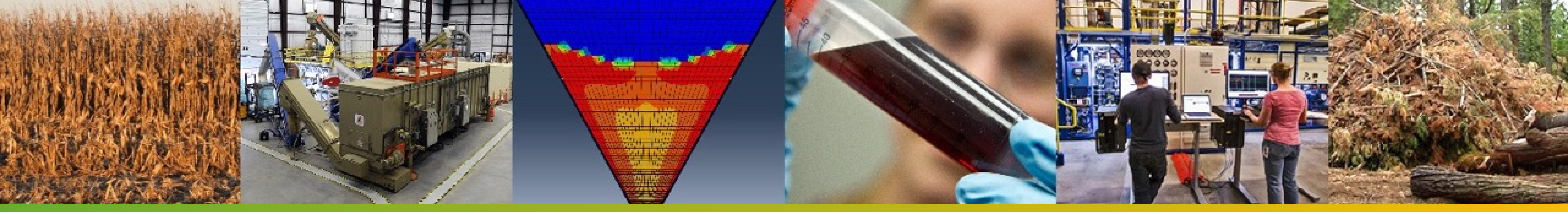


DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

FCIC – Forest Concepts DFO: Investigating and addressing the wear issue of the rotary shear biomass comminution system

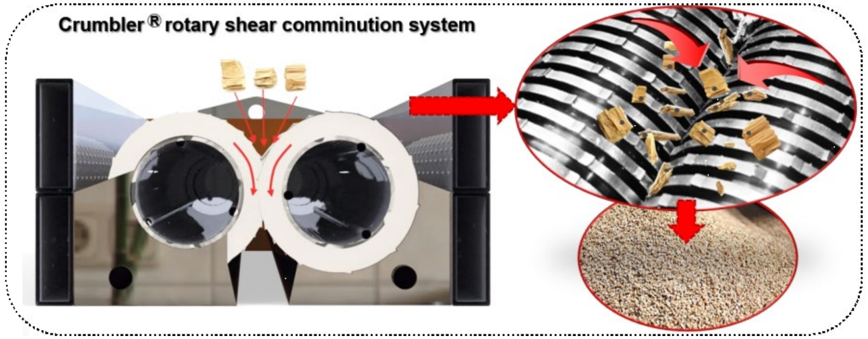
Date: March 16, 2021
Technology Area Session: FCIC

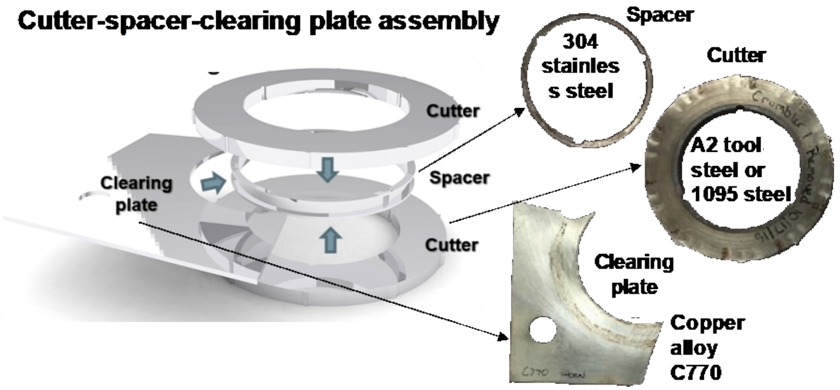
ORNL: Jun Qu, Kyungjun Lee, Lianshan Lin, Jim Keiser
ANL: George Fenske and Layo Ajayi
Forest Concepts: Dave Lanning

fcic
FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

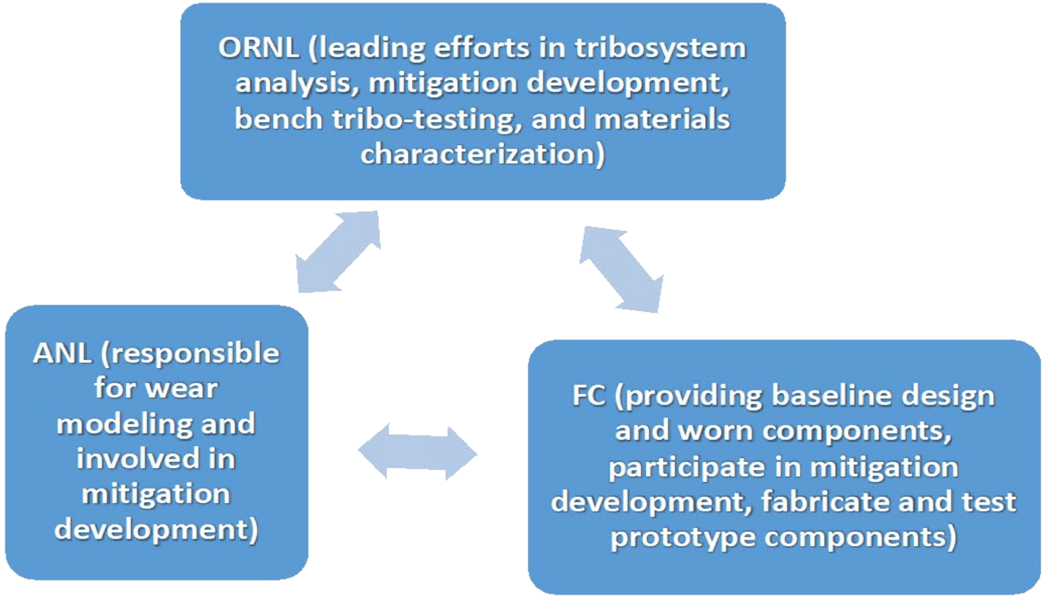
Project Overview

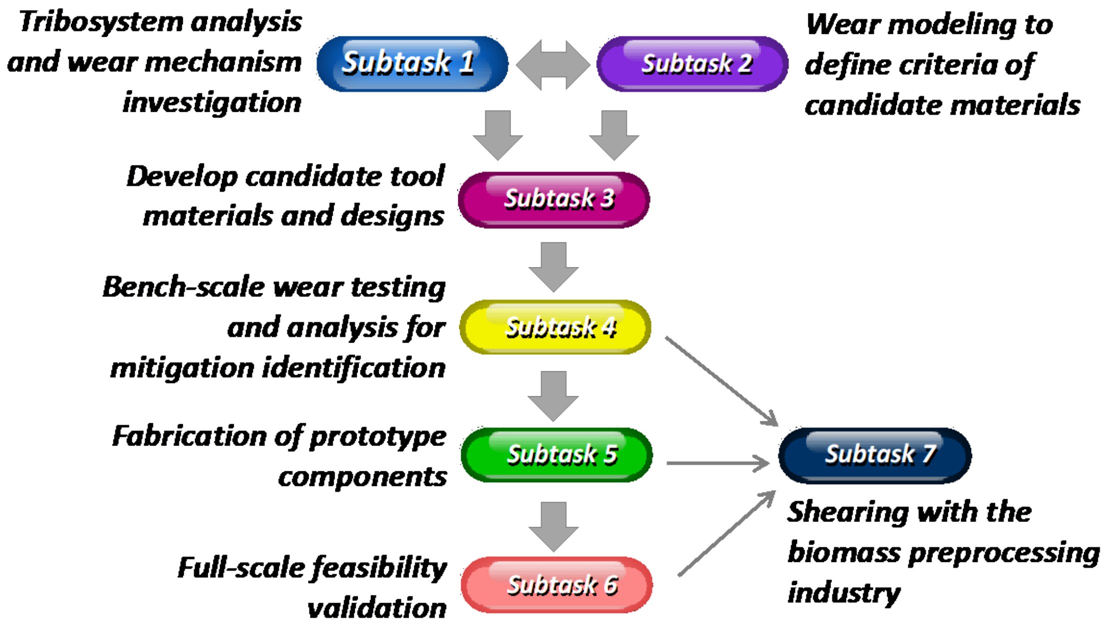
- **Objectives:**
  - Gain **mechanistic insights for the wear issues** experienced by the Crumbler® rotary shear comminution system,
  - Provide **combined materials and design solutions** to improve the tool lifetime and processing efficiency and reduce downtime for higher economics, and
  - **Share** the fundamentals and mitigations with the biomass industry.
- **Current limitations:** **Significant wear** of the cutter-spacer-clearing plate assembly in processing dirty biomass feedstocks (e.g., logging residues, ag residues, municipal solid waste) causing lower than desired cutter life. Target in excess of 1,200 operating hours, **but actually as few as 200 hours in particularly dirty woodchips.**
- **Relevance:** Forest Concepts has recently developed (with significant BETO support) a state-of-the-art biomass comminution system – Crumbler® rotary shear **with benefits of producing precision feedstock of narrower particle size distribution, lower particle aspect ratio for higher flowability, and less fines, and higher tolerance of high moisture variations.**
- **Risks:** Inconsistent wear behavior due to feedstock variations and mitigations difficult to implement due to high cost.





1 – Management





- **Risks/Mitigations:**
  - Inconsistent wear behavior due to biomass feedstock variations

  ***Mitigation**:* Characterization of the worn components and the feedstocks processed to allow direct correlations
  - Candidate mitigations difficult to scale-up due to cost or technical challenges

  ***Mitigation**:* Identification using techno-economic analysis (TEA)
- **Communication/Collaboration:**
  - Communicating with FCIC's Tasks 1, 2, and 5 for performance improvement and with Task 8 for TEA
  - Communicating and collaborating with component manufactuters and coating suppliers

2 – Approach

Technical Approach: ORNL and ANL closely work with Forest Concepts to fundamentally understand the wear mechanisms of the Crumbler® rotary shear, identify and implement advanced materials and designs for better tool life and performance, and conduct prototype feasibility tests to demonstrate improved economics.

