friction factor (m) can be estimated from analytically determined curves
- Based on change in shape of ring
  - Increase/decrease in internal diameter
  - Reduction in height

Height Reduction

Smaller ID

ID Change

Larger ID

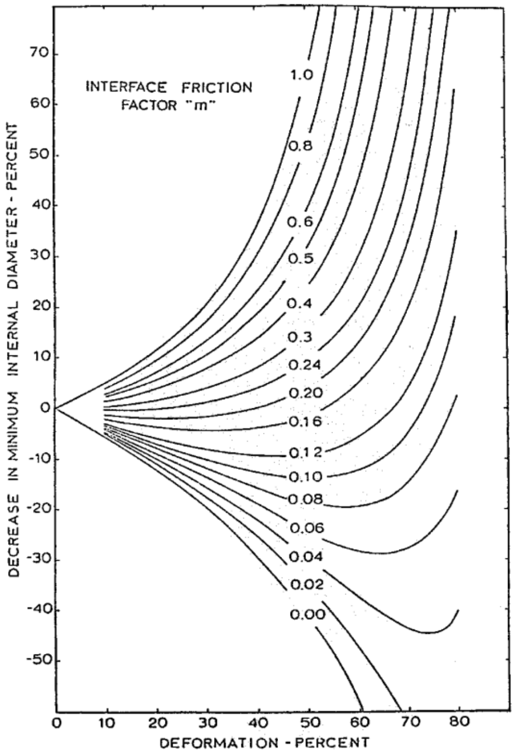


FIG. 6* CALIBRATION CURVES (WITH BULGE)

* From R. Kohser, Ph.D. Dissertation, Lehigh University (1975).

Planned Testing Approach

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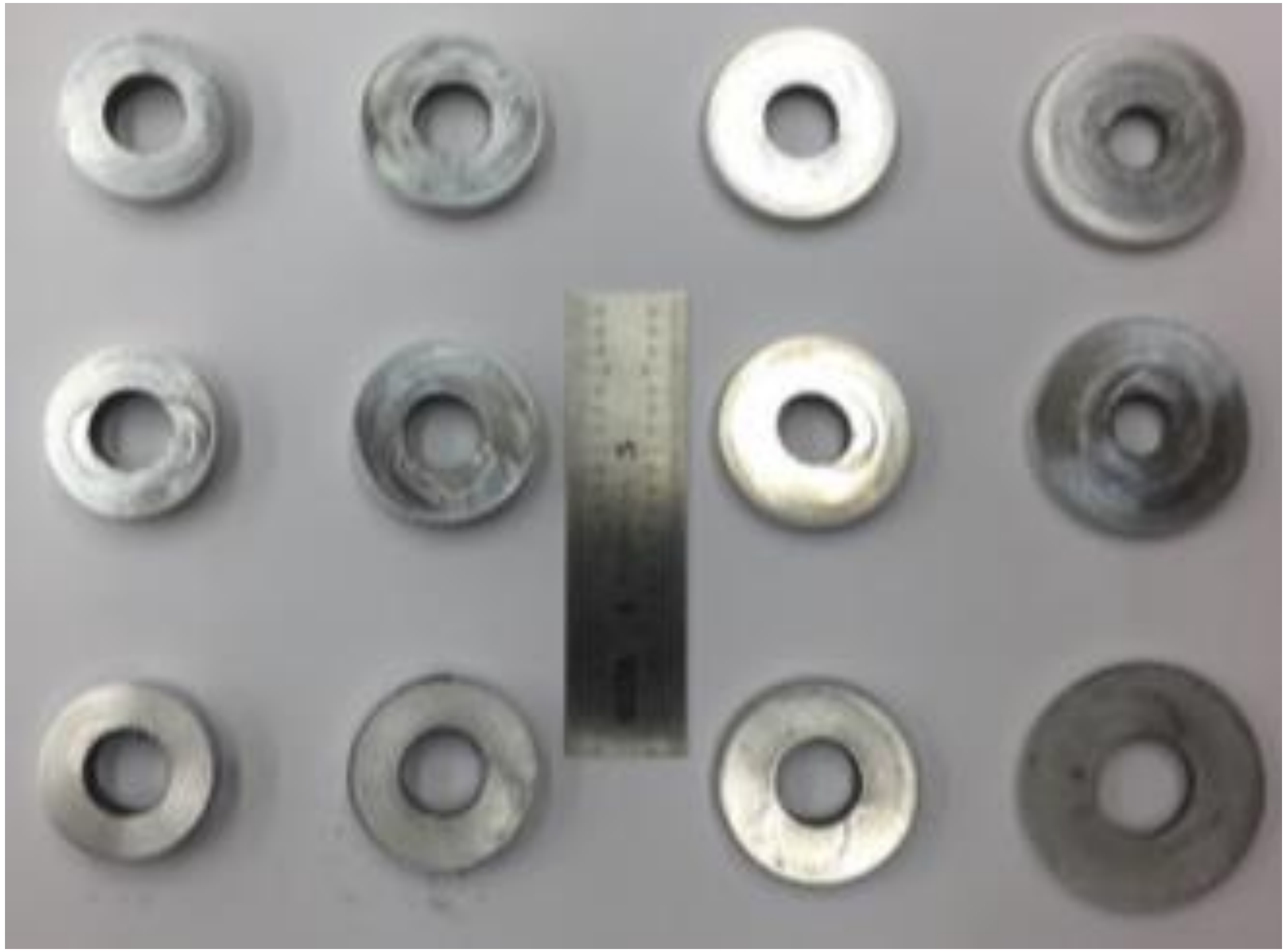
- 1st Stage: use the ring forge tester in the same 100-kip press as the preliminary project
  - Create baseline of uncoated dies
  - Perform RFT on coated dies
  - Test the viability of the heated die holders at forging temperatures
- 2nd Stage: use the larger 400-kip press
  - New tool holder design is needed to be able to mount the dies in this press
  - Enable to forge larger samples and other metals such as Fe
  - Can provides better control over die temperature

