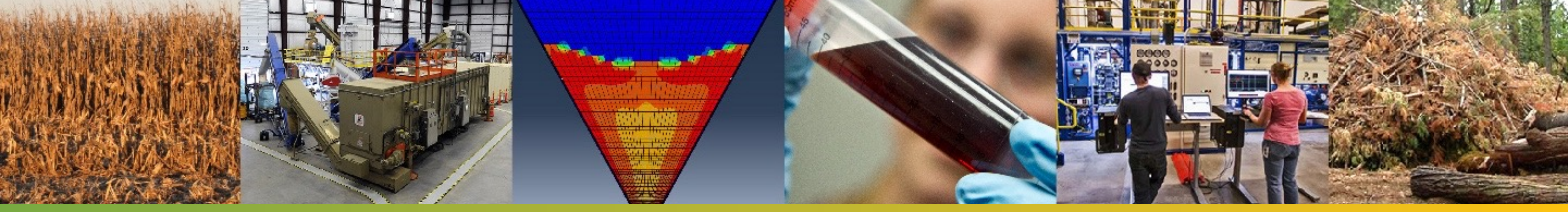

DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

FCIC – Task 1: Materials of Construction

April 6, 2023

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fcic FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

U.S. DEPARTMENT OF ENERGY

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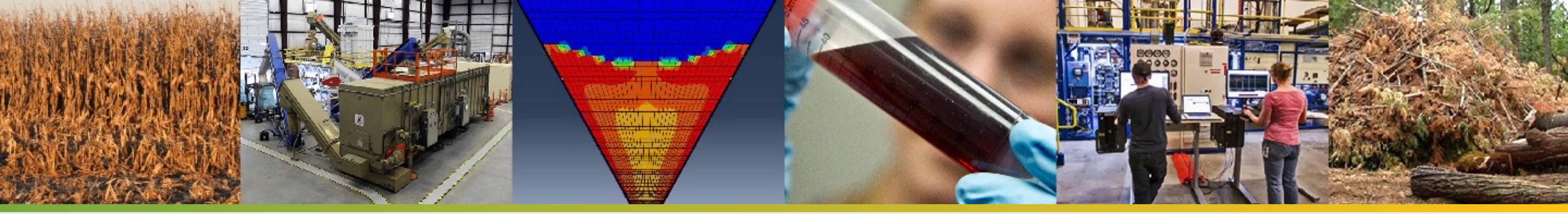

Project Overview

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FCIC Task Organization

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM
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Feedstock → **Preprocessing** → **Conversion**

Feedstock	Preprocessing	Conversion
Task 2: Feedstock Variability	Task 5: Preprocessing	Task 6: High-Temperature Conversion
Task 1: Materials of Construction		Task 7: Low-Temperature Conversion

Task 3: Materials Handling

Enabling Tasks

- Task X: Project Management
- Task 4: Data Integration
- Task 8: TEA/LCA
- Task 9: FMEA

Task X: Project Management: Provide scientific leadership and organizational project management

Task 1: Materials of Construction: Specify materials that do not wear, or break at unacceptable rates

Task 2: Feedstock Variability: Quantify & understand the sources of biomass resource and feedstock variability

Task 3: Materials Handling: Develop tools that enable continuous, steady, trouble free feed into reactors

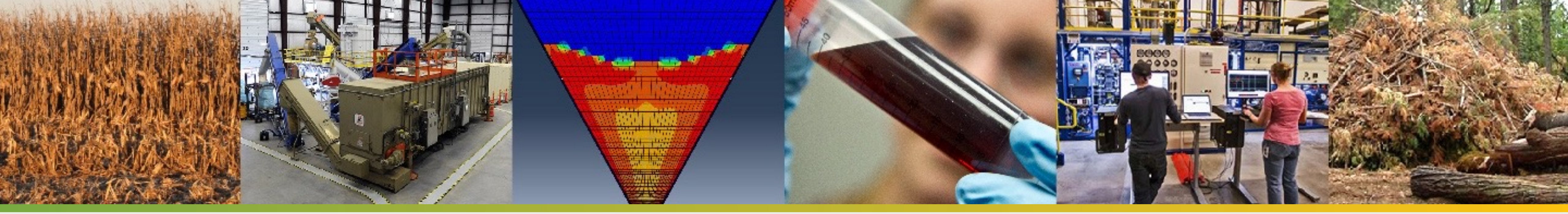
Task 4: Data Integration: Ensure the data generated in the FCIC are curated and stored – FAIR guidelines

Task 5: Preprocessing: Enable well-defined and homogeneous feedstock from variable biomass resources

Task 6 & 7: Conversion (High- & Low-Temp Pathways): Produce intermediates for further processing

Task 8:Crosscutting Analyses TEA/LCA: Valuation of intermediate streams & quantify variability impact

Task 9:Failure Mode & Effects Analysis (FMEA): Standardized approach for assessing attribute criticality



1 - Approach

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1 – Approach

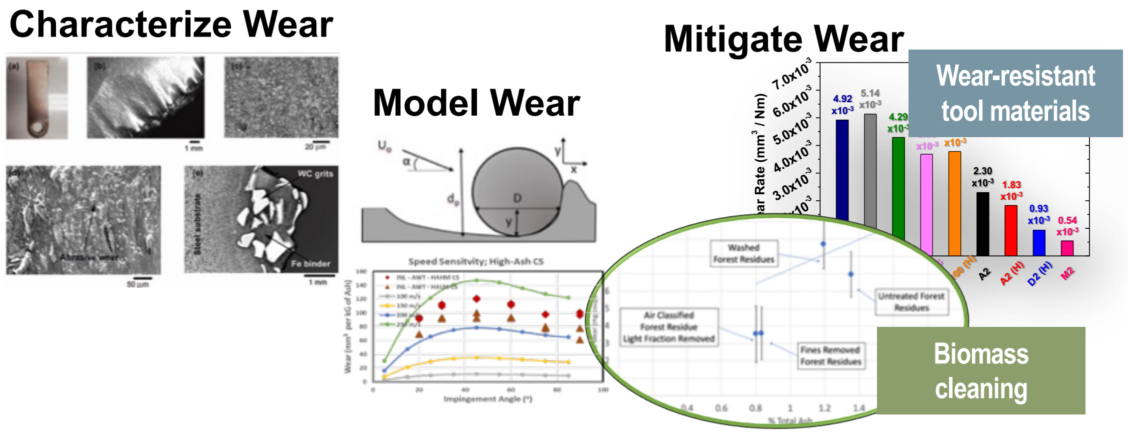
Technical Approach: Use a systematic quality-by-design approach with **integrated efforts of characterization, modeling, and testing** to gain fundamental understanding of the **failure modes and wear mechanisms** of biomass preprocessing tools, develop analytical **models to predict wear** and establish material property specifications, select and evaluate **candidate mitigations** based on modeling and lab-scale testing and identify top-performing mitigation for PDU validation, and **share** the fundamentals and mitigations with the biomass industry.

Challenges:

- **Complex wear mechanisms** requiring correlation among biomass intrinsic and extrinsic inorganics, tool alloy hardness and fracture toughness, and wear performance in both erosion and abrasion
- Development of **effective AND low-cost** mitigations
- Quantification of **combined benefits** from increased tool life and throughput as well as reduced downtime and power consumption

Metrics:

- Technical metrics: **wear modes**, **volumetric wear rate** in bench-scale erosion and abrasion testing, **blade edge sharpness** change in small knife mill testing
- Economic metrics: **costs** of tool materials and manufacturing, **cost savings** of reduced machine shutdown for tool replacement, **energy savings** by higher throughput, and improved **conversion efficiency** by more uniform particle sizes



1 – Approach (cont'd)

- Risks/mitigation
  - *Breakdowns or unavailability of instruments for characterization and testing*
    Mitigation: Among the three national labs, we are confident to find alternatives
  - *Wear models based solely on one wear mode would not capture other wear mechanisms*
    Mitigation: To incorporate multiple wear modes into the overall wear model by conducting the root cause analysis
  - *Candidate mitigations difficult to scale-up due to cost or technical challenges*
    Mitigation: To select and identify appropriate mitigations using techno-economic analysis (TEA) in collaboration with FCIC Task 8

- Collaboration
  - Inside FCIC:
    - With Task 2 for selecting and acquiring feedstocks for characterization and testing
    - With Tasks 3, 5, and 6 for understanding equipment wear and feedstock fouling issues
    - With Task 8 for TEA of mitigations
  - Outside FCIC:
    - Biomass size reduction equipment manufacturers: Eberbach, Jordan Reduction Solutions, Rawlings Manufacturing, and Forest Concepts
    - Coating/surface treatment providers: IBC Coatings Technologies, NCT, ATC, and C4E

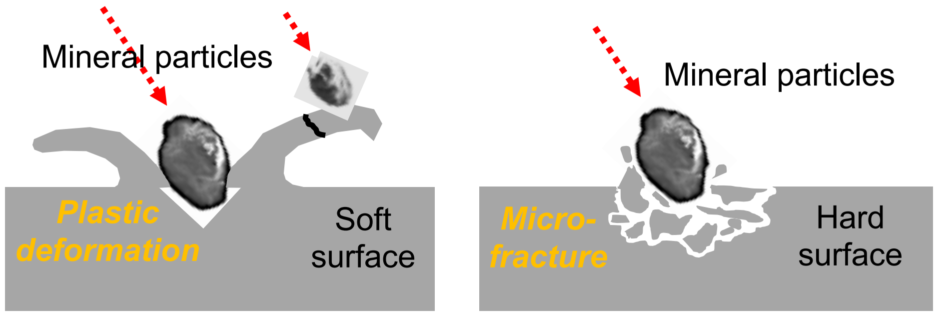
Fundamentals of Wear Modes

Knowledge

General Types of Wear

Other types:
adhesive wear, impact wear, contact fatigue, fretting wear, oxidative wear, corrosive wear, etc.