Challenges:

- Complex wear mechanisms requiring correlation among feedstock species, extrinsic minerals, tool material mechanical properties, and wear performance
- Development of effective AND low-cost tool materials and designs for wear mitigation
- Optimization of both the tool life and throughput (feedstock gripping and cutting efficiency)
- Quantification of combined benefits from increased tool life and throughput as well as reduced downtime and power consumption

Metrics:

- Technical metrics: wear modes, contact pressure at the tool-feedstock interface, volumetric wear rate of coupons in lab abrasion testing, geometric change of actual components in rotary shear operation
- Economic metrics: costs of tool material, machining, heat treatment, and coating, cost savings of machine shutdown for tool replacement, and energy savings by higher throughput

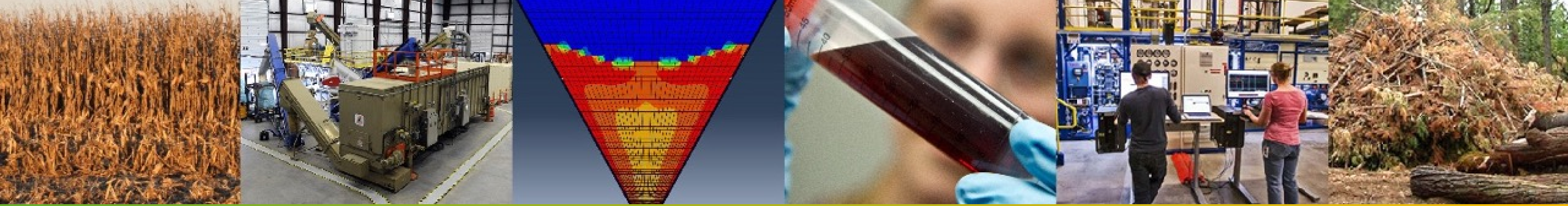
3 – Impact

Impact:

- Provide fundamental understanding of the wear mechanisms of the state-of-the-art Crumbler® rotary shear biomass comminution system
- Develop cost-effective materials and design mitigations for improving the overall economics by **increasing the processing efficiency and tool life** and **reducing the downtime and power consumption**.

Dissemination:

- 3-way CRADA signed among ORNL, ANL, and Forest Concepts on Sept. 27, 2019
- 1 journal paper published and 2 manuscripts in review
- 3 conference presentations accepted by the 2021 TMS, STLE, and WTC, respectively
- Communications with industry

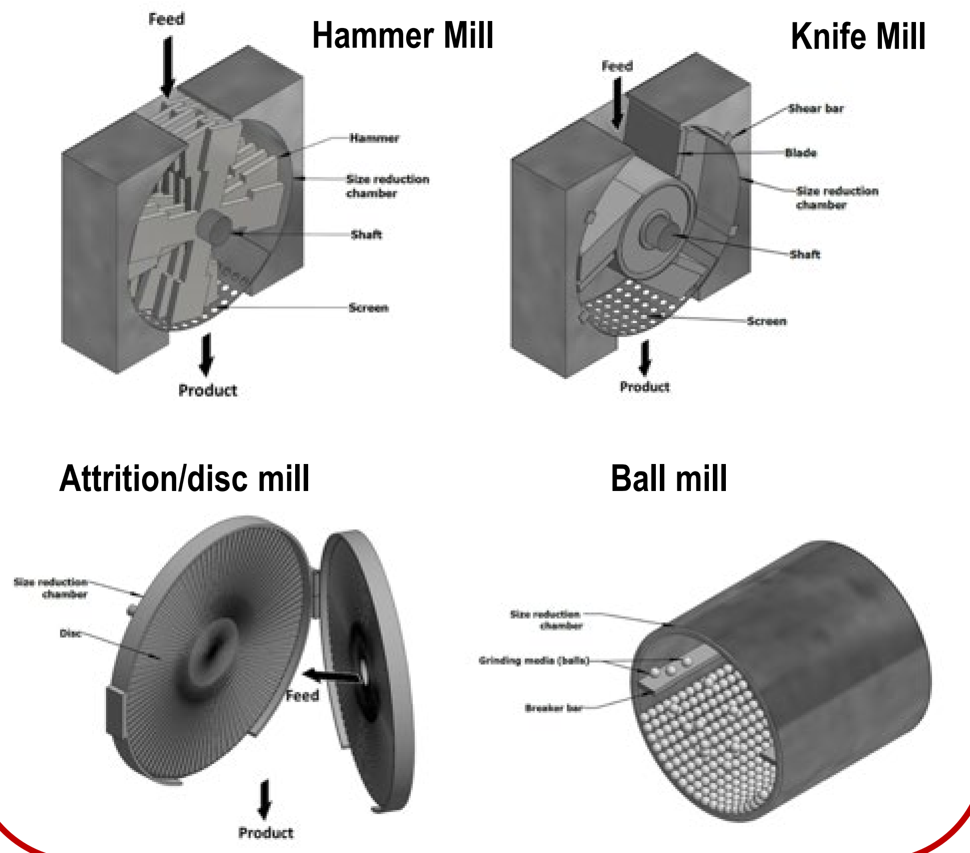


4 – Progress and Outcomes

Advance the state-of-the-art biomass size reduction equipment

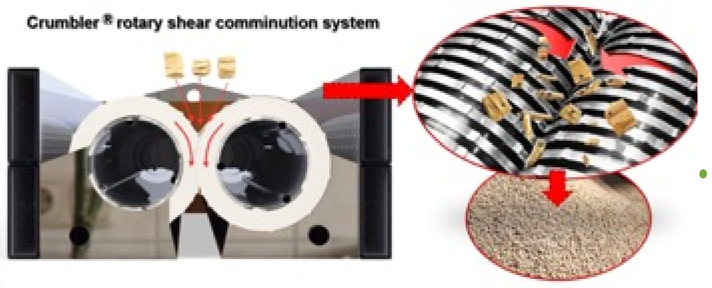
Knowledge

Conventional/Current



O. Oyedeji, P. Gitman, J. Qu, E. Webb, *ACS Sustainable Chemistry & Engineering* 8 (2020) 2327.

FC recently developed
Crumbler® Rotary Shear



- Benefits of rotary shear:
  - Narrower particle size distribution
  - Lower aspect ratio for high flowability
  - Less fines
  - Higher tolerance of high moisture variation
- Technical challenge:
  - Excessive tool wear in processing dirty feedstocks

- This work advances the state-of-the-art biomass size reduction technology by providing
  - Fundamental understanding of wear/failure mechanisms
  - Cost-effective wear-resistant tool materials
  - Optimized tool designs
- To gain
  - Improved tool life
  - Increased throughput
  - Reduced downtime and power consumption

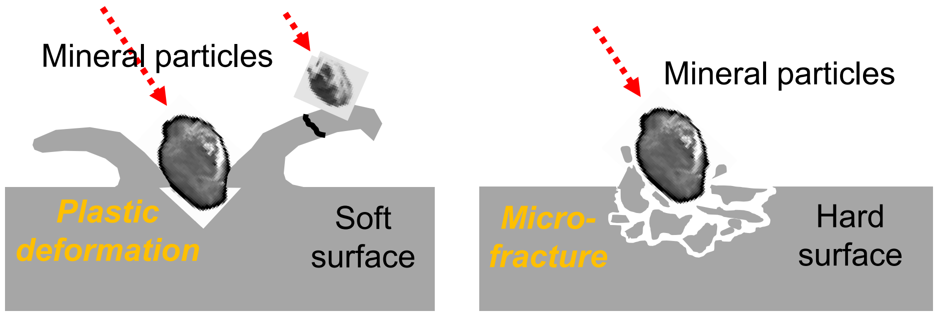
Fundamentals of Wear Modes

Knowledge

General Types of Wear

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

Erosive Wear

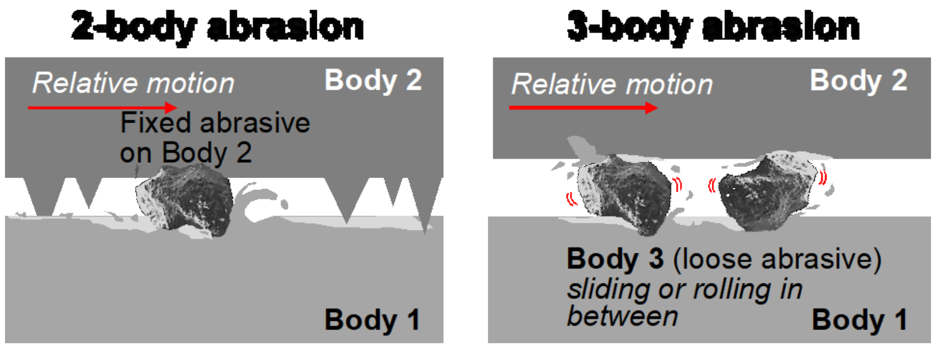


Manner of energy dissipation:
Plastic deformation, micro-fracture, heat

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

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

2-body/3-body Abrasive Wear



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

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

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

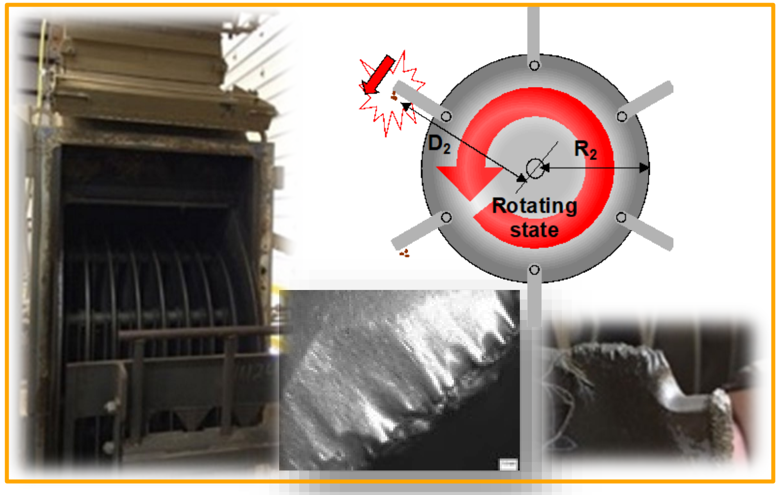
Distinguishing the wear mechanisms among biomass comminution systems