Ring forge testing equipment

Ring Friction Test: AL6061 at RT

CoF decrease



Height reduction

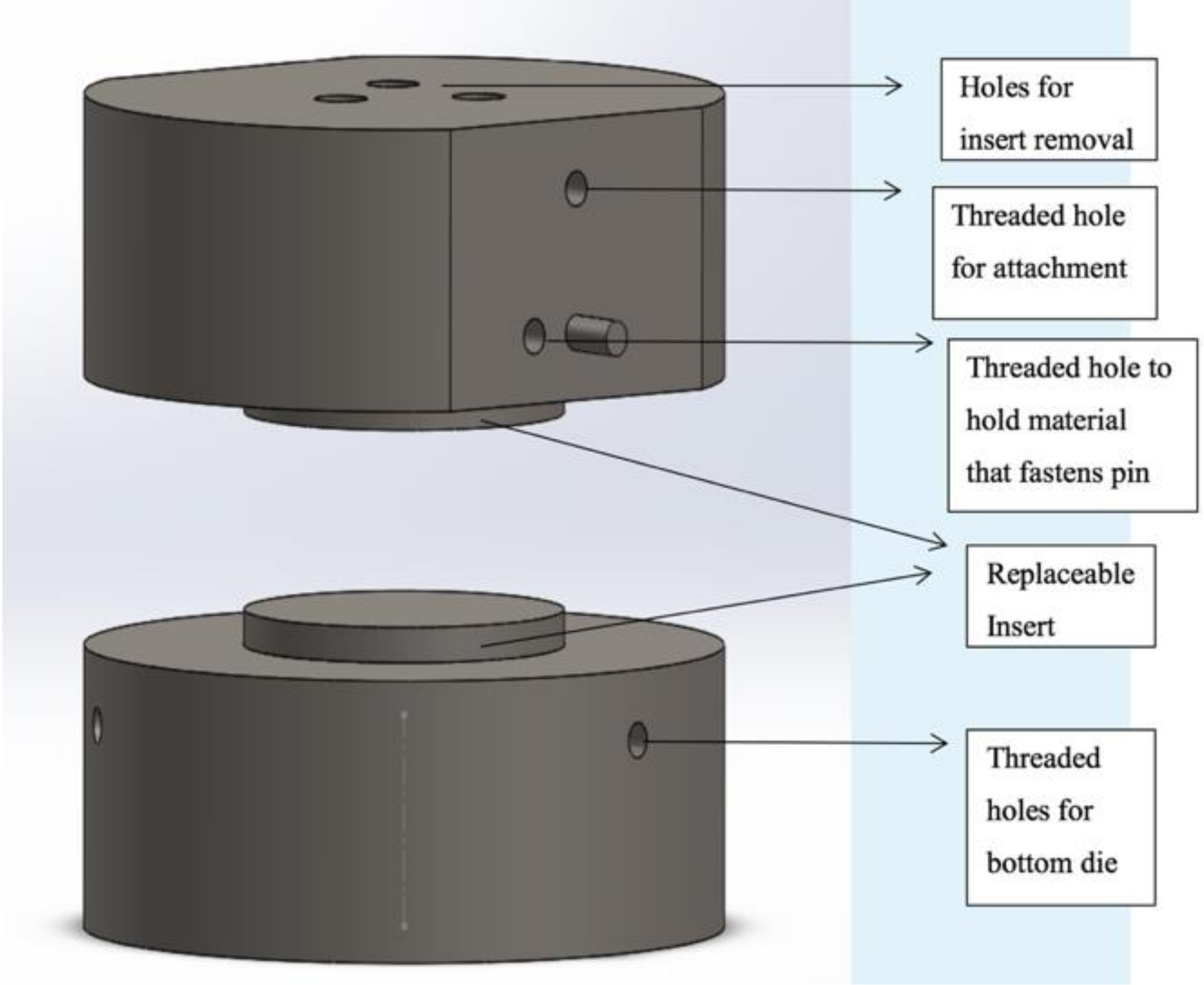
No lubricant

Dry graphite spray

MoS_2 grease

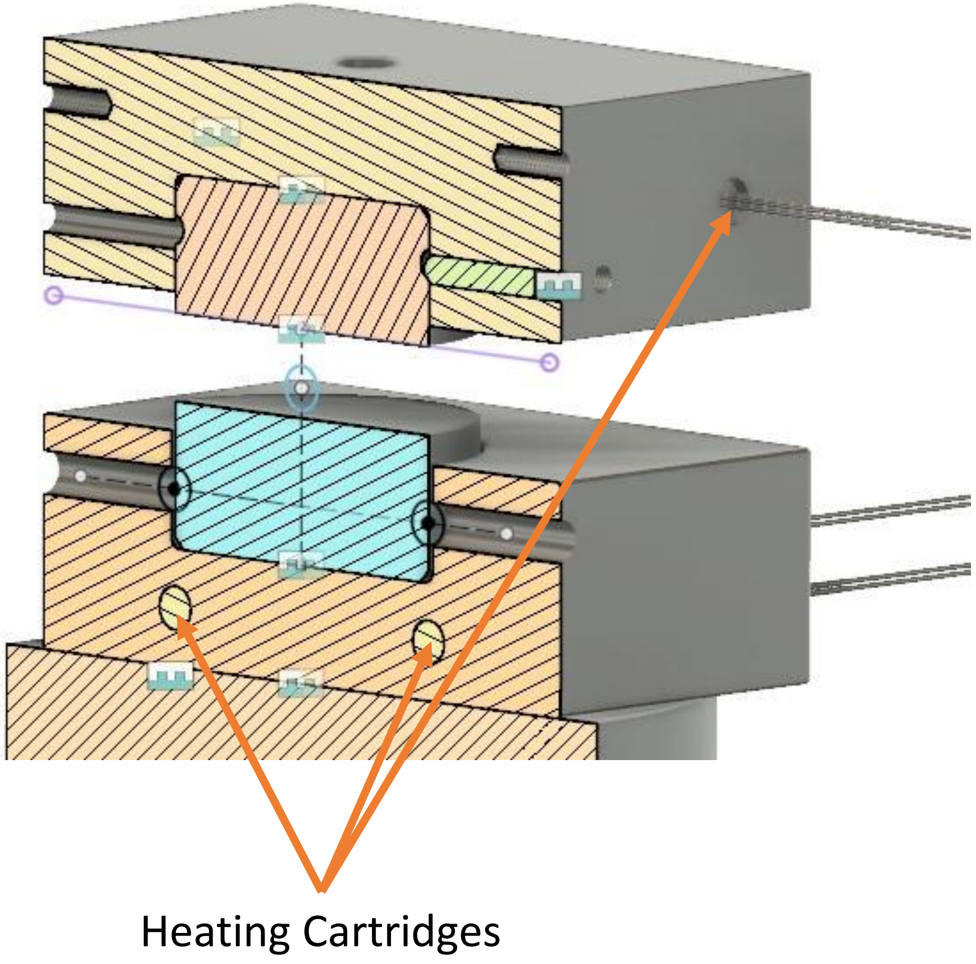
Test Equipment

- Current die holder design
  - Capability to fit the test equipment onto the 100-kip hydraulic press at CSM
  - Ability to quickly switch die inserts
  - Measure both load and displacement during testing
  - 40 inserts donated by Bohler to make 20 sets of dies
  - High temperature tests requires preheating the dies in a separate furnace
  - No temperature control when in use