Erosive Wear

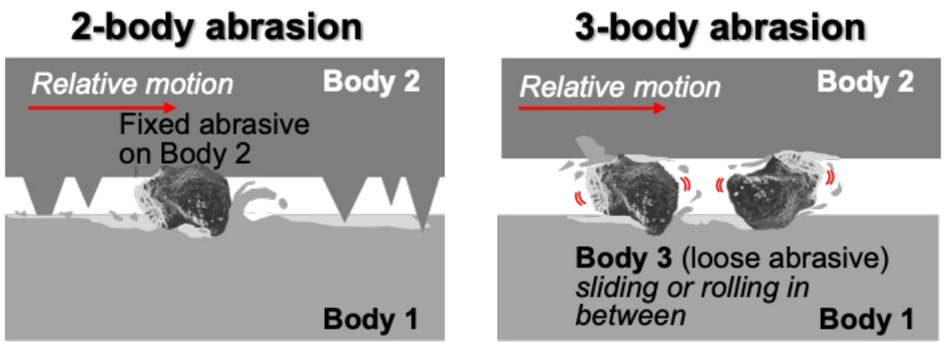


Manner of energy dissipation:
Plastic deformation, micro-fracture, heat

Critical tool material mechanical properties:
Fracture toughness, hardness, fatigue ductility, yield strength

Key processing parameters:
Particle hardness, velocity, and size, impingement angle

Abrasive Wear



Manner of energy dissipation:
Groove plowing, cutting chips, grit fracture, heat

Critical tool material mechanical properties:
Hardness, yield/shear strength, fracture toughness

Key processing parameters:
Abrasive grit shape/size, load, sliding speed/distance

Wear modes of biomass size reduction equipment

Knowledge

Hammer Mill

Rawlings Hog Mill

Rotary Shear

Erosive wear dominant

Little abrasive wear

Little erosive wear

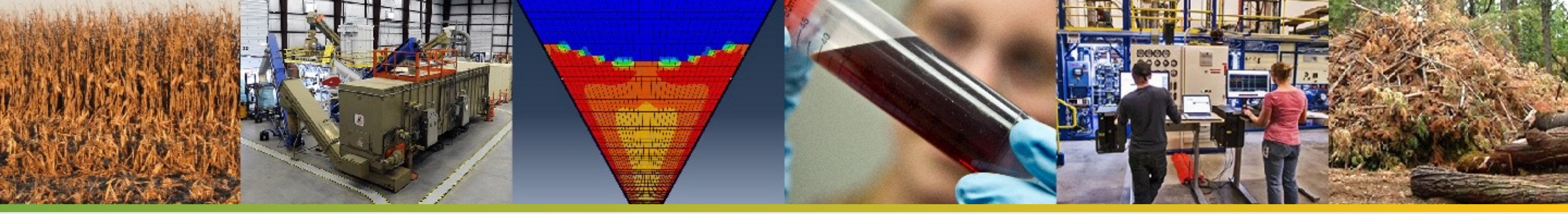
Abrasive wear dominant (2-body & 3-body)

Knife Mill

Shredder

Task 1 Quality-by-Design (QbD) summary

Unit Operation	CMA	CPP	CQA
Preprocessing Feedstock particle size reduction - Hammer Mill - Knife Mill - Shredder	<u>Feedstock CMA:</u> - Ash content, compositions, shapes, and mechanical properties (hardness, elastic modulus, fracture toughness) - Biomass particle size, density, compositions, and mechanical properties - Moisture content <u>Materials of Construction CMA</u> - Mechanical properties: hardness, yield/shear strength, fracture toughness, fatigue strength - Tool design and contact geometry with feedstock	Equipment operating variables: - Speed - Load - Environment - Feed rate - Time	<u>Equipment</u> - Tool wear rate (service life) - Throughput - Power consumption <u>Feedstock</u> - Particle size distribution - Fines



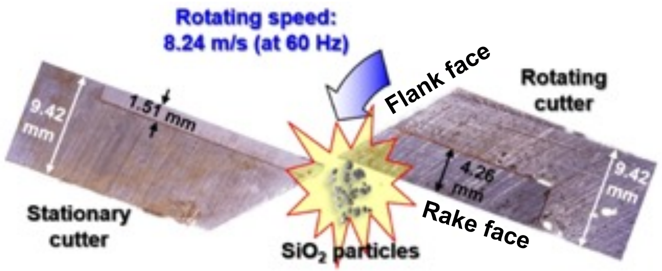
2 – Progress and Outcomes

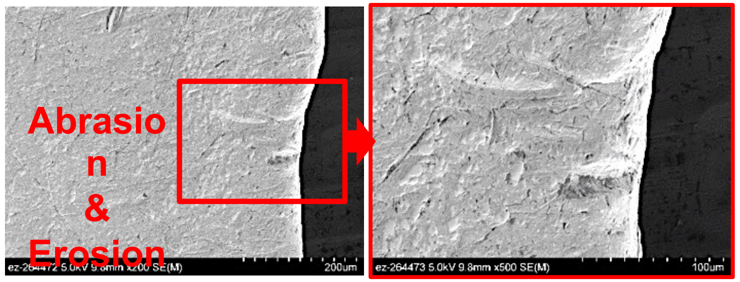
Knife mill wear: erosion + abrasion

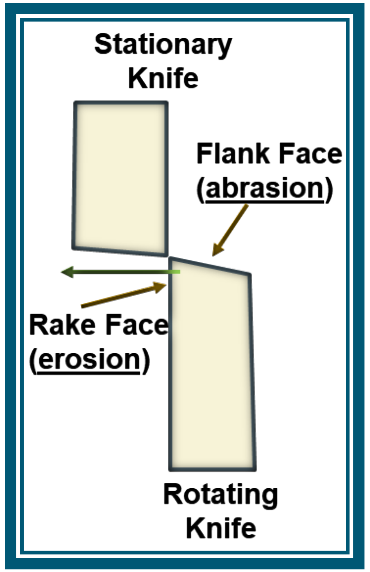
Knowledge

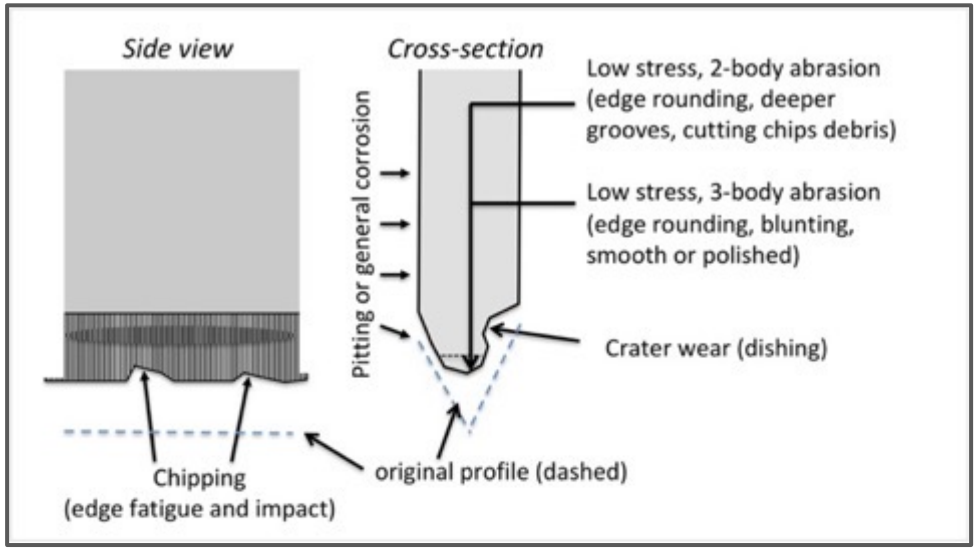
Comminution modes: Sharp blades @ medium-high speed → Cutting + Crushing

Wear modes of blades: Erosive wear + Abrasive wear (both important)









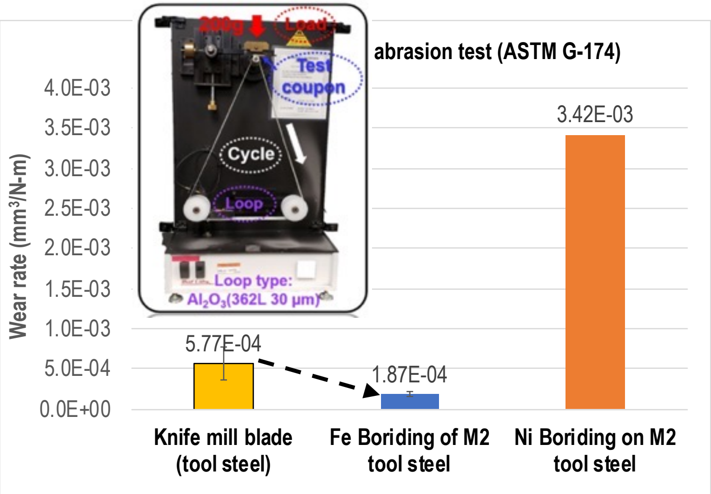
Screening of candidate materials & surface treatments to mitigate wear