- **Different wear mechanisms have been identified** based on tribosystem analysis (relative motions, contact mechanics, operating conditions, etc.) and worn component characterization

Hammer Mill

Blunt blades @ high speed
→ **Crushing**

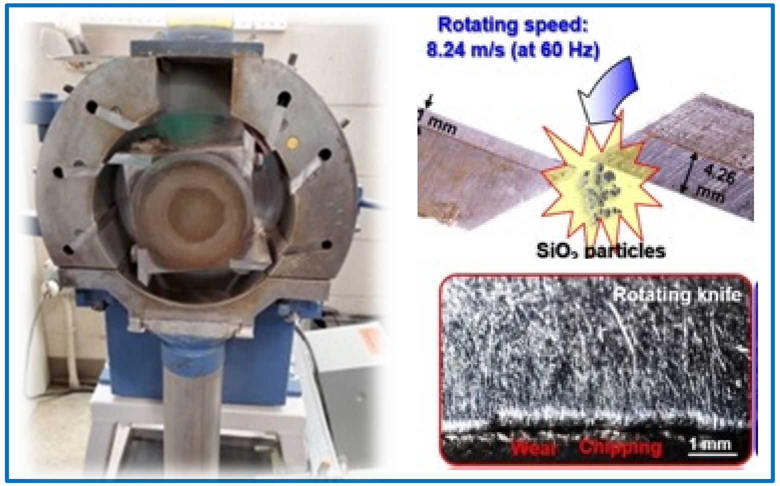
Erosive wear (dominant) + 2-body/3-body Abrasive wear (secondary)



Knife Mill

Sharp blades @ medium-high speed
→ **Cutting + Crushing**

2-body/3-body **Abrasive** wear **+ Erosive** wear (both important, *depending on operation conditions*)



Crumbler® Rotary Shear

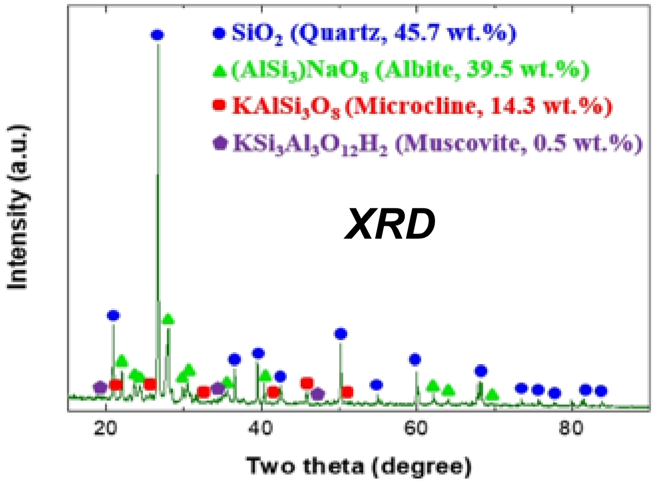
Sharp edges/corners @ low speed
→ **Cutting/Shearing**

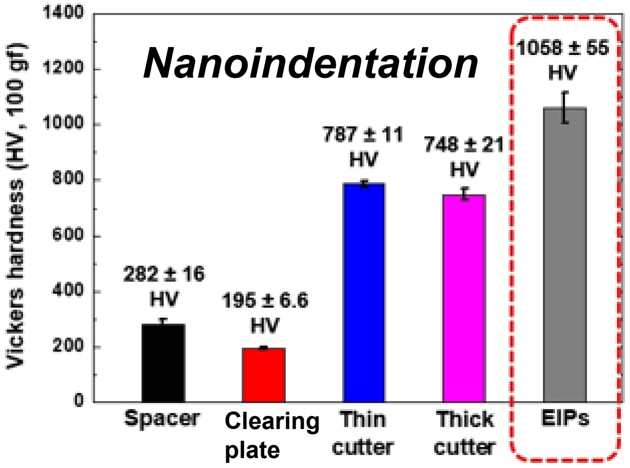
2-body/3-body **Abrasive** wear (dominant) + chipping (secondary)
**Erosion negligible*

Extrinsic mineral particles of woodchips and their impact on cutter wear

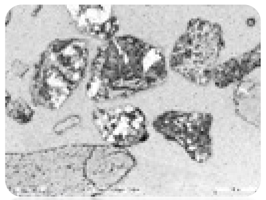
Knowledge

- **Extrinsic mineral particles**

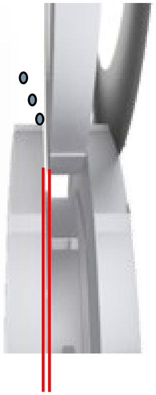




Extracted, mounted, and polished extrinsic inorganic particles

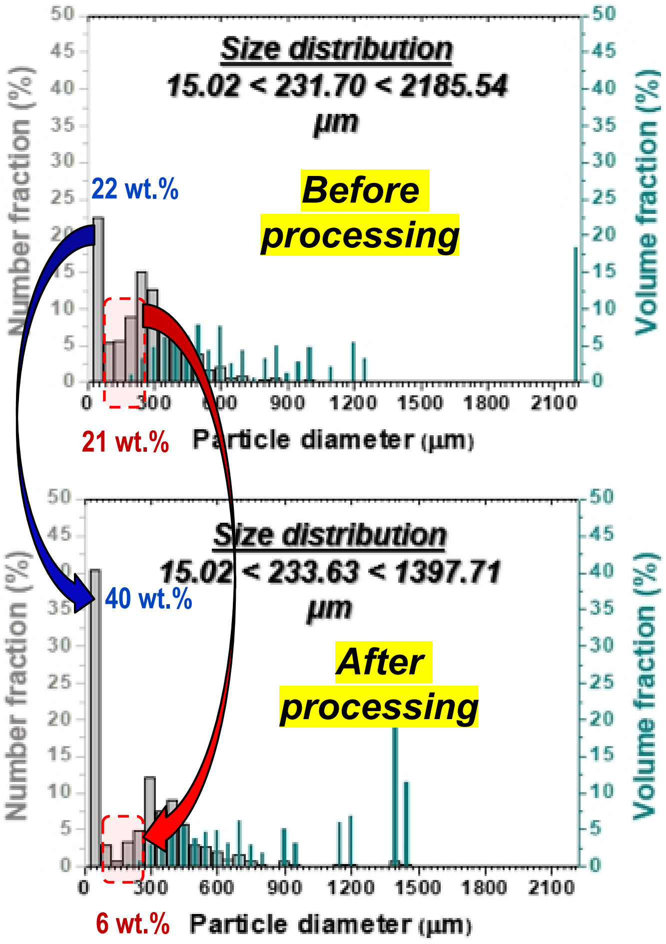


- **Extrinsic mineral particles cause 2-body/2-body abrasive wear**



Gap between cutters: <100 μm new and up to 200 μm used

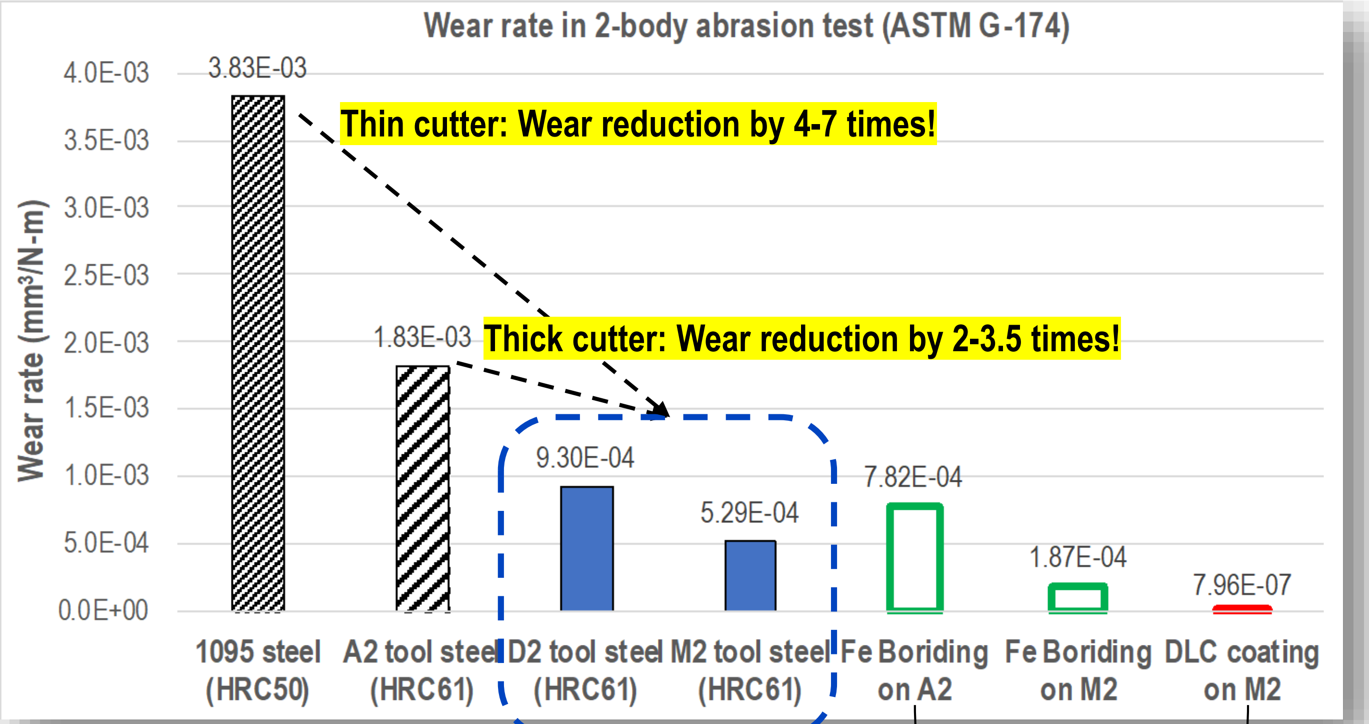
- **Mineral particles of 70-200 μm are trapped in the gap between cutters and crushed into smaller ones**
  - 70-200 μm-sized minerals decreased from 21 wt.% to 6 wt.%
  - <30 μm-sized minerals increased from 22 wt.% to 40 wt.%