Test Equipment

- Heated die holder design
  - Integrated heating cartridges will provide an in situ controlled temperature
  - Switched to a six-inch square design to increase the size of heating cartridges
  - Four heating cartridges of 1kW should heat the die holder to 500°C



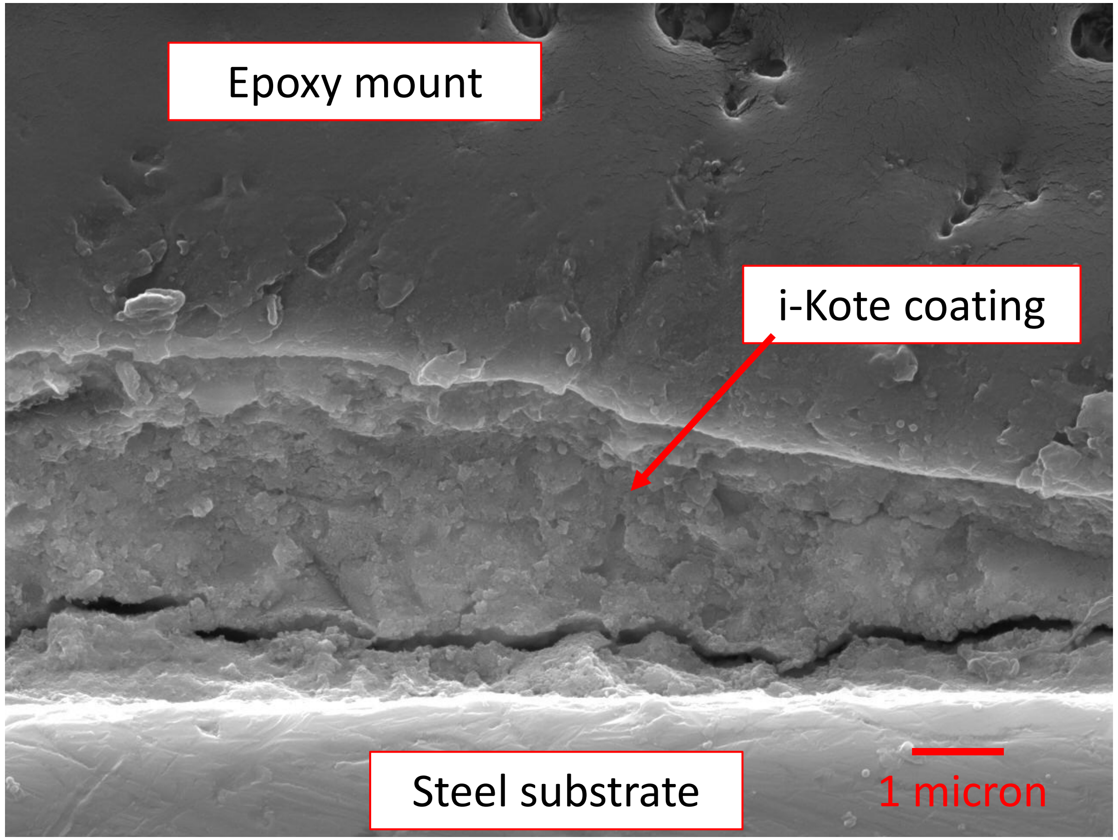
i-Kote Coating

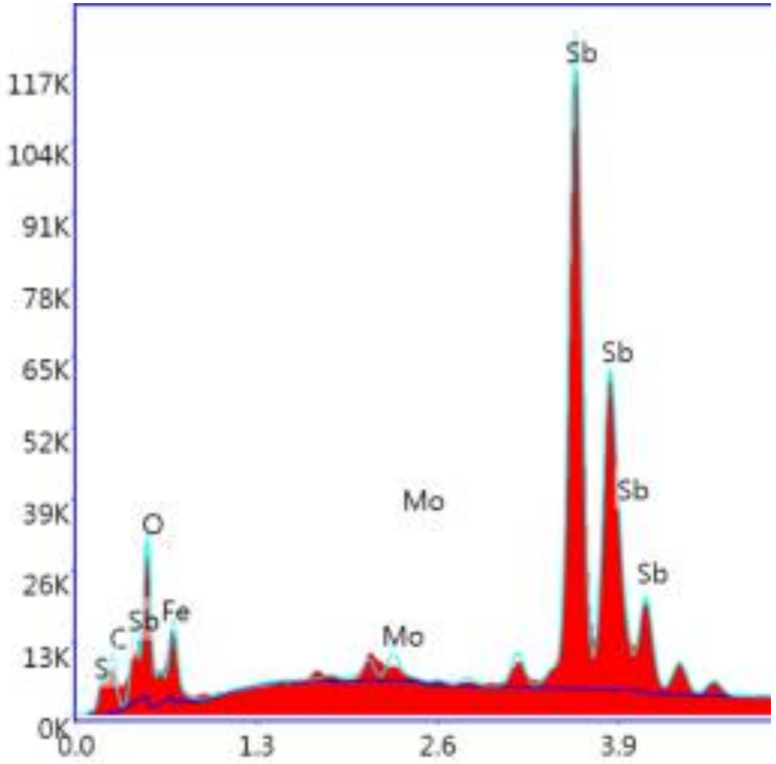
- Provided the best results for unlubricated RFT in the previous study
- Advance solid lubricant: “smart nanocomposite coating with adaptive behavior to reduce friction or wear in severe and variable environments with a coefficient of <0.01”
- It is a MoS_2, Sb based coating
- Friction factor m from the FIERF funded project [1] using the RFT of Al6061 machined samples

