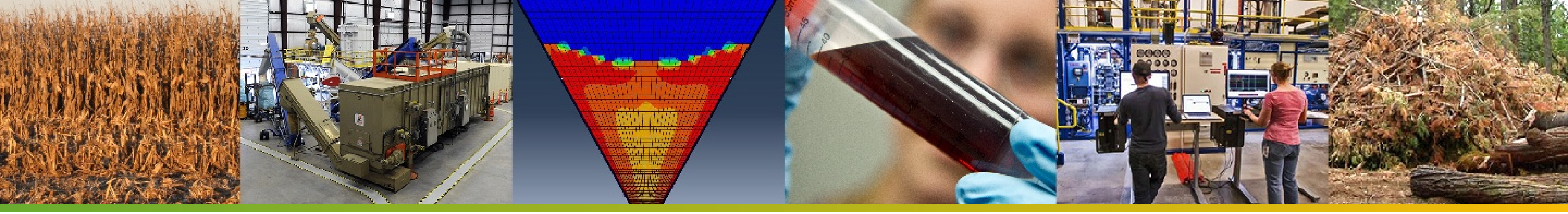


Characterization, modeling, and mitigation of wear issues for conventional and state-of-the-art biomass comminution systems

Date: May 27, 2021

ORNL: Jun Qu, Kyungjun Lee, Xin He, and Jim Keiser
ANL: George Fenske and Layo Ajayi
INL: Jeffrey Lacey and Vicki Thompson
Forest Concepts: David Lanning

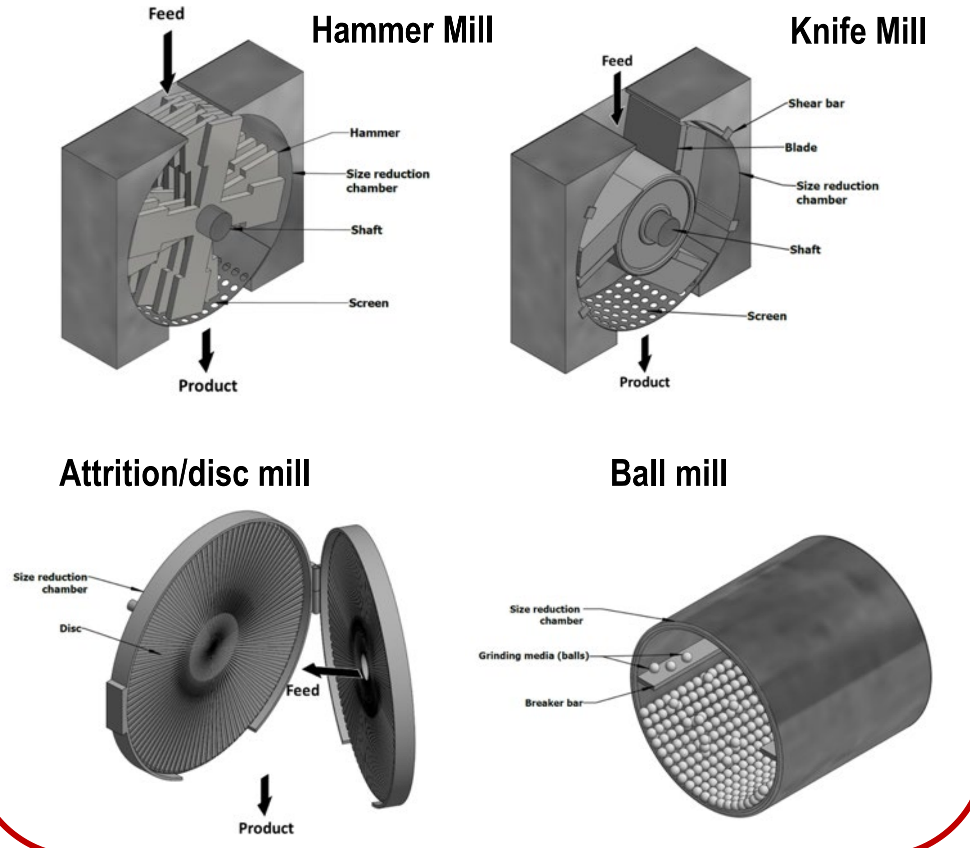
Oak Ridge National Laboratory
Argonne National Laboratory
Idaho National Laboratory
forestconcepts