Knowledge

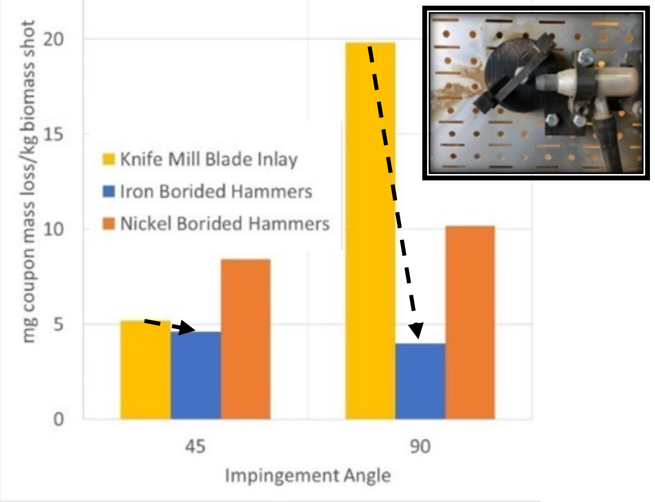
- **Abrasive** and **Erosive** wear can be mitigated by selecting tool materials with optimum mechanical properties
  - Increasing **hardness** – lowers **abrasive wear**
  - Increasing **fracture toughness and fatigue ductility** – reduces **erosive wear**

– Achieving all three attributes is a challenge and requires innovative material solutions.

Abrasion test at ORNL



Erosion test at INL



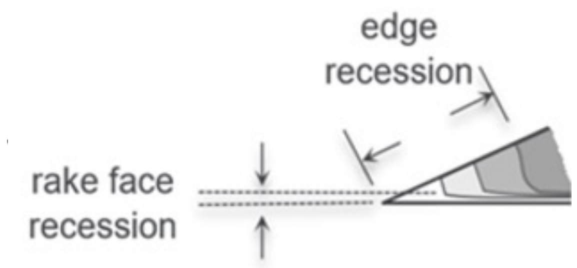
	Nickel Boriding (coating)	Iron Boriding (case hardening)	Thin diamond-like carbon coating (DLC)	Thick diamond-like carbon coating (DLC) coating	Tungsten carbide (bulk)
Hardness	Up to 1200 HV	1200-1900 HV	1800-2800 HV	1000-2000 HV	1600-1900 HV
Thickness	Up to 100 µm	Up to 300 µm	1-5 µm	Up to 100 µm	bulk
Microstructure	columnar	columnar	amorphous	amorphous	columnar
Vendor	Autocatalytic **[UCT]**	Deep case boriding **[IBC]**	PECVD **[NCT]**	PECVD **[C4E]**	**[Eberbach]**
Deposition Temperature	RT followed by crystallization at 385 ^{o}C	1000^{+} ^{o}C followed by heat treat/tempering	< 300 ^{o}C	< 300 ^{o}C	

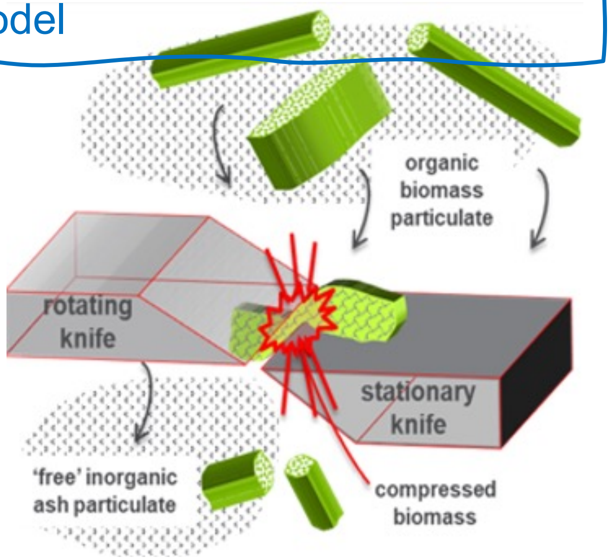
Open-source knife mill blade wear model

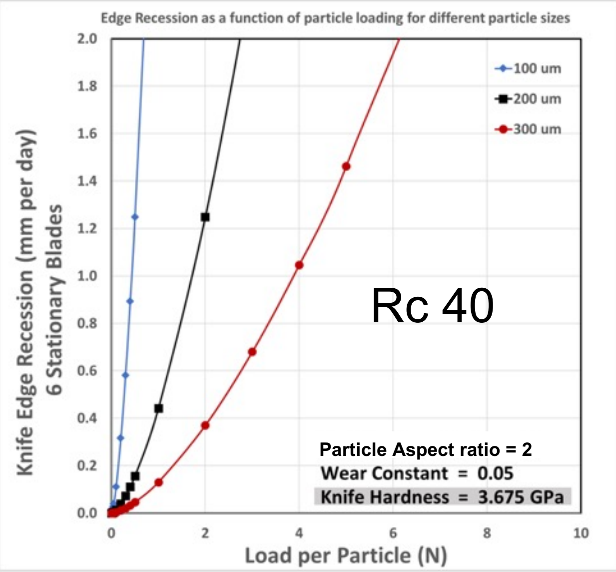
Tools

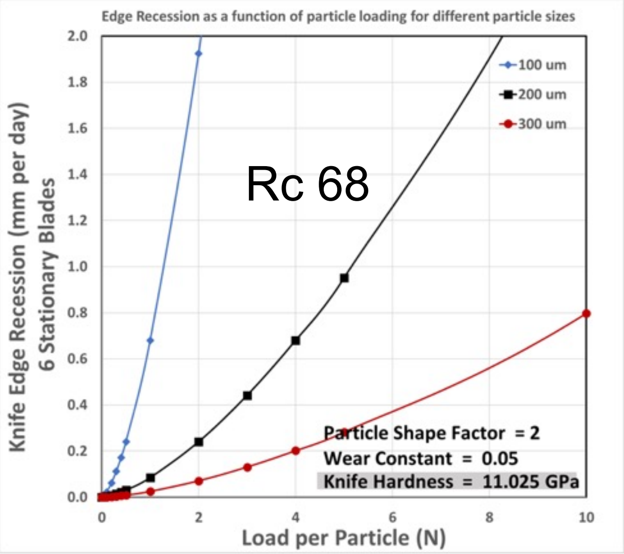
- **Technical progress:** Developed a workable analytical abrasion model that relates critical knife-mill process parameters (geometry and rotational speed) to critical material attributes of inorganic mineral species in feedstock (density, size, and aspect ratio) and substrate (hardness and elastic modulus) was formulated to model wear of knives in knife-milling systems.

Outcome: Open Source excel-based model for predicting edge recession rate in knife mill cutters. Available at: https://www.anl.gov/amd/abrade-model









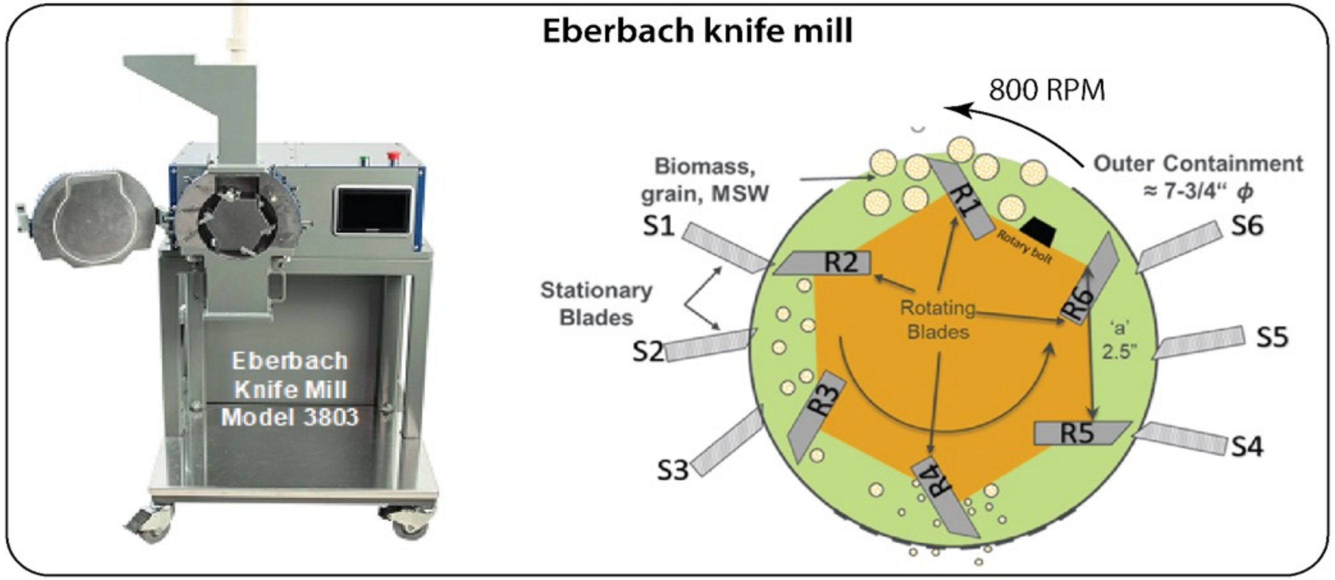
Knife blade recession after 24 hours operation for 100, 200, and 300 µm particles as a function of particle load