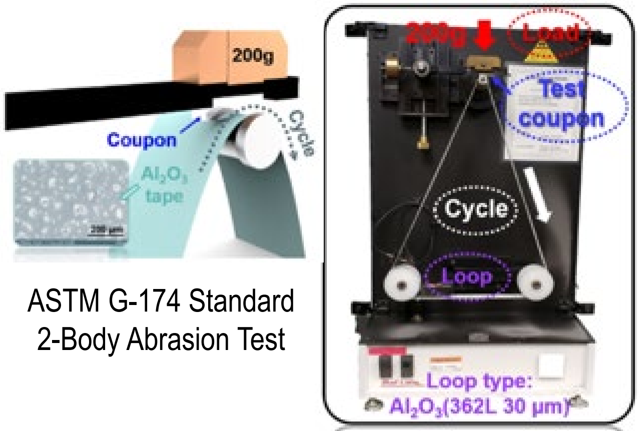


Improve cutter life by using more wear-resistant alloys

Knowledge

- *For Thin Cutter*: M2 tool steel ranks on the top with 7X better wear resistance at 3.5X cost compared with the baseline 1095 high-carbon steel
- *For Thick Cutter*: D2 tool steel ranks on the top with 2X better wear resistance at 1.25X cost compared with the baseline A2 tool steel





ASTM G-174 Standard 2-Body Abrasion Test

For thin cutter (1/16")		Wear rate ($x10^{-3}$ mm^3/Nm)	Potentially improved life	4.25"-dia. cutter cost*	Cutter cost factor
Baseline (current)	1095 steel	3.83	Baseline	~$18	Baseline
Baseline (previous)	A2 tool steel	1.83	~2.1x	~$31	~1.7x
Candidate alloys	D2 tool steel	0.93	~4.1x	~$54	~3x
	M2 tool steel	0.53	**~7.2x**	~$62	**~3.5x**

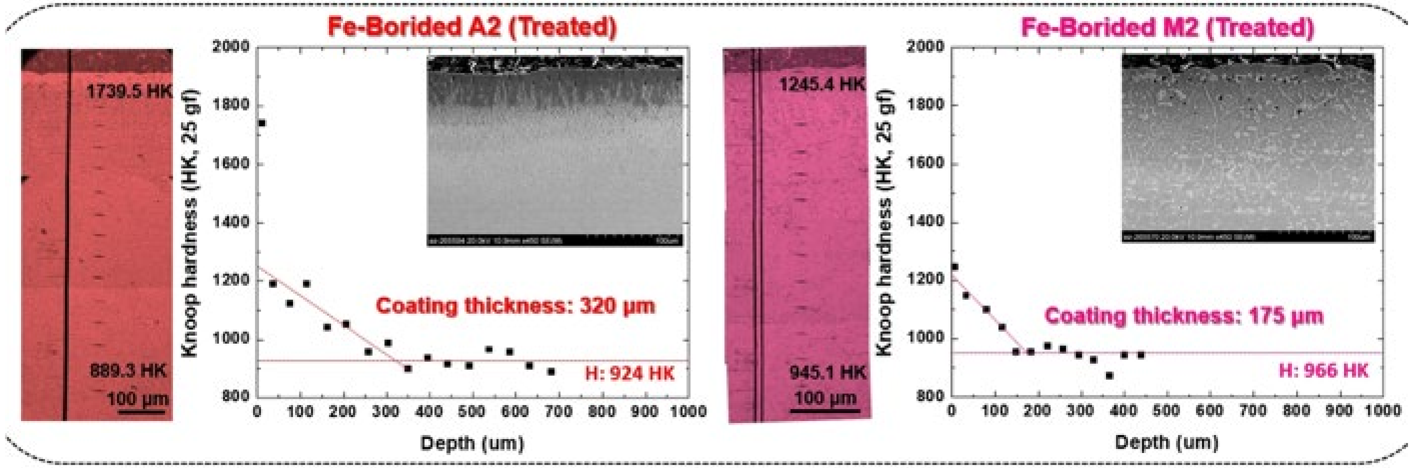
For thick cutter (3/16")		Wear rate ($x10^{-3}$ mm^3/Nm)	Potentially improved life	4.25"-dia. cutter cost*	Cutter cost factor
Baseline	A2 tool steel	1.83	Baseline	~$40	Baseline
Candidate alloys	**D2 tool steel**	0.93	**~2x**	~$50	**~1.25x**
	M2 tool steel	0.53	~3.5x	~$76	~1.9x

**Cutter cost including material, machining, and heat treatment for batches of 100 parts*

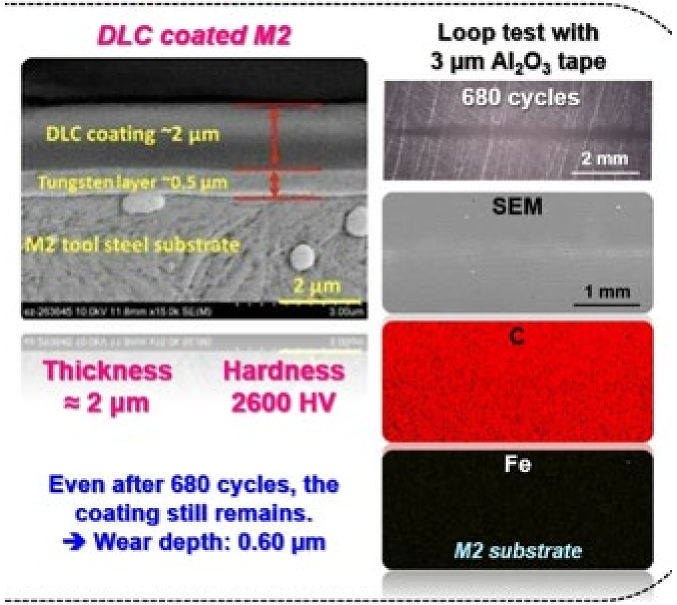
Improve cutter life by using more wear-resistant **coatings**

Tools

- **Coatings/surface treatments selection:**
  - Abrasive wear and localized chipping can be mitigated by selecting materials with optimum mechanical properties
    - Increasing **hardness** – to reduce **abrasive wear**
    - Maintaining good **fracture toughness and fatigue ductility** – not to worsen **cutting edge chipping**
  - Achieving all three attributes is a challenge and requires innovative material solutions.



	Iron Boriding	Thin diamond-like carbon (DLC)	Thick DLC
Hardness	1200-1900 HV	1000-2800 HV	1000-2800 HV
Thickness	100-300 µm	2-5 µm	Up to 100 µm
Microstructure	columnar	amorphous	amorphous
Process [Manufacturer]	Diffusion-based case-hardening **[IBC]**	Plasma-enhanced chemical vapor deposition (PECVD) **[NCT]**	PECVD **[C4E]**
Deposition Temperature	1000⁺ °C followed by heat treat/tempering	< 300 °C	< 300 °C