fcic
FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

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

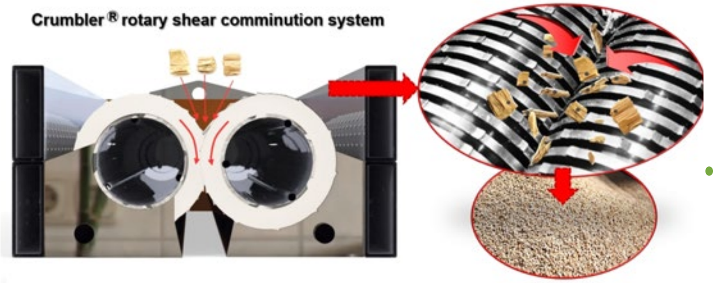
Knowledge

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

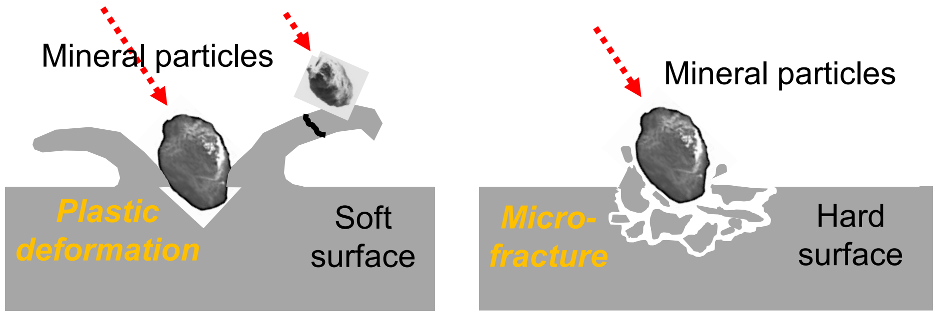
- This work advances the state-of-the-art biomass size reduction technology by providing
  - Fundamental understanding of wear/failure mechanisms
  - Cost-effective wear-resistant tool materials
  - Optimized tool designs
- To gain
  - Improved tool life
  - Increased throughput
  - Reduced downtime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

Fundamentals of Wear Modes

Knowledge

General Types of Wear

Erosive Wear

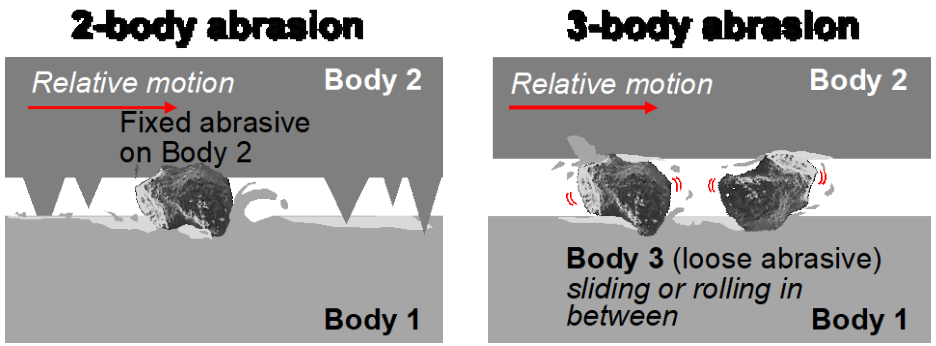


Manner of energy dissipation:
Plastic deformation, micro-fracture, heat

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

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

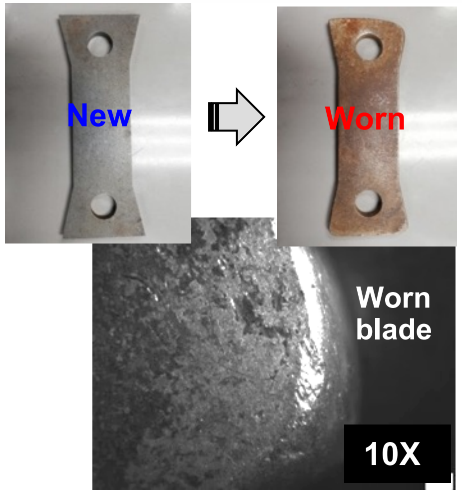
Tribosystem analysis of hammer mill to correlate wear with inorganic particles