Coating	Lubricant	Temperature (°C)	m
i-Kote	None	RT	0.35
None	Graphite	RT	0.30
i-Kote	None	100	0.44
None	Graphite	100	0.30
i-Kote	None	200	0.63
None	Graphite	200	0.80

i-Kote Coating

Secondary electron images - provide better idea of surface topography





- Coating was compromised and appears that oxidation has created Mo and Sb oxides

Coatings from Literature Review

- Coatings
  - Graphite based coatings
    - Graphene
  - Disulfide based coatings
  - Oxidation study of V, Mo and W containing coatings to provide oxidation resistance at high temperature
- Coating techniques
  - Plasma spray
  - Burnishing
  - Plasma electrolytic oxidation
  - Spark plasma sintering
  - Arc evaporation
  - Atomic layer deposition
- Expand the literature review

Oxidation study of V, Mo and W containing coatings

- These oxides form layered structures with weak van der Waals bonding that enable easy sliding
- These second phases may increase the hardness and wear resistance on nitride coatings
- V_2O_5 has a relatively low melting temperature that may even provide liquid lubrication at forging temperatures. [3]

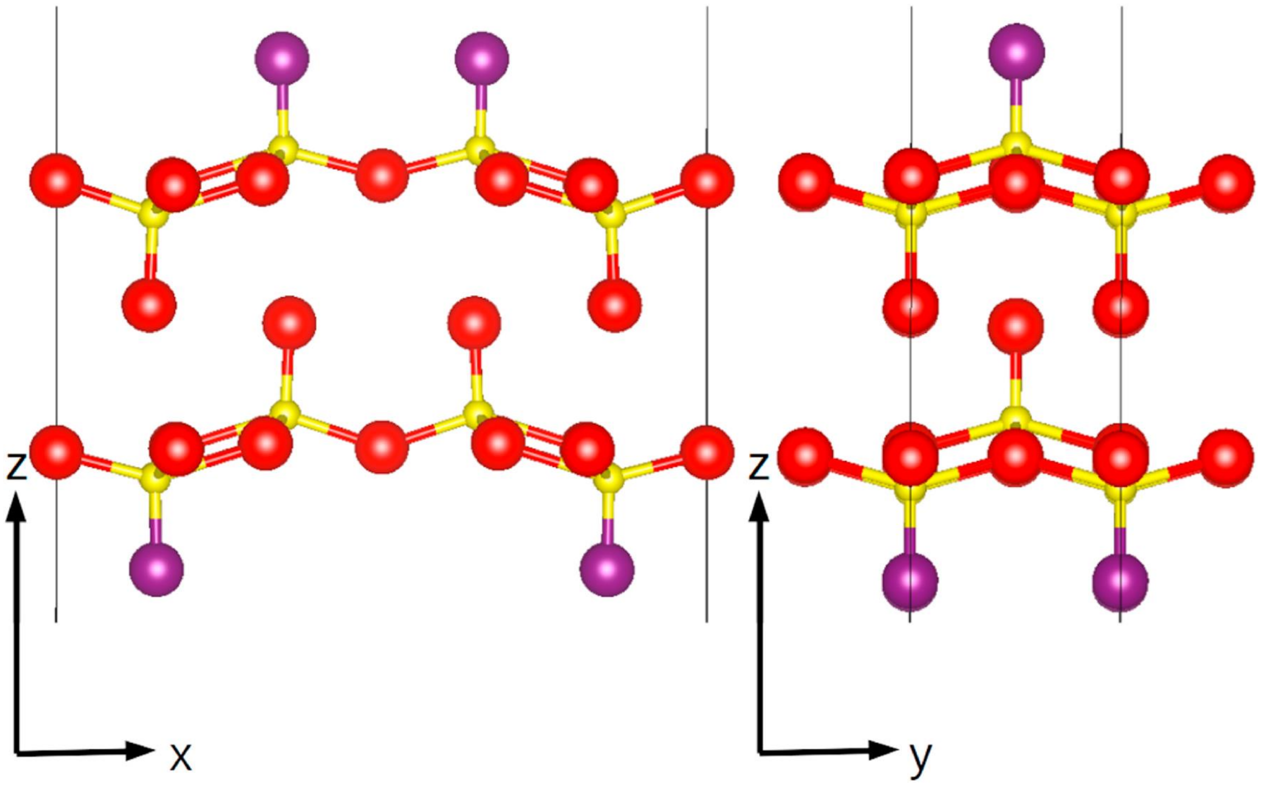


Fig. 1. Two V_2O_5 layers, views along y (left) and x (right) axes are displayed. 20 Å of vacuum are added in the z-direction. Red and purple atoms are O, yellow atoms are V. [3]