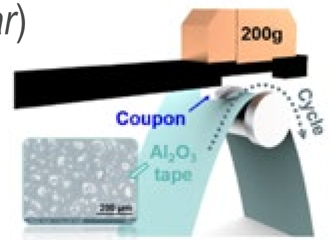


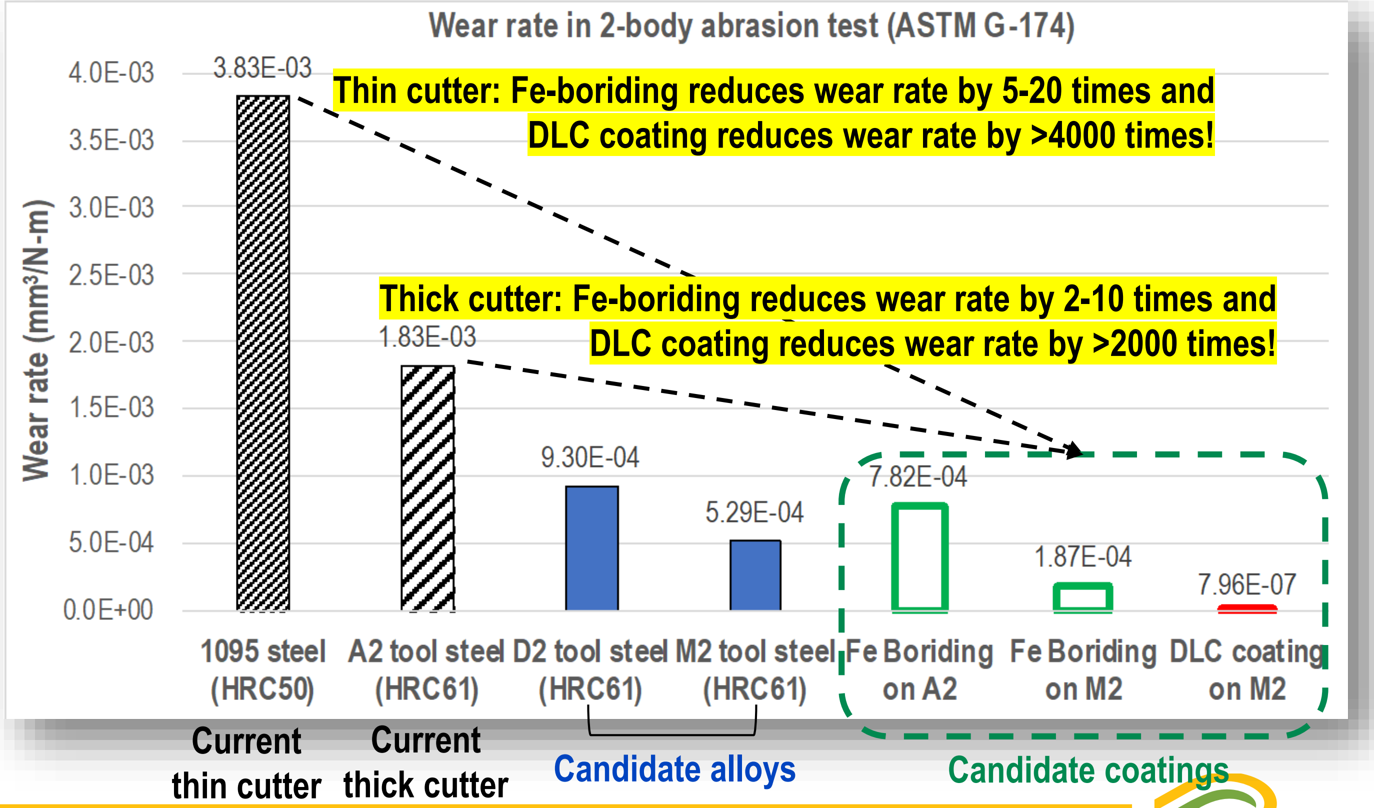
Improve cutter life by using more wear-resistant coatings

Knowledge

- ***Fe-boriding***: **2-20X tool life extension with gradual degradation**
- ***Thin DLC coating***: **3 orders of magnitude lower wear rate!** (*But would such a thin coating last long enough? TBD in rotary shear*)
- *Thick DLC coating*: in process to be acquired and evaluated
- D2 tool steel to be explored as the substrate for potential cost reduction

ASTM G-174 Standard
2-Body Abrasion Test





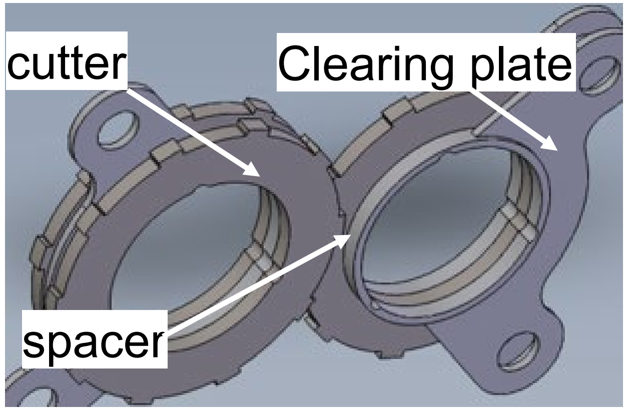
For thin cutter (1/16")		Wear rate ($x10^{-3}$ mm^3/Nm)	Potentially improved life	4.25"-dia. cutter cost*	Cutter cost factor
Baseline (1095 steel)		3.83	Baseline	~$18	Baseline
Candidate coatings	Fe-borided A2	0.78	~5x	~$43	~2.4x
	Fe-borided M2	0.19	**~20x**	~$74	**~4.1x**
	DLC-coated M2	0.0008	**>4000x**	~$63	**~3.5x**

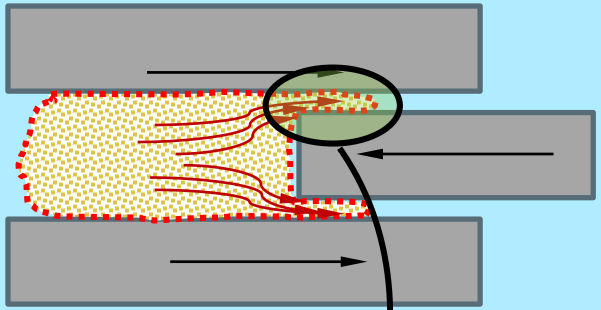
For thick cutter (3/16")		Wear rate ($x10^{-3}$ mm^3/Nm)	Potentially improved life	4.25"-dia. cutter cost*	Cutter cost factor
Baseline (A2 tool steel)		1.83	Baseline	~$40	Baseline
Candidate alloys	Fe-borided A2	0.78	~2x	~$52	~1.3x
	Fe-borided M2	0.19	**~10x**	~$88	**~2.2x**
	DLC-coated M2	0.0008	**>2000x**	~$80	**~2x**

**Coating cost estimates based on batches of 100 parts*

Modeling activities for rotary shear

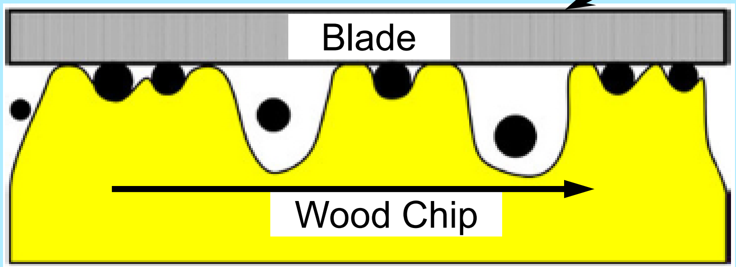
- **Progress:**
  - Guided by literature and experimental characterization of FC Crumbler components, **physical models** and **mathematical models** are being developed to analytically predict abrasive wear of cutter and clearance blades as functions of **feedstock properties**, **blade properties**, and **operational parameters.**

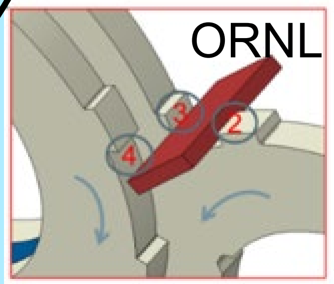




Woodchips entrained between counterrotating cutter blades are sheared, compressed, and trapped between blades. The relative motion between counterrotating blades sets up a 2/3 body abrasion environment where extrinsic and intrinsic abrasive inorganic particles abrade leading edges and surfaces of components.

Constitutive equations developed for Chemical Mechanical Polishing (CMP) are used to relate wear to feedstock properties, blade properties, and operational parameters.





$$V_{abr} = n^2 \frac{P_y E W^{3/2}}{K_{Ic}^2 H^{3/2}} L,$$

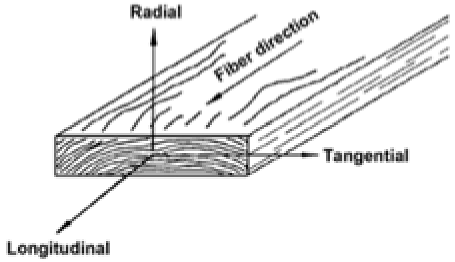
Stolarski

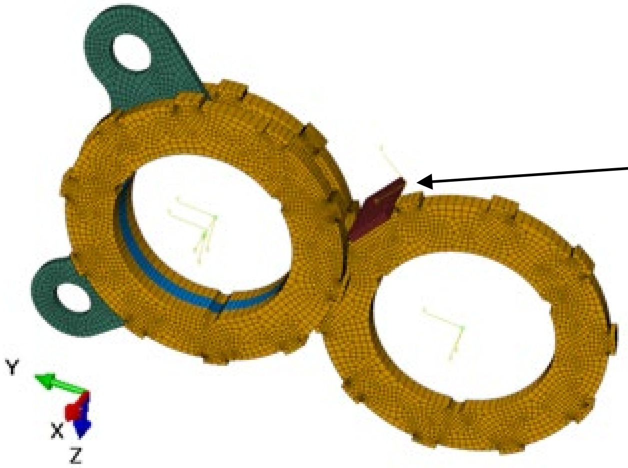
Finite Element Analysis (FEA) by ORNL of chip/cutter interactions provide input on interfacial forces for CMP modeling of abrasive wear

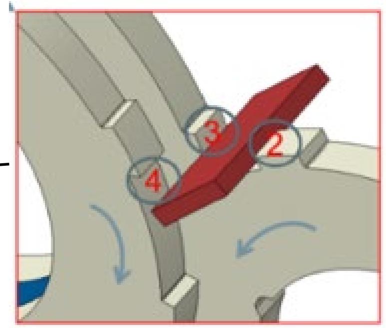
FEA modeling to calculate contact stresses at the cutting interfaces

Tools

- **Finite Element Analysis (FEA) simulation of the contact stress at critical interfaces for cutters against the woodchips as well as extrinsic inorganic particles.**
- **To provide insights of the cutter wear process and woodchip gripping to help improve the component design.**