Knowledge

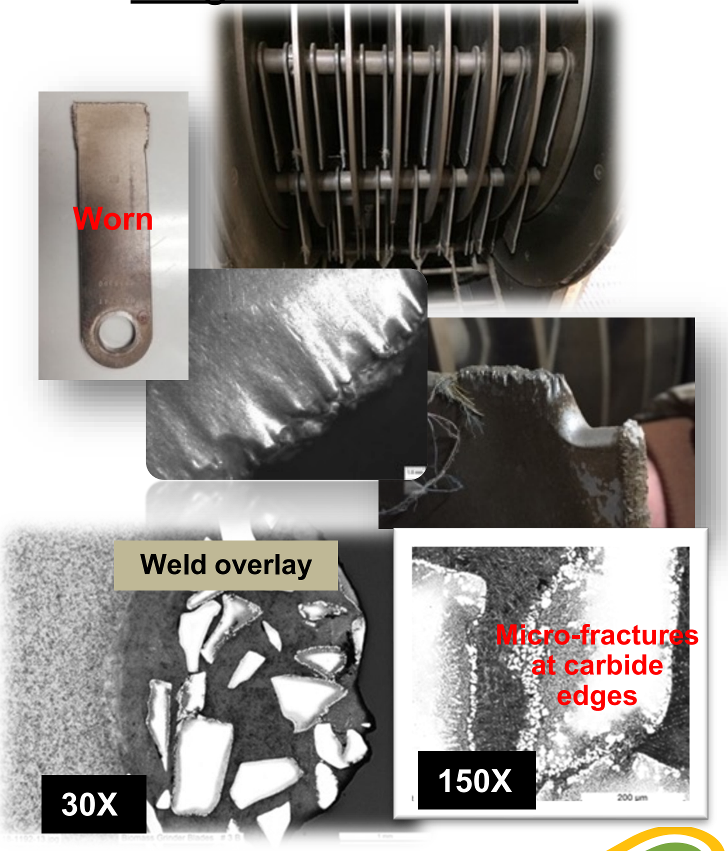
Hammer Mill: Blunt blades; Comminution mode: Crushing

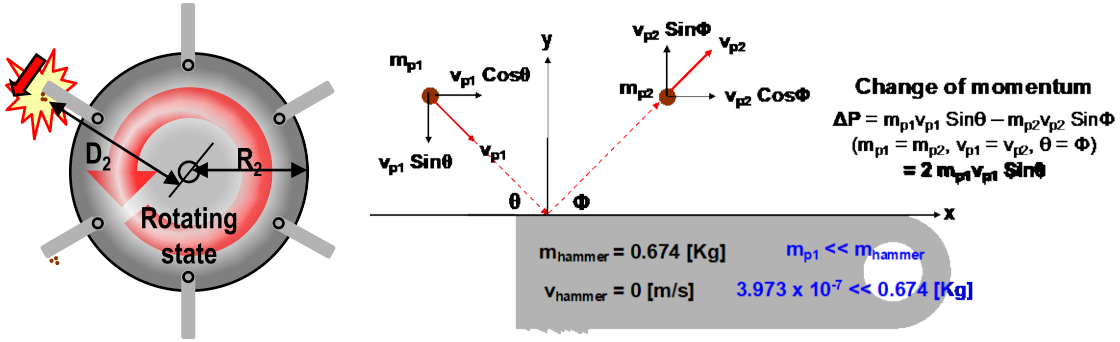
Wear modes: Erosive wear (dominant) + 2-body/3-body Abrasive wear (secondary)