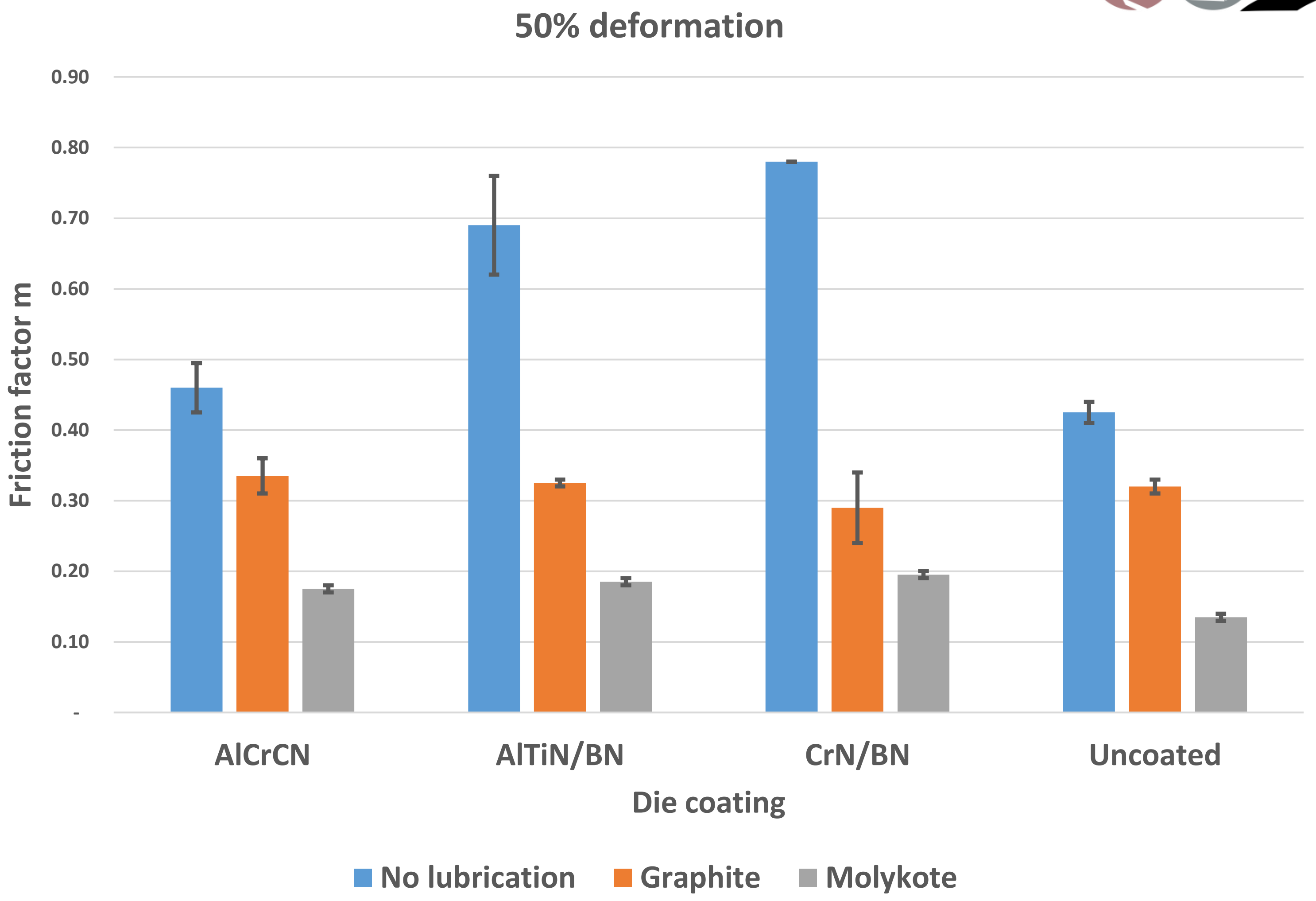
Ring Forging Test

Initial tests

- Al6061 samples and uncoated die ground to 1200 grit
- Coated dies tested as received from manufacturers
  - Dies shipped for coating ground to 1200 grit
  - Each manufacturer prepared the surface to their specifications required to be coated.
    - Surface preparation unknown
  - AlCrCN
  - AlTiN-BN
  - CrN-BN
- Selected a 50% deformation of height
- Results are the average of three RFT

Ring Forging Test Friction Factor m

Al6061 samples and uncoated die ground to 1200 grit



Ring Forging Test

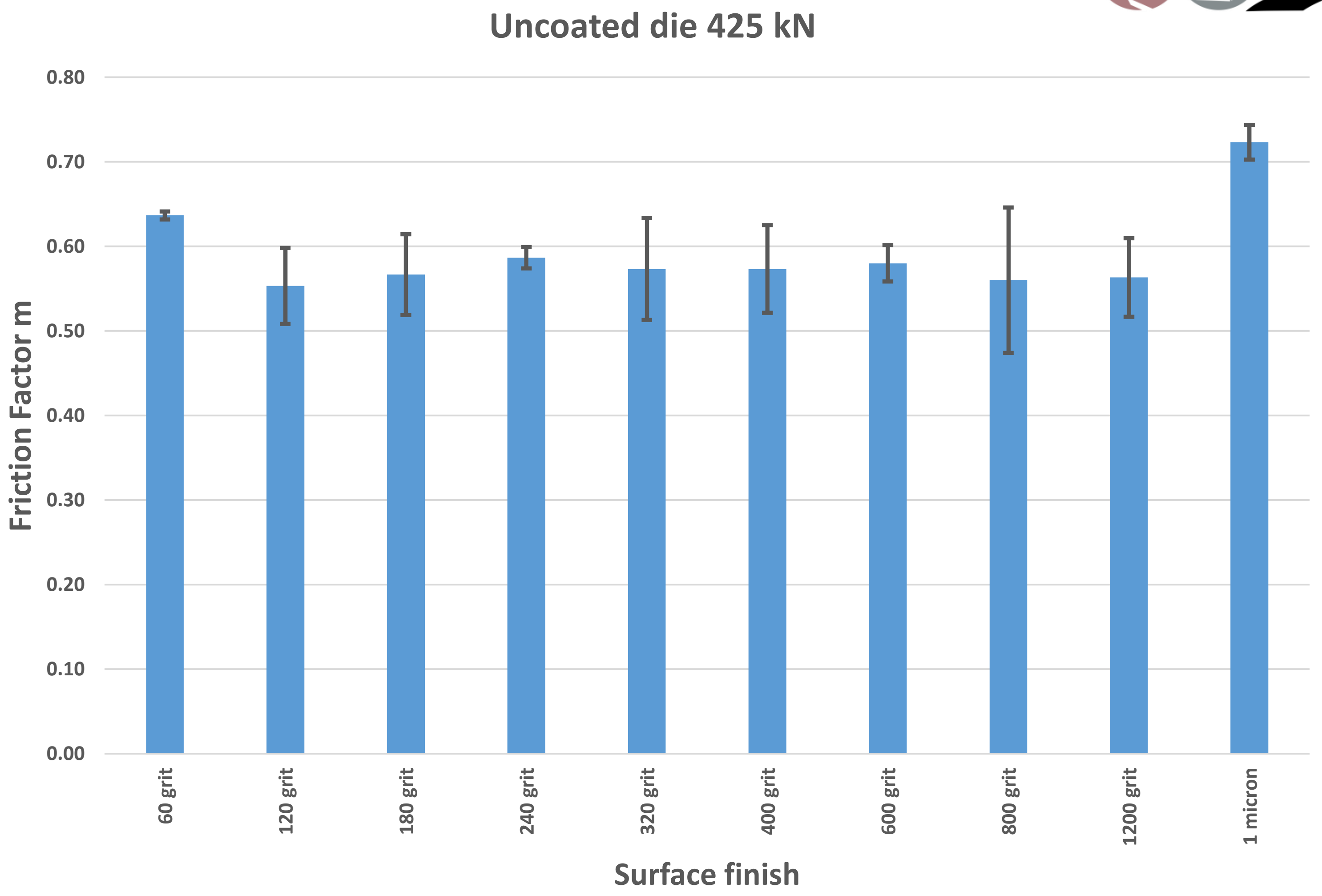
Current tests:

Determine if the surface preparation of the dies and samples influences the results of the RFT

- Used Al6061 samples lapped and polished to Ra<300 nm.
- Uncoated dies we ground from 60 grit to a polish of 1 micron
- Selected a maximum load of 425 kN
- Following results are the average of three RFT per surface condition

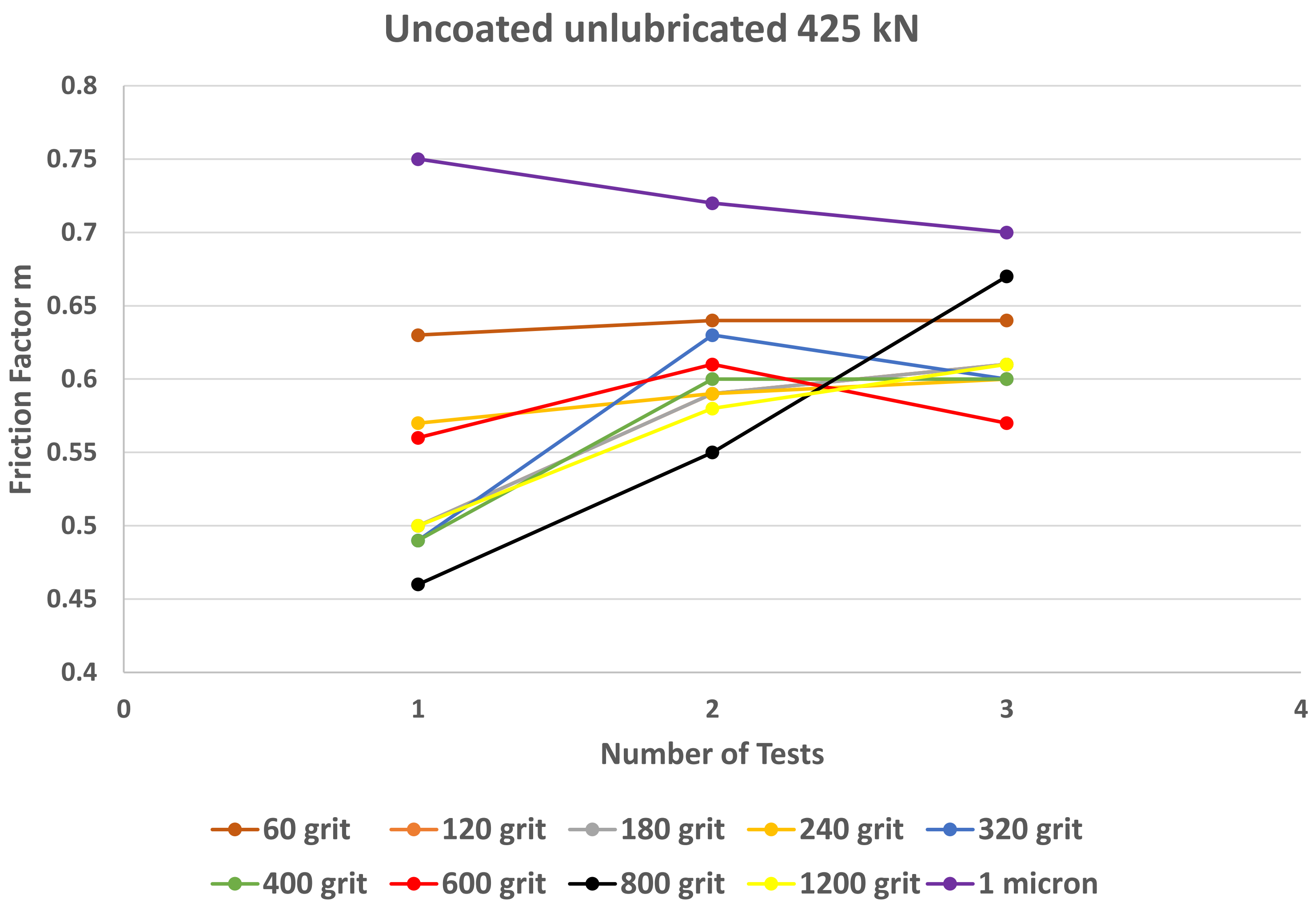
Ring Forging Test Friction Factor m

Al6061 samples lapped and polished to Ra < 300 nm



Ring Forging Test Friction Factor m

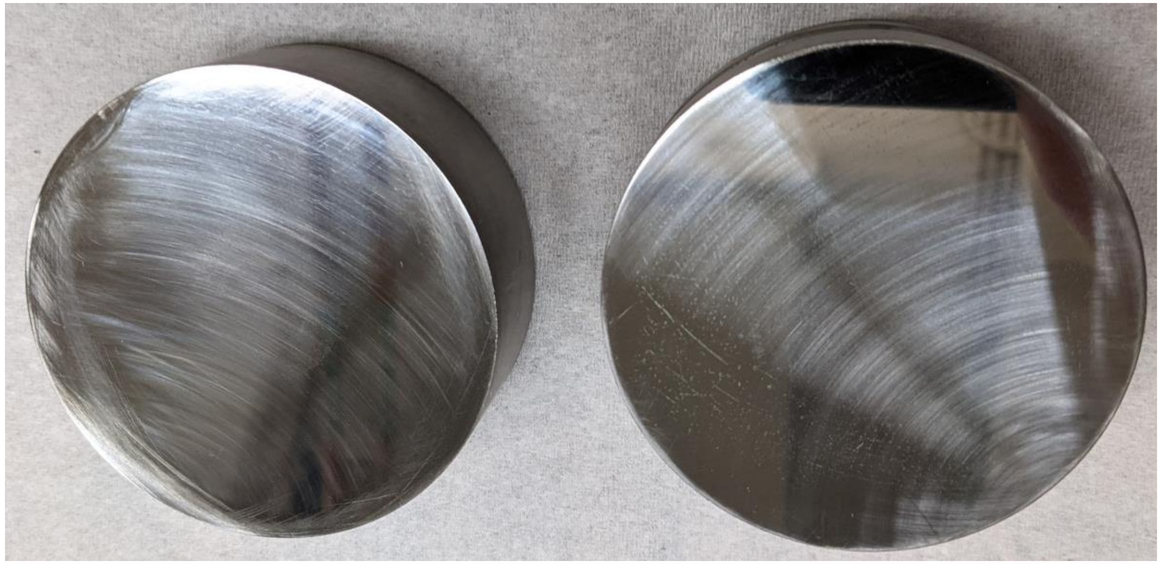
Al6061 samples lapped and polished to Ra < 300 nm