- 800 rpm
- 27.2 kg/hr feed rate
- 5% ash content

Hardness HV	Recession Rate mm/day
375	0.60
750	0.21
1125	0.12

Knife mill validation tests at INL

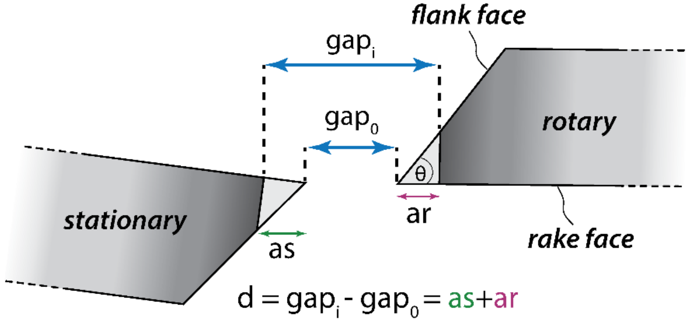
Case Study



Candidate materials

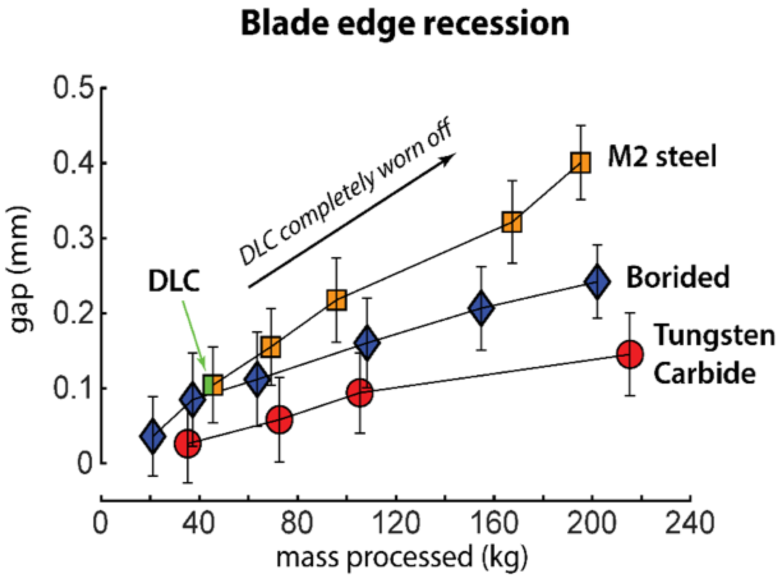
surface material (treatment)	Borided	DLC	Tungsten Carbide
			
base material	D2 tool steel	M2 tool steel	

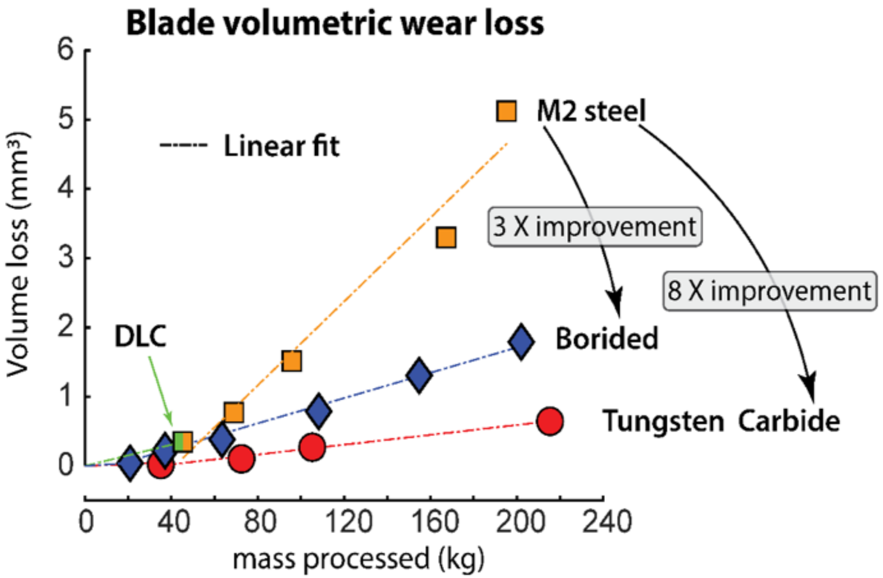
- 1.5 tons of wet, dirty forest residue hammer milled through a ¼" screen
- Particle size: 0.1-4.5 mm (0.7 mm ave.)
- Ash content: ~8.8%
- Moisture level: ~11%.



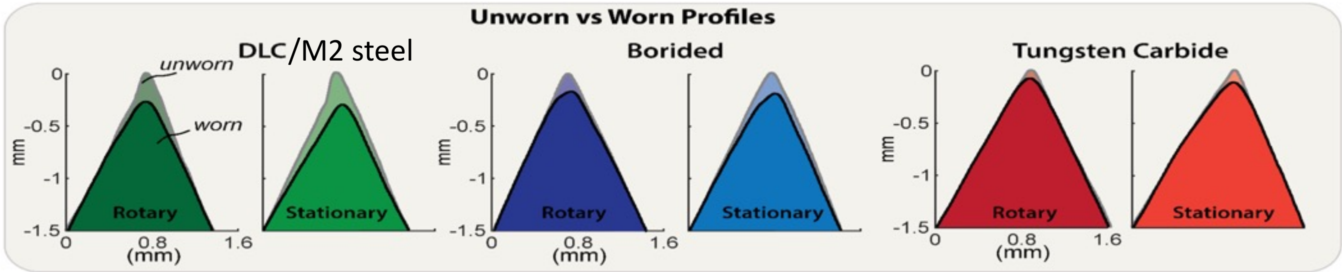
Advanced blade materials demonstrated 3-8X improved tool life

Case Study





- Linear relationship between the blade volumetric wear loss and the mass of feedstock processed.
- **Iron boriding reduced the tool wear rate by 3X.**
- **Tungsten carbide had 8X lower tool wear rate than the standard.**
- DLC coating on the blade tip was worn out after 40 kg of feedstock.
- *Wear rate of standard blade (M2 steel): Estimated by the wear rate of the DLC-coated blade after coating worn out.*

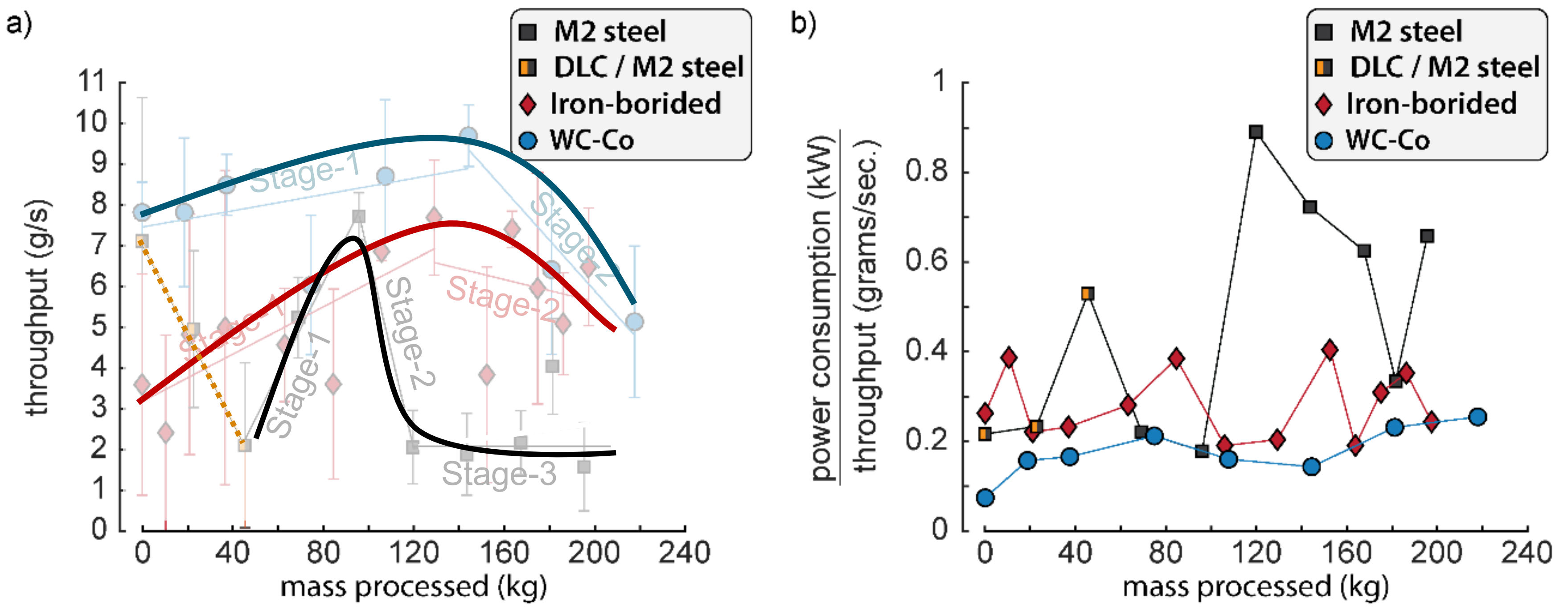


Surprisingly, more wear on stationary blades than that on rotary blades $v_{p,f} \approx 2v_{b,i}$

(*See more detailed discussion in additional slides*)

Wear-resistant blades demonstrated 3X higher throughput and lower power consumption