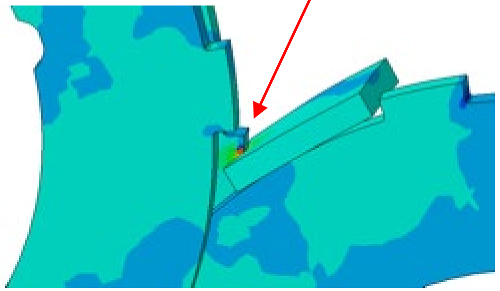






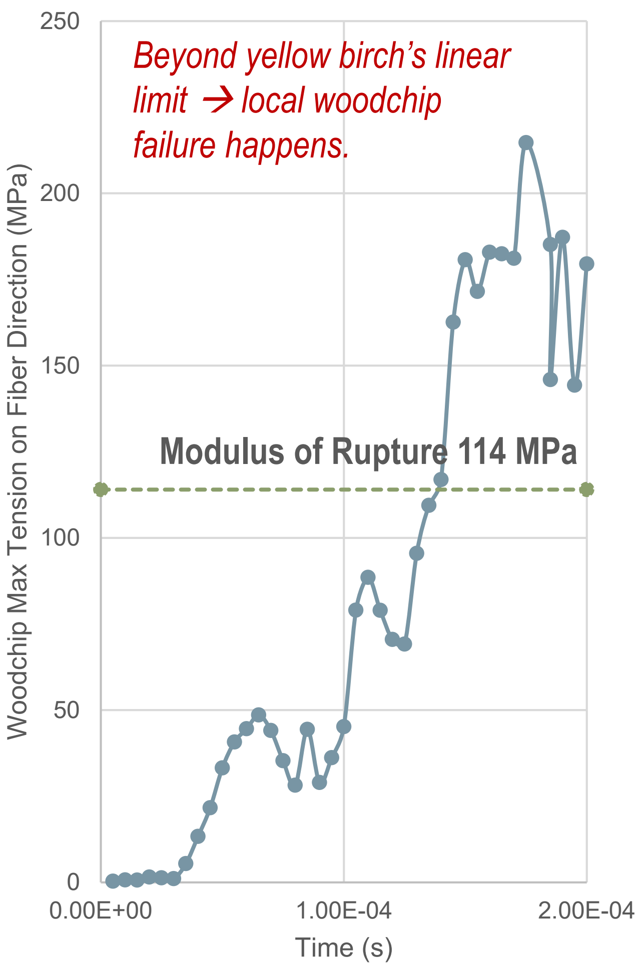
Time = 0.12 milliseconds

Contact pressure = 187.7 MPa



Wood – anisotropic mechanical properties

Wood	Density (kg/m³)	E_L (Pa)	E_T (Pa)	E_R (Pa)	G_{LR} (Pa)	G_{LT} (Pa)	G_{RT} (Pa)	μ_{LR}	μ_{LT}	μ_{RT}	$E_{rupture}$ (Pa)
Birch, Yellow 12% moisture	762	1.39 e+10	6.95 e+8	1.08 e+9	1.03 e+9	9.45 e+8	2.36 e+8	0.426	0.451	0.697	1.14e+8
Oak, Southern red, 12% moisture	661	1.03 e+10	8.45 e+8	1.59 e+9	9.17 e+8	8.34 e+8	2.16 e+8	0.350	0.448	0.560	7.5e+7
Douglas-fir, coast, 12% moisture	582	1.34 e+10	6.7e +8	9.11 e+8	8.58 e+8	1.05 e+9	0.94 e+8	0.292	0.449	0.390	8.5e+7

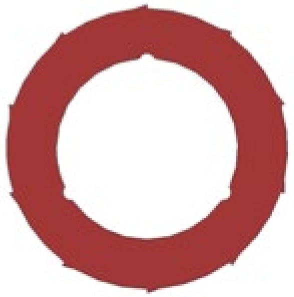


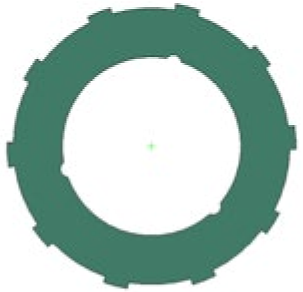
Stress of 3 mm thick woodchip on fiber direction

Comparison of cutter tooth designs

Knowledge

- **In general, the new square corner (DZ) tooth design produced a lower max contact pressure than the original tooth design** (with a few exceptions), **suggesting a longer tool life.**
  - Exceptions might reflect effects from other aspects such as the woodchip's thickness and its relative location to the cutter assembly.

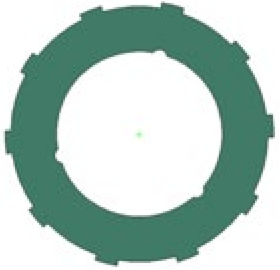


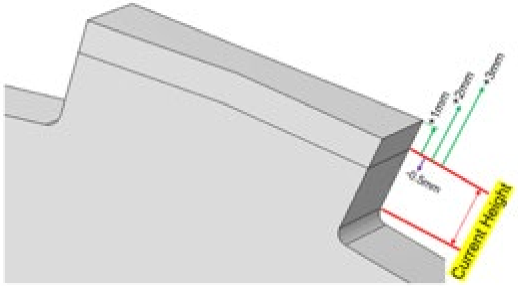


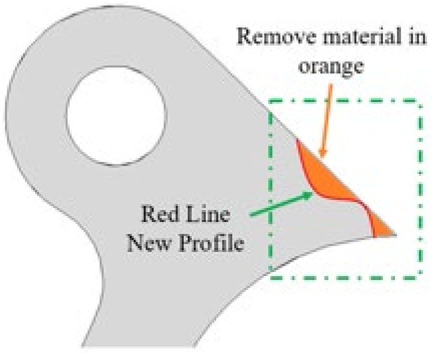
Case #	Cutter Thickness	Woodchip Size (mm)	Woodchip	Woodchip Modulus of Rupture (MPa)	Original Tooth Max Contact Pressure (MPa)	DZ Tooth Max Contact Pressure (MPa)
4	1/16" (1.6 mm)	6x6x6	Yellow Birch, 12%	114	**1249**	1038
5			Red Oak, 12%	75	**770**	627
6			White Cedar, green	29	397	486
13			Douglas-fir, 12%	85	**861**	528
14			Douglas-fir, green	53	**678**	356
7	1/4" (6.35 mm)	6x6x15	Yellow Birch, 12%	114	**815**	276
8			Red Oak, 12%	75	**280**	263
9			White Cedar, green	29	**197**	66
10		10x20x50	Yellow Birch, 12%	114	1065	1284
11			Red Oak, 12%	75	**1093**	1209
12			White Cedar	29	**729**	384
15			Douglas-fir, 12%	85	810	996

Initial design ideas for cutter and clearing plate

- ***Cutter***: A higher DZ tooth height to reduce the contact pressure AND to increase the woodchip gripping
  - 2 mm height increase seems to effectively reduce contact pressure
- ***Clearing plate***: A less-sharp S-shape corner for the clearing plate for a lower contact pressure and better woodchip flow around it

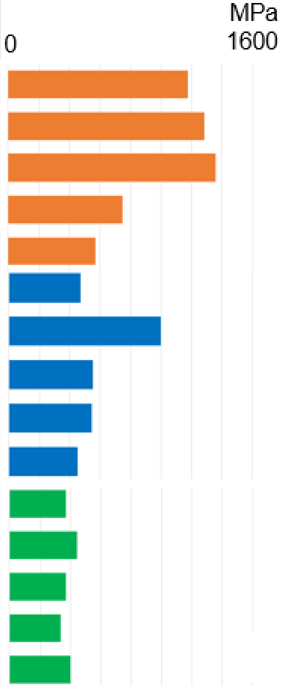






New Design to Reduce Wear

Case	Cutter Thickness (mm)	Cutter Height Adjustment (mm)	Woodchip (mm)	Wood Species	DZ Tooth Design Maximum Contact Pressure (MPa)
1	6.35	-0.5	10x20x50	Yellow Birch, 12%	1176
2	6.35	0	10x20x50	Yellow Birch, 12%	1284
3	6.35	1	10x20x50	Yellow Birch, 12%	1357
4	6.35	2	10x20x50	Yellow Birch, 12%	748.1
5	6.35	3	10x20x50	Yellow Birch, 12%	571.4
6	6.35	-0.5	10x20x50	Douglas-fir, 12%	469.2
7	6.35	0	10x20x50	Douglas-fir, 12%	995.9
8	6.35	1	10x20x50	Douglas-fir, 12%	550.5
9	6.35	2	10x20x50	Douglas-fir, 12%	542.7
10	6.35	3	10x20x50	Douglas-fir, 12%	451.1
11	6.35	-0.5	10x20x50	Douglas-fir, green	367.9
12	6.35	0	10x20x50	Douglas-fir, green	443.9
13	6.35	1	10x20x50	Douglas-fir, green	369.3
14	6.35	2	10x20x50	Douglas-fir, green	335.7
15	6.35	3	10x20x50	Douglas-fir, green	400.6



Summary

Management: Collaboration of ORNL, ANL, and FC for joint modeling, design, testing, and analysis efforts

Technical Approach: ORNL and ANL closely work with Forest Concepts to fundamentally understand the wear mechanisms of the Crumbler® rotary shear, to identify and implement advanced materials and/or designs for better tool life and performance, and conduct prototype feasibility tests to demonstrate improved economics.

Impact: Provide fundamental understanding of the wear mechanisms of the Crumbler® rotary shear comminution and develop materials and design mitigations for improving the overall economics by increasing the processing efficiency and tool life and reducing the downtime and power consumption.

Progress:

- Learned baseline designs and materials of the cutters, clearing plates, and spacers [complete]
- Gained fundamental understanding of failure modes and wear mechanisms based on tribosystem analysis and worn component characterization [complete]
- Constructed FEA to help understand the cutter-feedstock interface [complete]
- Developing an analytical abrasive wear model to predict wear to help design and select tool materials [on-going]
- Evaluating candidate wear-resistant alloys and coatings using an ASTM standard bench abrasion test [on-going]
- Optimizing geometric designs for cutters and clearing plates based on FEA [on-going]

Work plan for FY21-22

FY21 Q2-Q3
- Continue to develop the abrasion **wear model**
- Continue to evaluate candidate coatings
- Propose improved component **designs**

FY21 Q3-Q4
- Produce **prototypes** of cutters, spacers, and clearing plates using improved designs and/or materials

FY22 Q1-Q2
- Test prototypes on an actual rotary shear with various feedstocks from woodchips to municipal solid waste (MSW) to **demonstrate** improved tool life and process efficiency
- **TEA** to predict improved economics

FY22 Q3
- **Share** fundamental findings and mitigation strategies with the biomass preprocessing industry through publications and exchanges

Quad Chart Overview (Competitive Project)

fcic
FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

Timeline

- Sept. 27, 2019 – July 31, 2022

	FY20 Costed	Total Award
DOE Funding	$337,000	$1,200,000
Project Cost Share	$85,000	$942,412

Project Partner

- **Forest Concepts**

Project Goal

The major outcomes include **gaining understanding of the wear mechanisms** of the Crumbler® rotary shear comminution systems and **providing materials and design recommendations** based on bench-scale and pilot testing, materials characterization, and modeling. This work is expected to significantly **improve the overall economics** of biomass pre-processing systems, by improving the processing efficiency, reducing the downtime during changeout of worn parts, and reducing the material and labor costs of replacing tools.