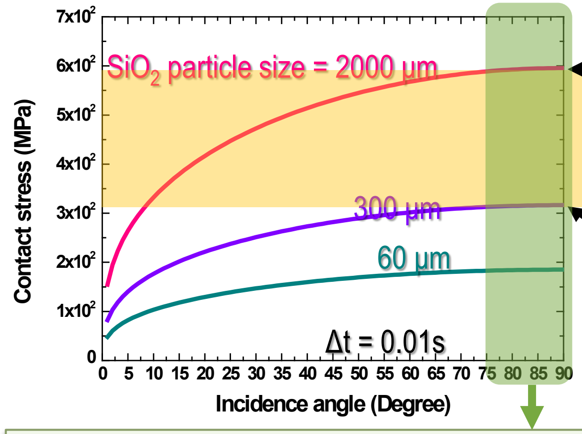
Stage 1 Hammer mill



Stage 2 Hammer mill







Contact pressure by SiO_2 particles: up to 600 MPa

Hammer strength: 300-500 MPa

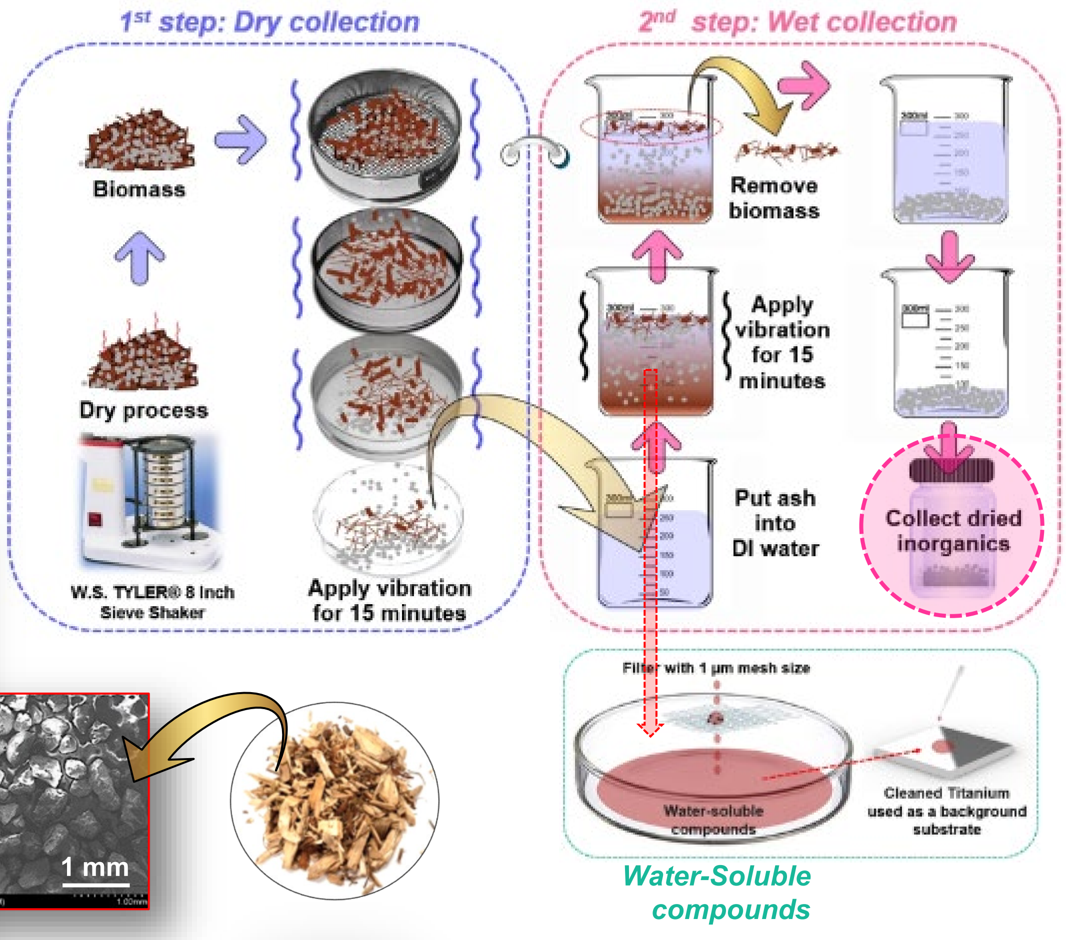
Min particle size to cause plastic deformation: ~300 μm