Case Study

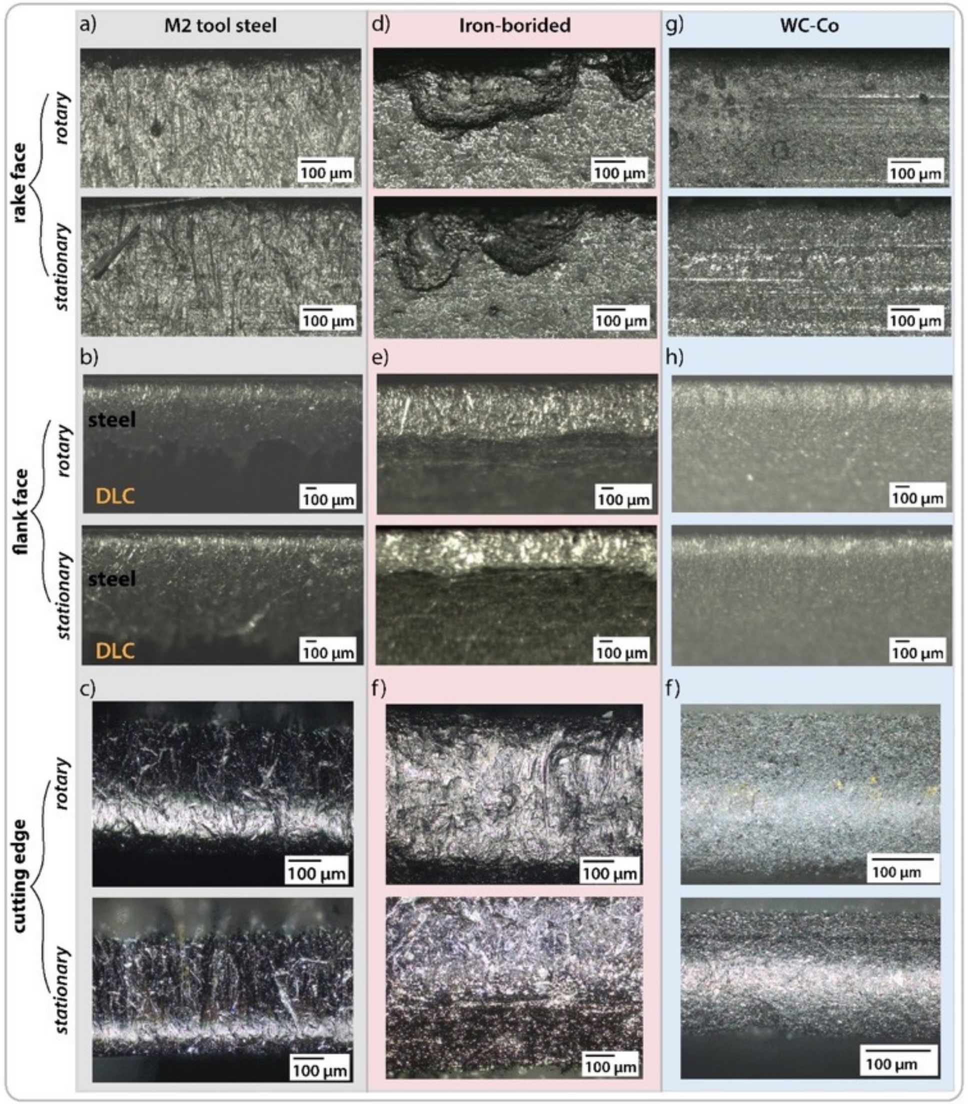


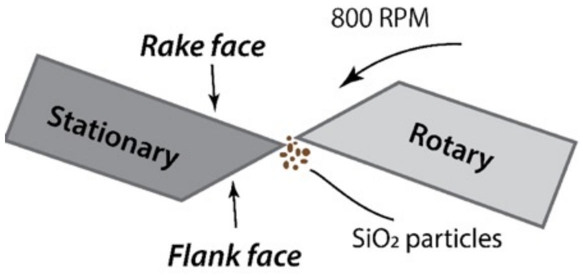
- **Stage 1.** Chipping-induced 'artificial edge sharpening' outweighing blunting
- **Stage 2.** Blunting dominant
- **Stage 3.** Blade gap too large to effectively shear the feedstock

(*See more detailed discussion in additional slides*)

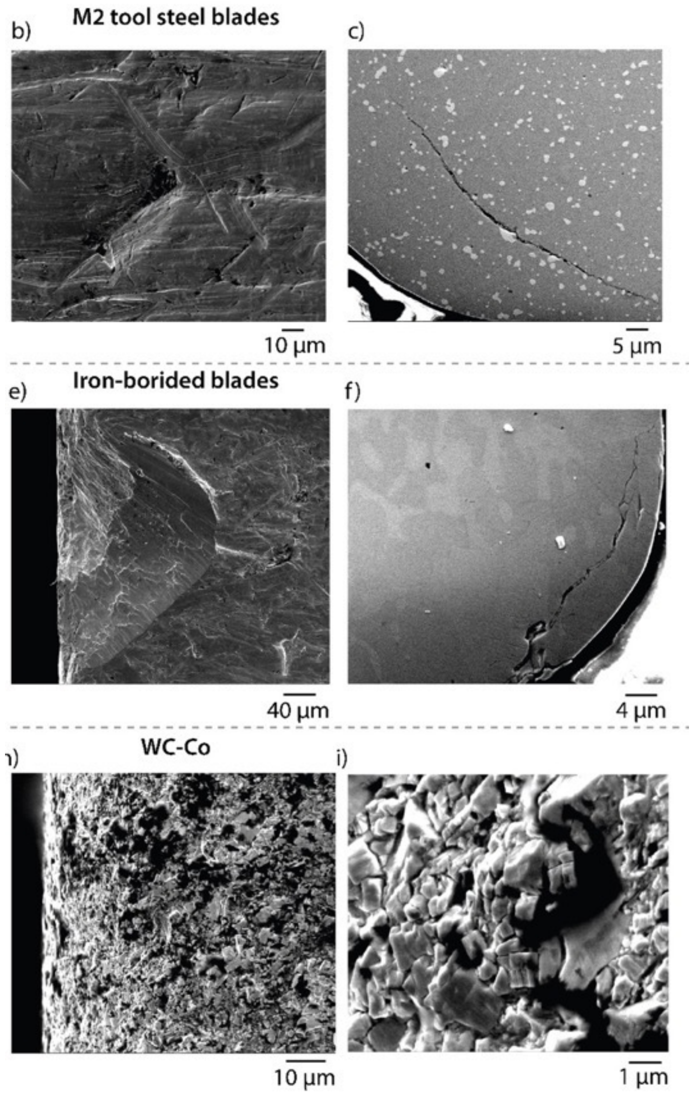
Worn blade characterization

Case Study





- ***Rake face experienced more erosion than flank face***
- ***DLC-coated blades***
  - Erosion quickly removed the thin coating
  - Exposed steel substrate shows clear evidence of both abrasive & erosive wear
- ***Iron borided blades***
  - Rake face has significant chipping due to severe erosion
  - Flank face is dominated by abrasive wear
- ***Tungsten carbide blades***
  - Rake face shows erosion-induced micro fracture
  - Flank face is slightly polished



TEA of blade material upgrade for knife mill

Case Study

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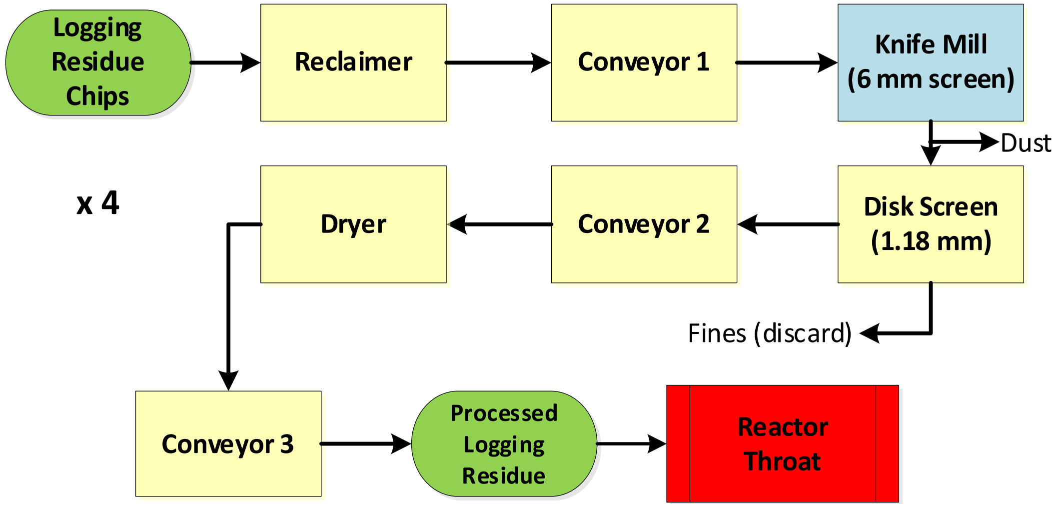
- Discrete Event Simulation for 350 days
- Knife mill - assumed JRS 14CSH, 4 parallel machines per line, 36 rotating knives and 3 stationary knives per machine, purchase price: $482,500/ea. Throughput: 6.25 TPH per machine or 600 TPH per line
- System - 4 parallel lines, Throughput: 2,400 TPD
- Initial investments for four sets of knives: M2 tool steel: $54,600, Fe-B: $56,940, W-C: $117,000
- Resharpening - 3 resharpenings per set before replacement at $42.50 per knife, reboriding cost for Fe-B of $15 per knife
- Lifespans (tons of ash passing): M2 tool steel: 100, Fe-B: 326, W-C: 746
- Assumed throughput degrading similarly in all three blade materials based on the percentage of life remaining