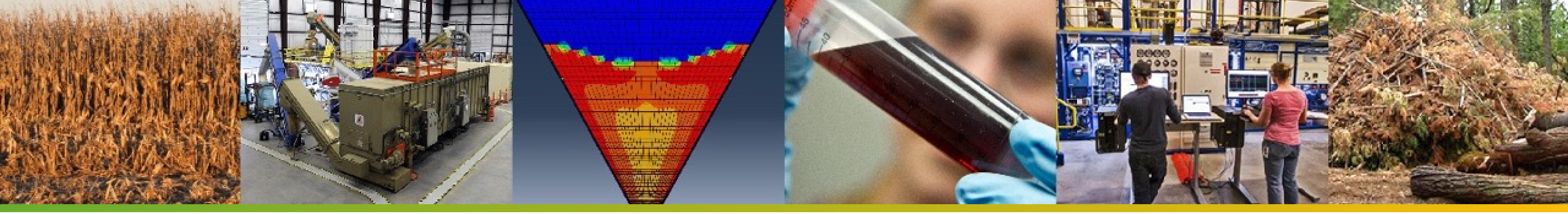
The team will **share the fundamental understanding and potential material/design solutions with the biomass pre-processing industry** by presenting and publishing the results achieved in this project. FC does not plan to place limitations on the publication of technical and scientific results from this project.

End of Project Milestone

Develop and disseminate a strategy for improved wear resistance applicable to biomass cutting components based on the fundamental understanding, including potential design/material wear solutions with the biomass pre-processing industry through publications and exchanges and validation of this approach with FC equipment.

Funding Mechanism

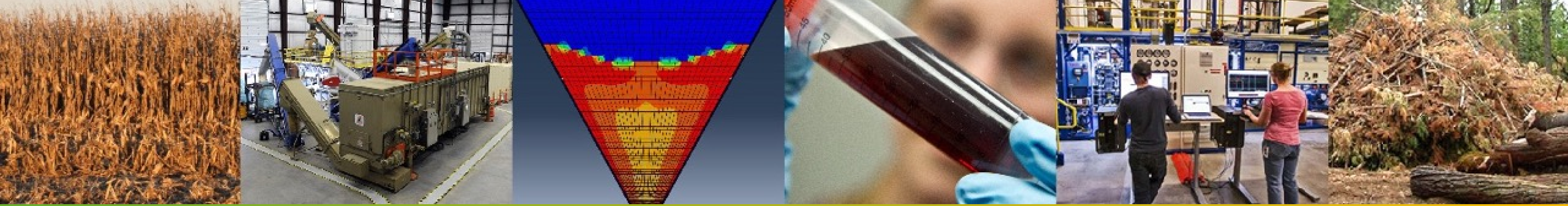
FCIC Directed Funding Opportunity (DFO)



Thank you

energy.gov/fcic

fcic
FEEDSTOCK-CONVERSION
INTERFACE CONSORTIUM



Additional Slides

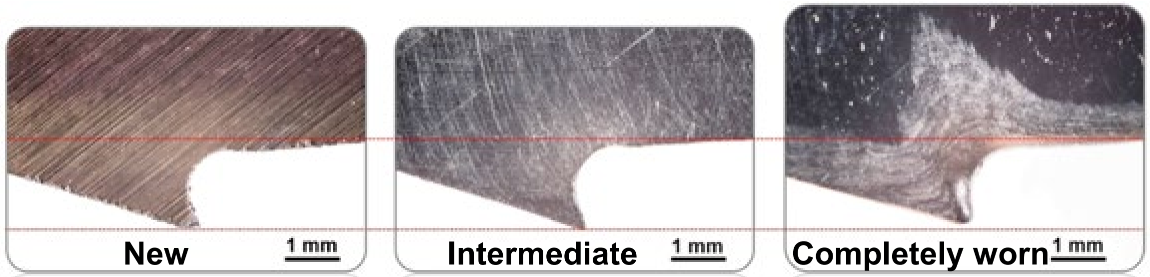
FY20-21 Task 1 Milestones

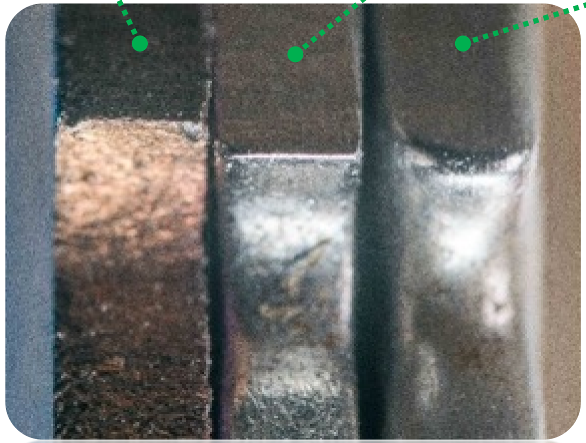
Milestone	Lead	Milestone Description	Status
FY20 Q1	ORNL	Understand baseline design and materials of the feeding teeth and cutters as well as the clearing plates and to determine the ranges of contact pressure and sliding velocity at the tool-biomass interface.	**Complete – Milestone report submitted**
FY20 Q2	ORNL	Conduct material characterization on the worn cutters of the Crumbler® rotary shear with known history of biomass comminution.	**Complete – Milestone report submitted**
FY20 Q3	ANL	Develop a wear prediction mode for the rotary shear comminution system based on fundamental understanding of the wear process and mechanisms	[*Delayed to FY21 Q2 due to pandemic*]
FY20 Q4 FY21 Q1	ORNL	Identify candidate materials and surface treatments and propose potentially improved design for the cutters, spacers, and clearing plates	[*Delayed to FY21 Q1 due to pandemic*] **Complete – Milestone report submitted**
FY21 Q2	ANL	Identify abrasion wear models and develop constitutive equations to predict contact forces and wear of cutter and clearing plates as functions of rotary shear process parameters to help design and select materials and coatings to improve durability and reliability	
FY21 Q3	ORNL	Propose improved cutter design(s) and/or assembly based on finite element analysis and wear modeling	
FY21 Q4	FC	Fabricate prototype Crumbler® rotary shear cutters, spacers, and clearing plates using improved design and/or advanced material(s)/surface treatment(s)	

Identifying wear mechanisms – thick cutter (hardened A2 tool steel)

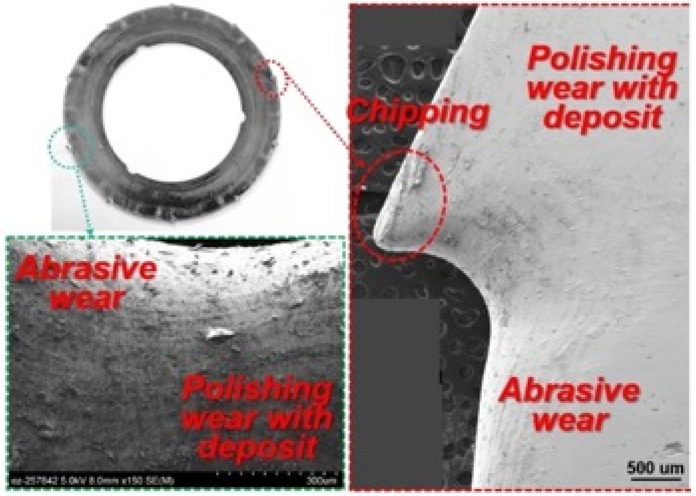
Knowledge

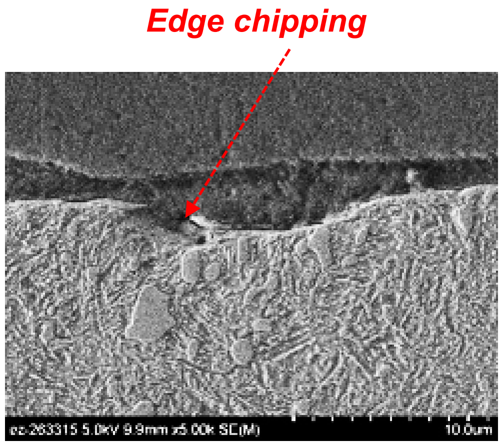
- Wear modes: **abrasive wear and localized chipping**.