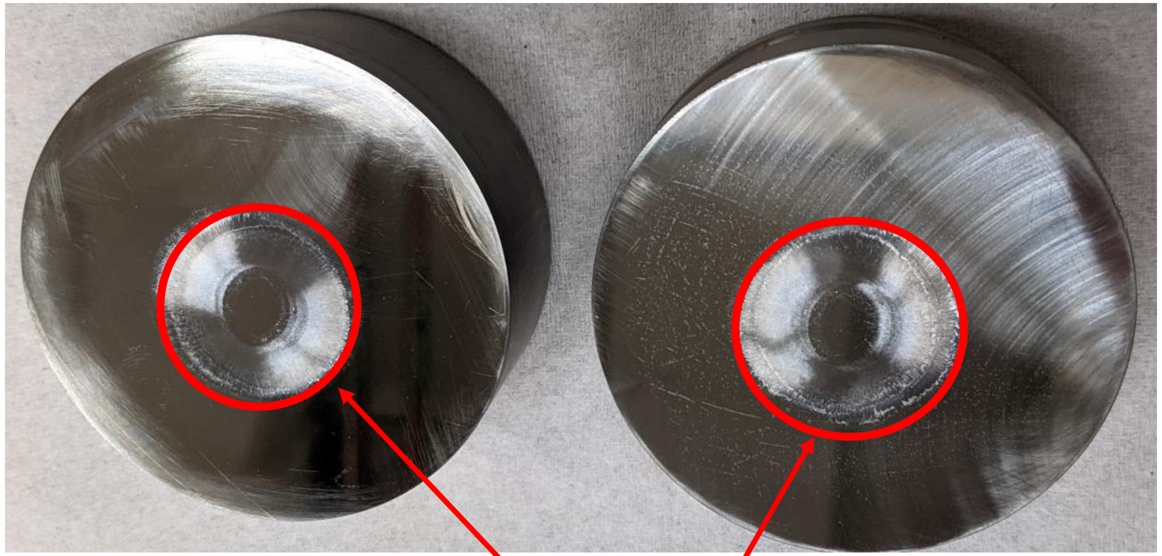
Ring Forging Test

Al6061 samples lapped and polished to Ra < 300 nm

Uncoated 3-inch diameter dies ground to 800 grit



Before testing

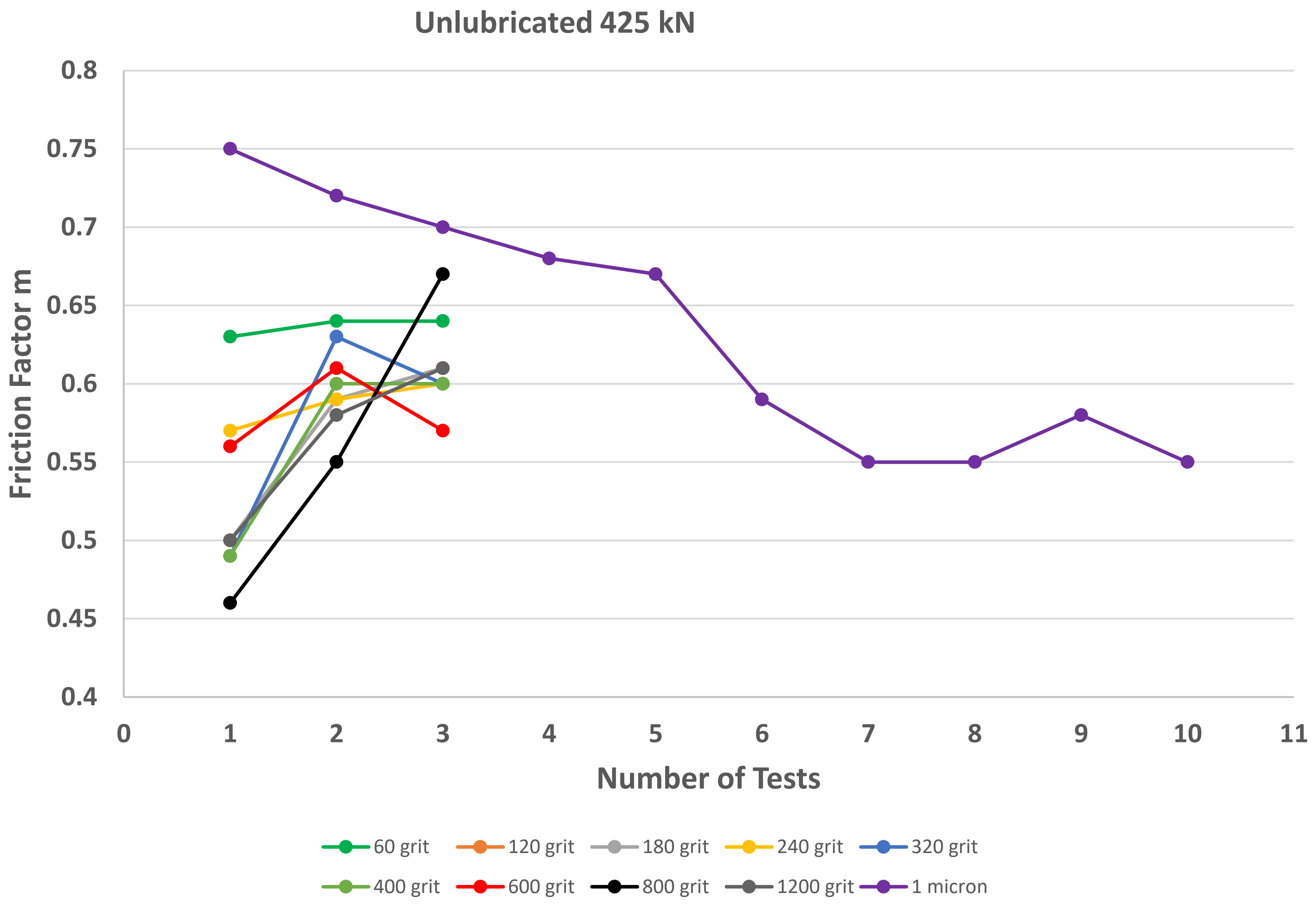


Aluminum build up

After 5 unlubricated tests

Ring Forging Test Friction Factor m

Al6061 samples lapped and polished to Ra < 300 nm



Second Series of Coatings

- Future coatings to be tested:
  - i-Kote
    - Replicate previous results
  - i-Kote- BN
    - Higher operating temperature but also higher CoF
  - ZrOCN
    - CoF around 0.15
  - ZrOCN with a ZrO_2 top layer
    - Top layer provides oxidation resistance
  - Si doped DLC
    - Higher operation temperature than DLC
  - V and W containing PVD coatings
    - Form oxide oxide lubricious surface layers at ~500-700^{o}C
      - TiSiVN
      - AlCrVN
      - CrWN