Blade Material	Annual Knife Cost (USD)	Knife Cost per Ton (USD)	Total Cost (USD)	MFSP (USD/GGE)	IRR of Knife Upgrade (%)
M2 Steel	$2,059,200	$4.22	$75.71	$3.42	
Fe-B	$898,560	$1.84	$72.44	$3.37	16,991
W-C	$547,560	$1.10	$71.42	$3.35	734

FY23 – Paper-based MSW abrasiveness evaluation

Developed Lab scale experimental method based on ASTM standard to evaluate abrasiveness of MSW particles

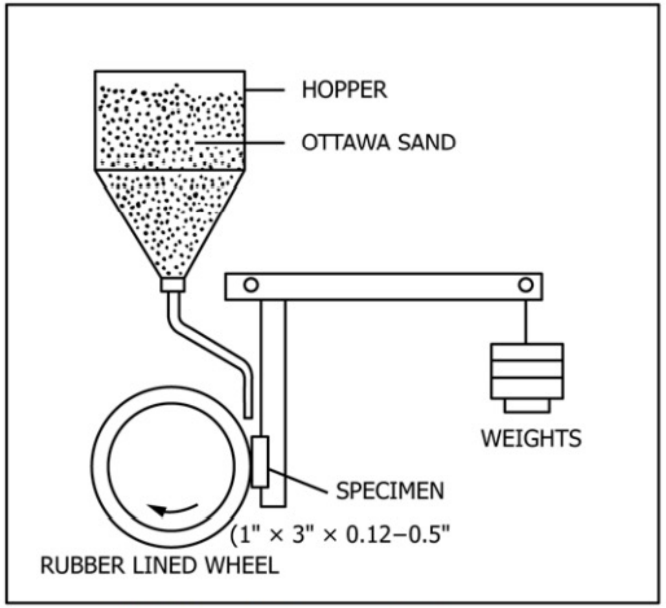


FIG. 1 Schematic Diagram of Test Apparatus

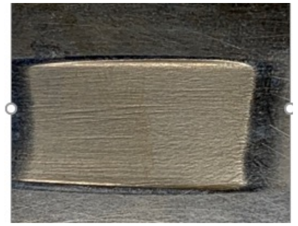
Falex test rig

Description

- Evaluation of abrasiveness of MSW feedstock is a challenging problem due to the size of equipment and wide variabilities in compositions and properties of MSW.
- Based on an ASTM test standard (G 65), a bench test method has been developed to evaluate the abrasiveness of MSW.

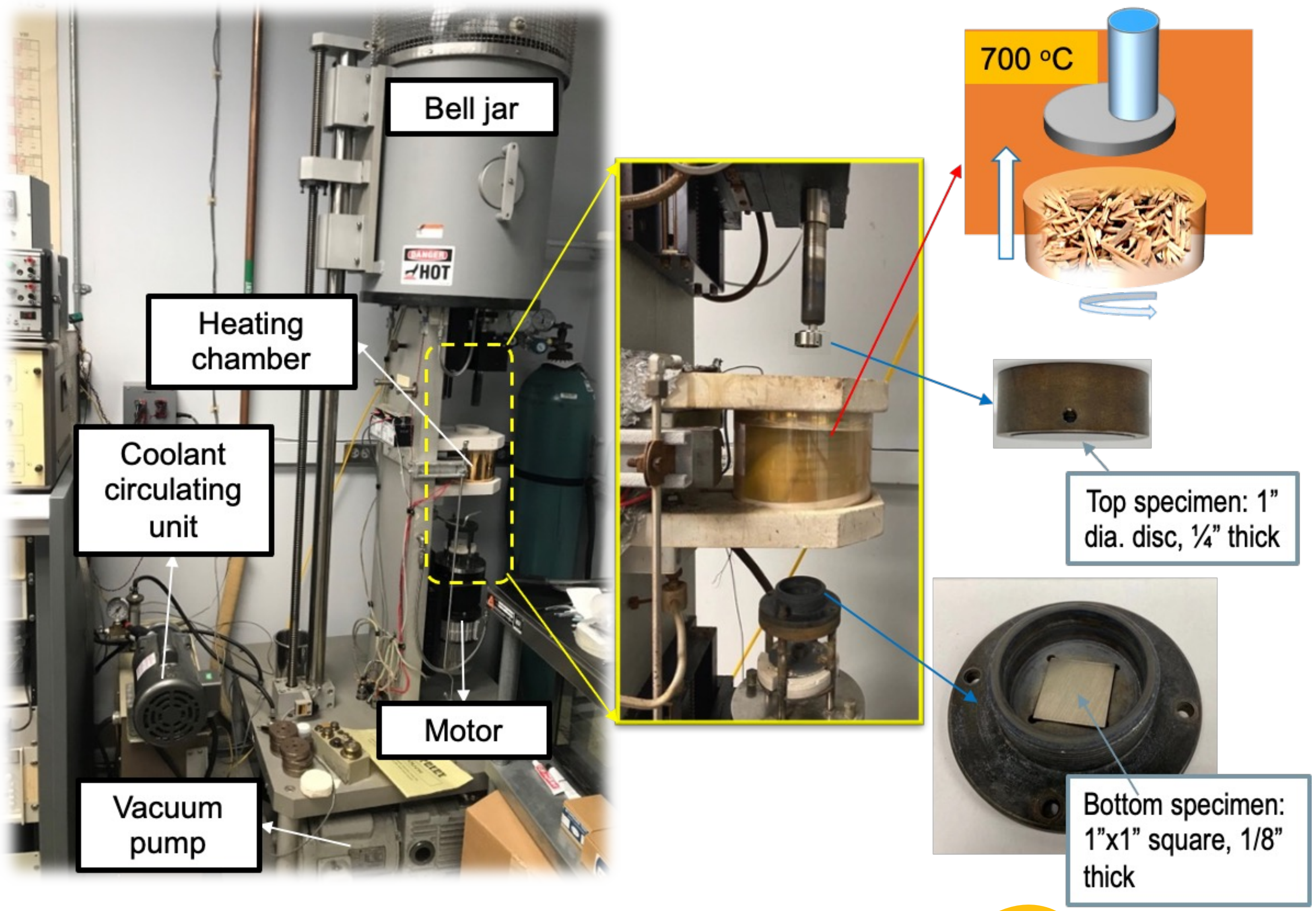
Specified Procedure	Force Against Specimen,[B] N (lb)	Wheel Revolutions	Lineal Abrasion[A] m	(ft)
A	130 (30)	6000	4309	(14 138)
B	130 (30)	2000	1436	(4 711)
C	130 (30)	100	71.8	(236)
D	45 (10.1)	6000	4309	(14 138)
E	130 (30)	1000	718	(2 360)

Typical test parameters for ASTM G65 standard



Example of typical wear scars

FY23 – Biomass/MSW fouling/gumming test



Experimental parameters:

- **Temperature: RT-1000 °C** (simulating the temperature of the pyrolysis screw feeder)
- **Gas environment: dry N_2 or CO_2** (simulating the gas environment of the screw feeder)
- **Normal load: 20-150 N** (simulating the contact pressure on the screw feeder)
- **Rotating speed: 5-500 rpm** (simulating surface speed of the screw feeder)
- **Test duration**: a variable to reveal the initiation/propagation of deposit formation

3 – Impact

Impact: Meets the objectives of FCIC by providing fundamental understanding, predictive tools, and mitigations for equipment wear in preprocessing. QbD approach to identify CMAs and CPPs to provide CQAs on wear, reliability, durability, and performance for individual unit operations.

- Provides fundamental understanding for **tool wear mechanisms** in biomass preprocessing.
- Develops **cost-effective mitigations** for improving tool life and throughput and reduce downtime and power consumption.
- The biomass industry is eager to learn both the fundamentals and mitigation strategies produced in this study, which will potentially improve the operation reliability and efficiency for better economics.

Dissemination:

- Open Source excel-based wear model available online
- 5 peer-reviewed journal papers and 1 conference proceeding
- 8 conference presentations/posters
- 3 technical reports (accessible through OSTI)
- Media report in *Biofuels Digest* (https://www.biofuelsdigest.com/bdigest/2021/01/10/ornls-latest-on-bio-oils-corrosion-and-degradation-the-digests-2020-multi-slide-guide-to-oak-ridge-national-laboratory/)
- Communications with size reduction equipment manufacturers: Eberbach, Jordan Reduction Solutions, Rawlings Manufacturing, and Forest Concepts, and coating/surface treatment providers: IBC, NCT, ATC, and C4E.

Summary

Technical Approach: Use integrated efforts of characterization, modeling, and testing to gain fundamental understanding of the failure modes and wear mechanisms of biomass preprocessing tools, develop candidate mitigations, and share findings with the biomass community.

Impact: Provides fundamental understanding for tool wear in biomass preprocessing, and develops cost-effective mitigations for improving the tool life, throughput, and particle size uniformity.