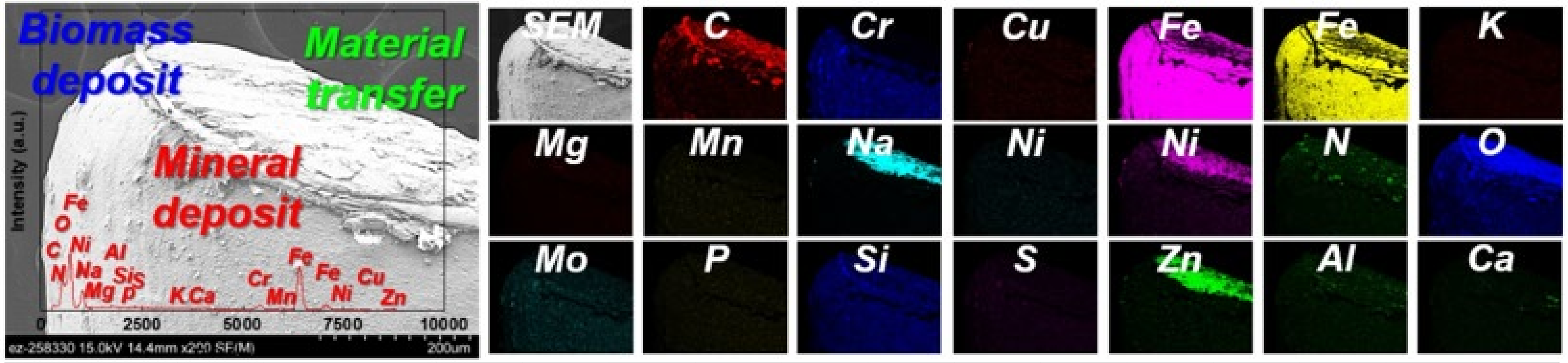




Cutter wear progress →



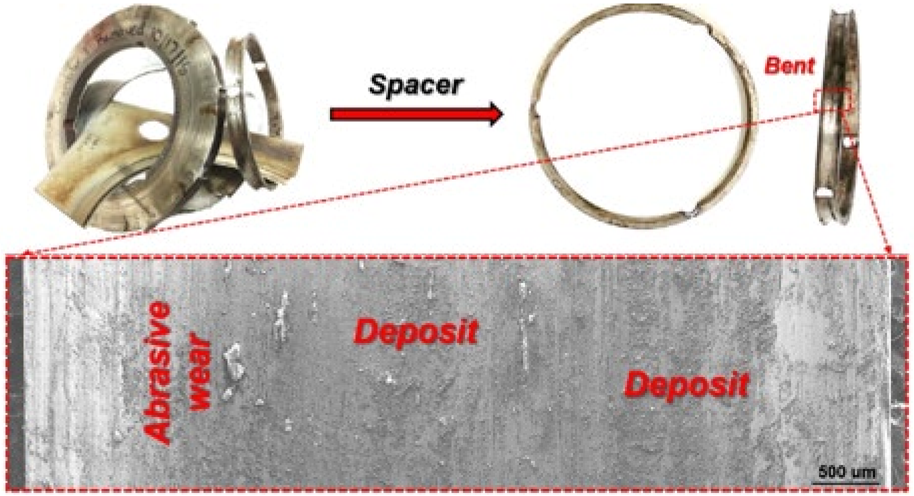


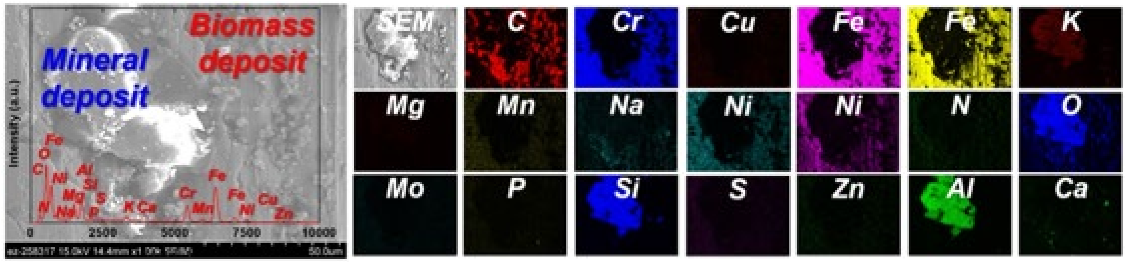


K Line	C	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	N	O	P	Si	S	Zn	Al	Ca
	12.52	1.6	0.16	17.17	0.03	0.06	0.16	9.55	0.19	5.04	15.83	0.03	0.47	0.22	1.73	0.24	0.1
L Line	Fe	Ni	Mo														
	24.09	0	0.03														

Characterization of worn components to identify wear modes - Spacer (304 stainless) and Clearing plate (copper alloy 770)

Spacer

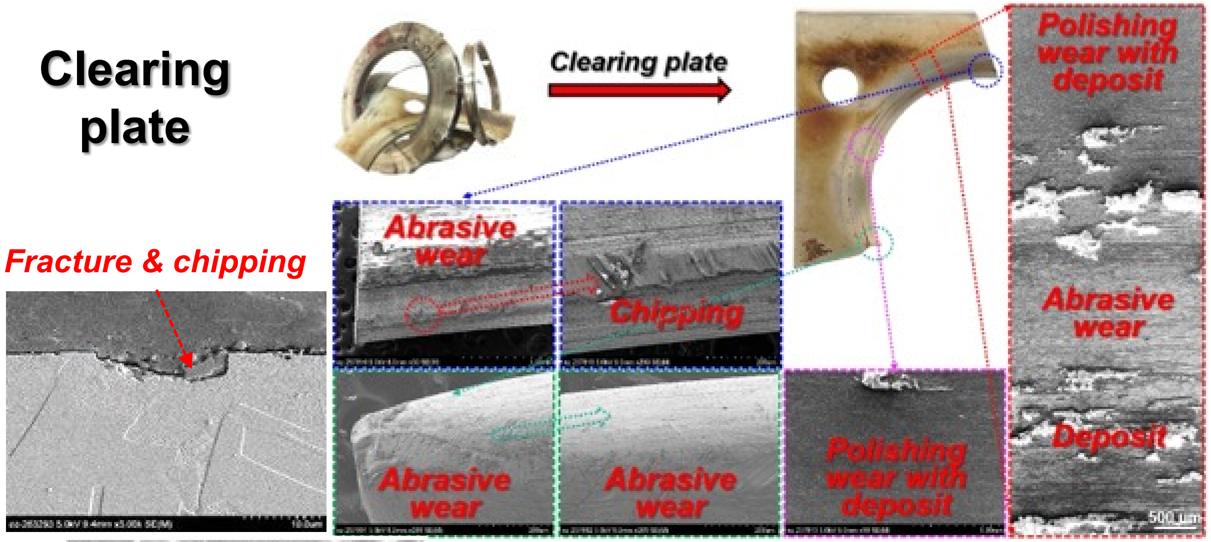


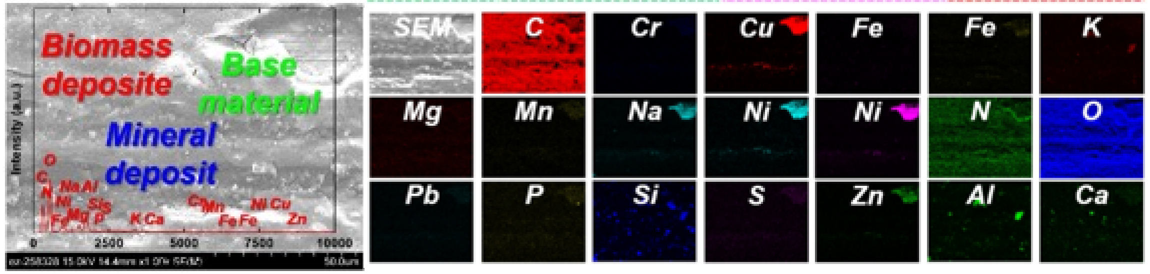


K Line	C	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	N	O	P	Si	S	Zn	Al	Ca
	15.92	4.6	0.12	18.42	0.76	0.2	0.26	0.34	2.99	4.42	26.32	0.03	3.64	0.1	0.08	3.22	0.22
L Line	Fe	Ni	Mo														
	16.06	1.7	0.6														

- Main wear modes: **abrasive wear** and **plastic deformation**.
- Inorganic particles of up to **50 µm** size from wood chips embedded into surface.

Clearing plate





K Line	C	Cr	Cu	Fe	K	Mg	Mn	Na	Ni	N	O	P	Si	S	Zn	Al	Ca
	45.13	0.02	0.92	0	0.49	0.45	0.03	0.55	0.54	4.97	41.8	0.04	2.74	0.01	0.44	0.89	0.27
L Line	Fe	Ni	Pb														
	0.23	0.34	0.14														

- Main wear modes: **abrasive wear, plastic deformation,** and **chipping.**

Publications, Patents, Presentations, Awards, and Commercialization

Publications:

- 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.
- L. Lin, D. Lanning, J.R. Keiser, J. Qu, "Investigation of cutter-woodchip contact pressure in a new biomass comminution system," ***ACS Sustainable Chemistry & Engineering*** (2021) (submitted, in peer review).
- K. Lee, D. Lanning, E. Cakmak, J.R. Keiser, J. Qu, "Wear mechanism analysis for a new rotary shear biomass comminution system," ***ACS Sustainable Chemistry & Engineering*** (2021) (in ORNL internal review).

Presentations:

- K. Lee, L. Lin, D. Lanning, E. Cakmak, J.R. Keiser, J. Qu, "Analysis of Wear Issues in the Rotary Shear Biomass Comminution System," ***TMS 2021 Annual Meeting***, March 14-18, 2021.
- K. Lee, L. Lin, D. Lanning, E. Cakmak, G.R. Fenske, O.O. Ajayi, J.R. Keiser, J. Qu, "Analysis of Wear Issues in the Rotary Shear Biomass Comminution System," ***75th STLE Annual Meeting***, May 16-20, 2021.
- K. Lee, L. Lin, D. Lanning, G.R. Fenske, O.O. Ajayi, J.R. Keiser, J. Qu, "Improving Biomass Comminution Performance by Optimizing Tool Design and Using Advanced Tool Materials," ***7th World Tribology Congress (WTC)***, September 5-10, 2021, Lyon, France.

Awards:

- Jun Qu – **2020 Distinguished Researcher Award**, Recognition of sustained and distinguished accomplishments with high impact in science and engineering, UT-Battelle Awards Night