Summary

- Reduced the number of variance inducing variables
  - Static fixture for the die holders
  - Standardized the sample preparation to a surface roughness of < 300 nm
  - Established a procedure for measuring samples before and after RFT using calipers.
  - Dies will be polished to 1 micron before shipping to coating companies
- Created a baseline for uncoated dies under unlubricated conditions
- Initiated testing of coated dies under three different lubrication conditions
- Four new coatings will be delivered before the end of October
  - i-Kote, i-Kote-BN, ZrOCN, ZrOCN with ZrO_2
- Heated die holders are in their final design review

Future Work

- Continue to expand the literature review
- Determine number of tests before aluminum build up starts to influence the results
- Develop analytical formulas more closely based on our tests parameters to allow us to graph the friction factor calibration curves
- Characterization of the current coatings dies
  - Characterize the coating microstructure to correlate it to the CoF results.
- RFT using heated die holder
- V and W containing coatings
  - Select oxidation heat treatment using tribometer results
  - Correlate tribometer and forging CoF results
- Investigate suppliers for graphite containing coatings
- Determine surface texturing techniques to be studied
- Design die holder for the 400-kip press
- Industrial scale testing

Challenges and Opportunities

- Finding suppliers for the selected coatings
- Understanding the mechanisms that control the reduction of the CoF in RFT
- Investigating what causes workpiece material build up on the coatings
  - Characterization
  - Prevention and/or mitigation
  - Will Fe have different mechanisms?
- Determining the lifetime of the coatings.
- Is minimizing the use or lubricants the best we can hope for?
- Will the RFT give quantifiable and repeatable results?
- Can the coatings be scaled up to Industrial forging?

Gantt Chart

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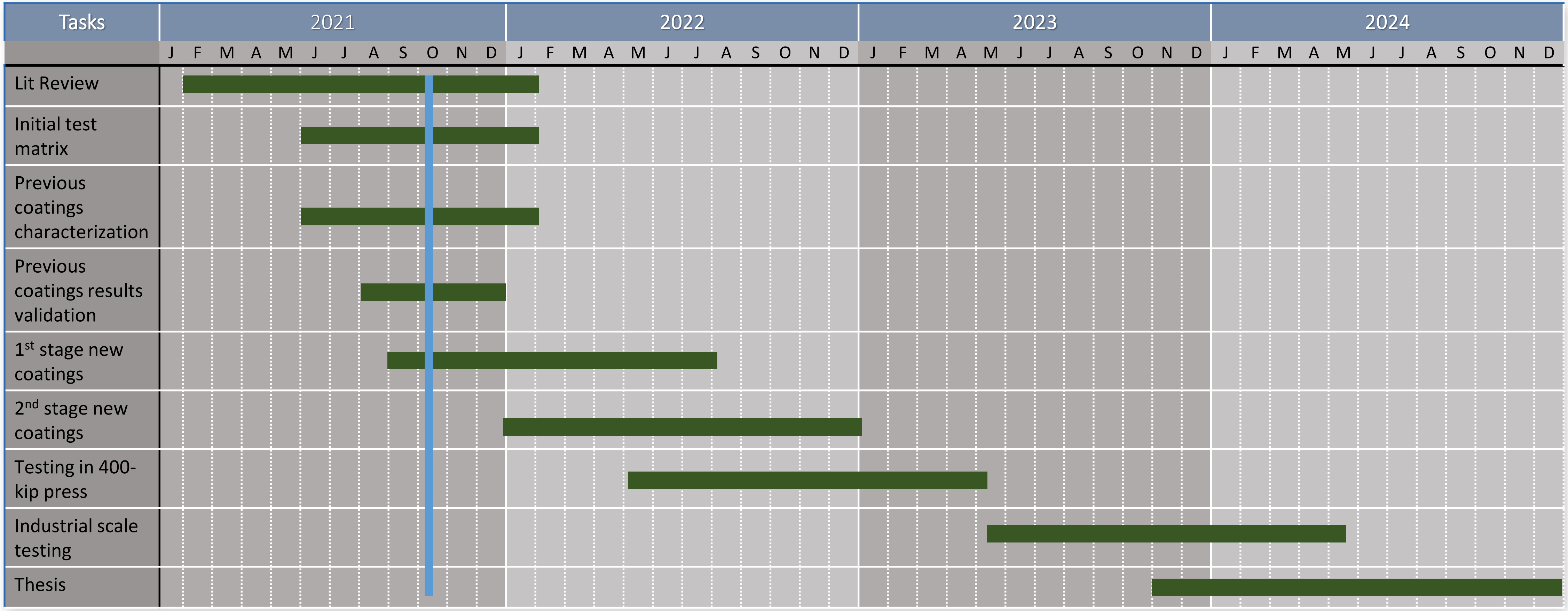

References

[1] T. Kehe, S. Randell, S. Midson, A. Korenyi-Both, K. Clarke. Laboratory Testing to Identify Permanent PVD Coatings to Minimize Lubricant Use During Forging: Final Report. CANFSA Report, Project 28, Oct 25, 2019.

[2] A. Male, M. Cockcroft. A method for the determination of the coefficient of friction of metals under condition of bulk plastic deformation. J. Inst. Metals 1964–1965, 93, 38–46.

[3] I. Ponomarev, T. Polcar, P. Nicolini, Tribological properties of V2O5 studied via reactive molecular dynamics simulations. *Tribology International 154 (2021) 106750*.

This Forging Defense Manufacturing Consortium (FDMC) project is sponsored by the Defense Logistics Agency (DLA) Information Operations, J68, Research & Development, Ft. Belvoir, VA, and by DLA-Troop Support, Philadelphia, PA.
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Thank you!

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