Progress:

- Fundamental understanding of the **wear mechanisms of both hammer mill and knife mill** [complete]
- Protocols developed for **extraction and characterization of both extrinsic and intrinsic inorganics** [complete]
- **Analytical erosive wear model** for predicting wear of hammer mill [complete]
- **Low-cost feedstock modifications** developed for improving tool life [complete]
- Evaluation of **candidate tool coatings and surface treatments** using bench-scale abrasion and erosion tests [complete]
- **Analytical abrasive wear model** to for knife mill durability and performance [complete]
- **Small knife mill validation tests for candidate wear-resistant blade materials with TEA** [complete]
- Development of bench-scale tests to study the **abrasiveness and gumming/fouling of MSW** [on-going]
- Small **shredder** testing for validation of candidate wear-resistant blade materials with TEA [on-going]

Quad Chart Overview

Timeline

- *10/01/2018*
- *09/30/2024*

	FY22 Costed	Total Award
DOE Funding	*$575K*	*FY19-21: $2,008K* *FY22-24: $1,725K*
Project Cost Share *		

TRL at Project Start: 2
TRL at Project End: 4

Project Goal

use a systematic quality-by-design approach with integrated efforts of characterization, modeling, and testing to gain fundamental understanding of the failure modes and wear mechanisms of biomass preprocessing equipment, develop analytical tools/models to predict wear and establish material property specifications, select and evaluate candidate mitigations based on modeling and lab-scale testing and identify top-performing mitigation for PDU validation, and share the fundamentals and mitigations with the biomass industry. To accommodate new policy directives on aviation fuels and MSW, the task will use its expertise to address issues related to durability, reliability and resilience of materials and components used in preprocessing of biomass and MSW.

End of Project Milestone

Publish a decision matrix for industry stakeholders on the FCIC DataHub and/or the FCIC website which combine experimental approaches and predictive models for developing material specifications and identifying materials solutions for mitigating equipment wear in preprocessing a variety of biomass and MSW feedstocks and guidance on TEA implications of mitigation strategies.

Funding Mechanism

N/A.

Project Partners*

- Knife mill OEM: Eberbach
- Coating/surface treatment vendors: IBC, UTC, NCT, C4E, and ATC

*Only fill out if applicable.

Additional slides

Why stationary blades wear faster than rotary blades?

Knowledge

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- Hypothesis before knife mill testing
  - **Stationary blades were thought to wear slower than rotary ones** because of
  - **Rotary blades** were expected to experience **both erosive wear** (upon impact against feedstock) **and abrasive wear** (when shearing feedstock together with stationary blades)
  - **Stationary blades were thought** to have **only abrasive wear** (when shearing feedstock together with stationary blades) but little erosive wear because of relatively slow speed of feedstock upon feeding
- Observation in knife mill testing
  - **Stationary blades actually wear faster than rotary ones!** This because
  - **Stationary blades** not only experienced **both abrasion and erosion** but also had **higher differential speed impacting against the feedstock.**

This may be explained by linear momentum and collision physics.

- Assuming an elastic collision between the rotary knife and the inorganic particle, both the momentum and mechanical energy are preserved and their interaction can be described as:

$$v_{p,f} = \left(\frac{2m_b}{m_b + m_p}\right) v_{b,i} + \left(\frac{m_p - m_b}{m_p + m_b}\right) v_{p,i}$$

where $v_{p,i}$ is the initial velocity of the particle, $v_{p,f}$ is the final velocity of the particle after a collision with the rotary blade, $v_{b,i}$ is the initial velocity of the rotary blade, m_b is the mass of the blade and m_p is the mass of the particle.

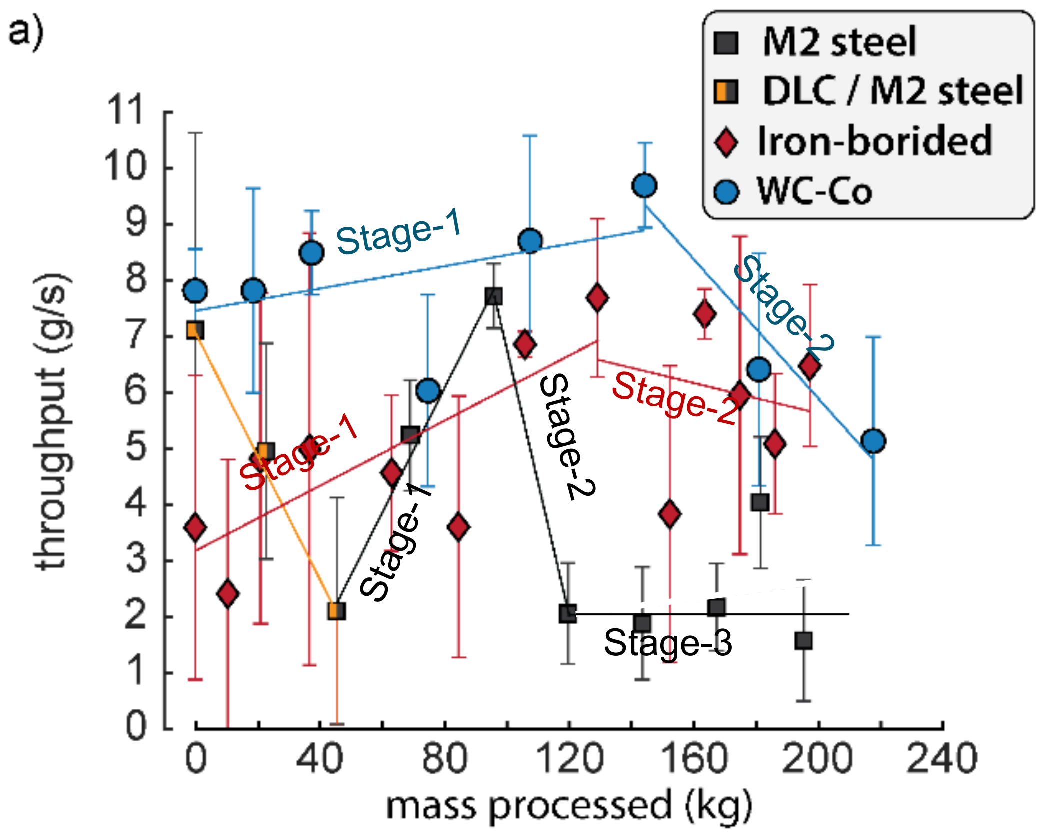
- Biomass particles are fed in a relatively slow speed with respect to the speed of the rotary blades. Therefore, the initial velocity of the particles can be neglected. Also, the mass of the particles can be also neglected as well since it is much smaller than the mass of the blades. Thus, the above equation becomes:

$$v_{p,f} \approx 2v_{b,i}$$

- This indicates that the velocity of the particle after a collision against the rotary blade is roughly twice the velocity of the rotary blade.
- **Then, the particle reflected from a rotary blade impacts a stationary blade at a 2X speed differential.**

Three stages of knife mill throughput as blades wear out …

- **Stage 1. Chipping-induced 'artificial edge sharpening' outweighing blunting**
  - Throughput initially rose because edge chipping increased the contact pressure against the feedstock outweighing the edge thickening (blunting)
- **Stage 2. Blunting dominant**
  - Throughput decreased when edge chipping became less significant because the edge was getting too thick to chip and its effect was overshadowed by blunting, and
- **Stage 3. Blade gap too large to effectively shear the feedstock**
  - Throughput dropped to a trendless lower level when the gap between the rotary and stationary blades was so large that the milling process was no longer sensitive to the edge sharpness.



Note: Edge chipping can be clearly seen on the worn blade images in Slide #18

Responses to Previous Reviewers' Comments

Reviewer 1

(1a): It would be good to understand whether the effort from this work is planned to result in new offerings from the OEMs.

RE: Yes. We have always been communicating with OEMs to understand the industrial needs for planning our work.

(1b): The presentation did not adequately demonstrate the overall impact of the work on the TEA. It is believable that the improvements could result in real dollars on the OpEx side of an analysis through increased uptime and better knowledge of spares; however, this is inferred rather than demonstrated in the presentation.

RE: Yes. We have already delivered a comprehensive TEA in collaboration with FCIC Task 8 for using advanced tool materials for knife mill.

(1c): Currently the work appears to be limited to the upstream milling equipment. However, wear should also be reviewed in softer materials such as seals, belts, and other equipment. This could be addressed in a larger roadmap.

RE: Fully agreed and will add the wear issues of seals, belts, and other equipment into the work scope in the future work.

(1d): During the Peer Review presentations, this project team learned about some work on silica that a different project discovered (feedstock variability group). This shows that the data from that group are not being properly disseminated as planned. FCIC should investigate how this particular piece of knowledge slipped through the cracks.

RE: Sorry for the confusion. We were aware of the Task 2's interesting observation that bale degradation may lead to translocation/migration of the intrinsic silica within corn stover tissue, but have not studied its specific impact on the tool wear yet. This could fit in the work scope in next phase.

Responses to Previous Reviewers’ Comments (cont’d)

Reviewer 2

(2a): Perhaps the challenge to the team is commercializing these developments into existing applications in the near term.

RE: We have started communicating with OEMs for technology implementation.

- **Reviewer 3**

(3a): The management approach for this project is less detailed (or takes a different approach) than that of other project presentations in that it does not define responsibility of subtasks.

RE: Subtask 1.1 conducts tribosystem analysis and develops wear mitigations, while Subtask 1.3 develops predictive wear models.

Responses to Previous Reviewers' Comments (cont'd)

Reviewer 4

(4a): There are several biorefinery unit operations whose processing equipment experiences materials of construction related corrosion, wear, and failure beyond milling including reaction vessels, plug screw feeders, and pulp disc refiners. An explanation for why this task chose to focus on milling wear only would be beneficial, particularly in terms of estimated impact to biorefinery downtime and operations and capital costs.

RE: We fully agree that many units in biomass preprocessing experience wear issues and need to be addressed. We chose to study the milling wear as a starting point for this program and plan to expand the work scope to address the wear issues in other biorefinery units in the future work.

(4b): To determine impact, more discussion is necessary on the industrial relevance of the hammermill and knife mill and the typical lifetime of wear parts for biomass processing, replacement costs, downtime to change parts, and impact of wear on particle size uniformity.

RE: Yes. We have already delivered a comprehensive TEA in collaboration with FCIC Task 8 for using advanced tool materials for knife mill.

(4c): The performance metrics and success factors for this task are not clear.

RE: The performance metrics and success factors include tool life extension, throughput increase, and energy savings and the resulted in improvement on overall economics by considering replacement costs and downtime.

Responses to Previous Reviewers' Comments (cont'd)

Reviewer 5

(5a): The task characterized CMAs for pine residue and correlated to a lab-scale impact test (hammer mill), but did not show the impact of material variability on knife wear.

RE: We agree and would like to run systematic knife mill tests in the future work to determine the impact of material variability on knife wear.

(5b): Although the overall FCIC objective (slide 2) states the purpose of this task is to develop tools that specify materials that do not "corrode, wear, or break at unacceptable rates," this task focused only on milling knife or hammer wear.

RE: Yes. Many units in biomass preprocessing experience excessive material degradation problems and need to be addressed. We chose to study the milling wear as a starting point for this program and plan to expand the work scope to address the wear issues in other biorefinery units, such as screw feeders, seals, and belts, in the future work.

FY21-23 Task 1 Milestones

Milestone	Lead Lab	Milestone Description (Original)	Milestone Description (Revised)	Status
FY21 Q1	ORNL	Produce prototype hammers using candidate alloy(s) or coating(s) selected based on bench-scale wear testing and conduct preliminary TEA (in collaboration with Task 8) for potentially 2X or better improved economics for OPEX.	Down select candidate alloys and surface treatments by bench-scale erosion (blasting) and abrasion (2-body) accelerated wear testing in comparison with the baseline knife alloys.	Complete – Milestone report submitted
FY21 Q2	ANL	Using erosion wear model testing results from subtask 1.1, define mechanical property operating envelope and tradeoffs for materials and coatings used in construction of hammers for industry.	Use erosion wear model and bench-scale testing results to define mechanical property operating envelope and tradeoffs for alloys and surface treatments used in construction of knives for industry.	Complete – Milestone report submitted
FY21 Q3	INL	Demonstrate at least 2X improved economics for hammer mill OPEX by using candidate alloy(s) and/or coating(s) based on demonstration on a Schutte Buffalo Hammer Mill and TEA (in collaboration with Task 8).	Produce prototype knives using the top-performing candidate alloy and/or surface treatment and demonstrate at least 3X better tool life on a small knife mill at INL.	Complete – Milestone report submitted
FY21 Q4	ORNL	Determine the wear mechanisms and mitigation approaches for knife mills.	Deliver a TEA (in collaboration with Task 8) based on bench-scale and as well as modeling for potentially 2X or higher economics for knife mill OPEX.	Complete – Milestone report submitted
FY22 Q1	INL	Through industry conversations with at least 5 companies and literature reviews, identify at least two comminution or handling devices used for MSW and biomass processing with documented problems associated with wear and TEA relevant information with Task 8 to guide future effort in improving MSW and biomass preprocessing.		Complete – Milestone report submitted
FY22 Q2	ANL	Release an open-access Excel-based analytical wear model for knife mill as a design tool for predicting component wear life and start finite element analysis for further model enhancement.		Complete – Milestone report submitted
FY22 Q3	ORNL	Publish a comprehensive TEA on the FCIC website or Data Hub (in collaboration with Task 8) for knife mill for the overall increased economics from improved blade life, throughput, particle size distribution, and power consumption by using wear-resistant coatings or surface treatments.		Complete – Milestone report submitted
FY22 Q4	ANL	Implement and validate an industry-accepted ASTM abrasion testing protocol and materials characterization to evaluate the abrasiveness of MSW constituents in comparison with biomass feedstock and available literature to help establish a science-based metric for comminution equipment design, operation and maintenance.		Complete – Milestone report submitted
FY23 Q2 (GNG)	ORNL	Identify at least one material or surface treatment technology that demonstrates 3X improved wear resistance compared with a commonly used material for a specific unit		Complete
FY23 Q4	ANL	Deliver analytical predictive wear model for shredder blades used for processing MSW feedstock. Informed by tribo-system analysis and appropriate wear mechanism, with input consisting of critical process parameters (CPPs), critical shredder blade material attributes (CMAs), and attributes of the MSW feedstock (ash content, particle size & shape, compositions).		In progress

Publications, Patents, Presentations, Awards, and Commercialization

Publications:

1. S. Roy, K. Lee, J.A. Lacey, V.S. Thompson, J.R. Keiser, J. Qu, "Material characterization-based wear mechanism investigation for biomass hammer mills," ***ACS Sustainable Chemistry & Engineering*** 8 (2020) 3541−3546.
2. K. Lee, S. Roy, E. Cakmak, J.A. Lacey, T.R. Watkins, H.M. Meyer, V.S. Thompson, J.R. Keiser, J. Qu, "Composition-preserving extraction and characterization of biomass extrinsic and intrinsic inorganic compounds," ***ACS Sustainable Chemistry & Engineering*** 8 (2020) 1599−1610.
3. O. Oyedeji, P. Gitman, J. Qu, E. Webb, "Understanding the impact of lignocellulosic biomass variability on size reduction process: a review," ***ACS Sustainable Chemistry & Engineering*** 8 (2020) 2327-2343.
4. J. A. Lacey, J. E. Aston, S. Hernandez, V. S. Thompson, M. S. Intwan, K. Lee, J. Qu, "Wear and Why? How Ash Elements Can Help Define Wear Profiles of Biomass Feedstocks," DOI: 10.13031/aim.201901446, ***Proceedings of 2019 ASABE Annual International Meeting***, Boston, MA, July 7–10, 2019.
5. P.J. Blau, T. Grejtak, J. Qu, "The characterization of wear-causing particles and silica sand in particular," ***Wear*** (2023) (in press)
6. T. Grejtak, J.A. Lacey, M.W. Kuns, D.S. Hartley, D.N. Thompson, G. Fenske, O.O. Ajayi, J. Qu*, "Improving knife milling performance for biomass preprocessing by using advanced blade materials," ***Wear*** (2023) (in press)

Open Source Wear Model: G.R. Fenske, O.O. Ajayi, Open Source excel-based model for predicting edge recession rate for knife mill blades, https://www.anl.gov/amd/abrade-model, 2022.

Presentations:

1. J. A. Lacey, J. E. Aston, S. Hernandez, V. S. Thompson, M. S. Intwan, K. Lee, J. Qu, "Wear and Why? How Ash Elements Can Help Define Wear Profiles of Biomass Feedstocks," ***2019 ASABE Annual International Meeting***, Boston, MA, July 7–10, 2019.
2. K Lee, J Keiser, V Thompson, E Kuhn, E Wolfrum, J Qu, "Investigation of Equipment Wear Issues in Biomass Pre-Processing and Pre-Treatment," ***TMS 2019 Annual Meeting***, San Antonio, Mar. 10, 2019.
3. K Lee, J Qu, E Kuhn, J Keiser, E Wolfrum, "Ash-induced wear on biomass pre-conversion equipment," ***74th STLE Annual Meeting***, Nashville, May 19, 2019.
4. K. Lee, S. Roy, E. Cakmak, J.A. Lacey, H.M. Meyer, V.S. Thompson, J.R. Keiser, J. Qu, "Composition and abrasiveness of biomass extrinsic and intrinsic inorganic compounds," ***TMS 2020 Annual Meeting***, Feb. 23-27, 2020, San Diego.
5. K. Lee, P.J. Blau, J.A. Lacey, V. Thompson, G.R. Fenske, R. Elander, J.R. Keiser, J. Qu, "Wear characterization and mitigation strategy on the cutting blade of knife mill used in the biomass size reduction process," ***75th STLE Annual Meeting***, May 17-20, 2021 (Virtual)
6. J. Qu, K. Lee, L. Lin, D. Lanning, J.A. Lacey, G.R. Fenske, P.J. Blau, J.R. Keiser, O.O. Ajayi, V. Thompson, "Tool Wear Analysis and Mitigation for Various Biomass Comminution Systems," ***2021 AIChE Annual Meeting***, Nov. 7-12, 2021. (Virtual)
7. T. Grejtak, J. Lacey, M. Kuns, G.R. Fenske, O.O. Ajayi, J.R. Keiser, P.J. Blau, Vicki Thompson, E. Wolfrum, J. Qu, "Understanding and Mitigation of Knife Mill Wear in Biomass Preprocessing," ***76th STLE Annual Meeting***, May 15-19, 2022, Orlando, FL.
8. J. Qu, K. Lee, L. Lin, D. Lanning, G.R. Fenske, O.O. Ajayi, J.R. Keiser, "Improving Biomass Comminution Performance by Optimizing Tool Design and Using Advanced Tool Materials," ***7th World Tribology Congress***, July 10-15, 2022, Lyon, France.

Media Report: "ORNL's latest on bio-oils corrosion and degradation: The Digest's 2020 multi-slide guide to Oak Ridge National Laboratory," ***Biofuels Digest***, Jan. 10, 2021.