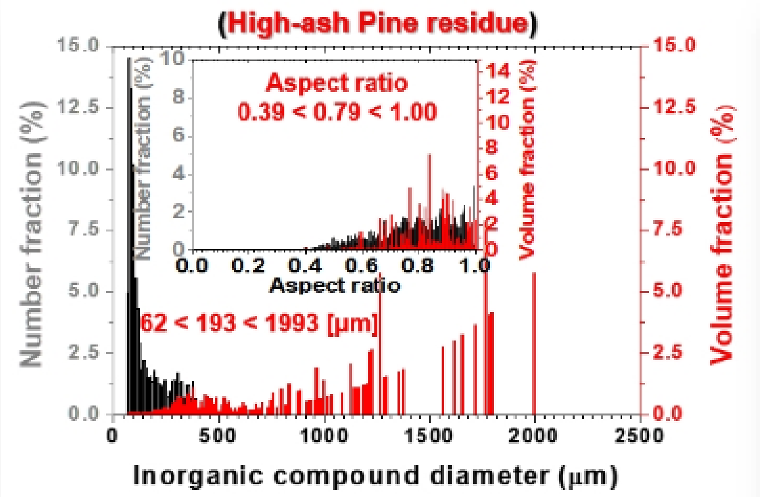
- A smooth hammer would hit most particles at nearly 90 degree
- A very rough hammer would hit particles at various angles but biased towards large angles

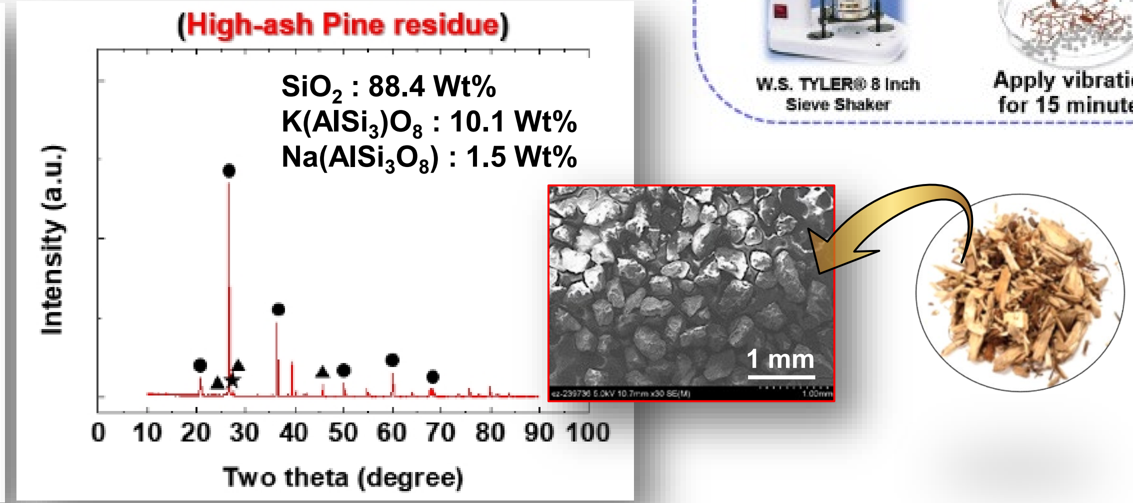
Characterization of extrinsic inorganic particles

- Conventional measurement of inorganic content of biomass
  : ISO 176 and TAPPI T211 ➔ combust wood at 525 ºC
  ASTM D1102 ➔ uses dry oxidation of wood at 580~600 ºC
  ASTM D3174 ➔ produces ash of coal in furnace at 750 ºC

- **ORNL newly developed composition-preserving extraction and characterization method allows to discover the original morphology, size, and composition of extrinsic inorganic particles.**





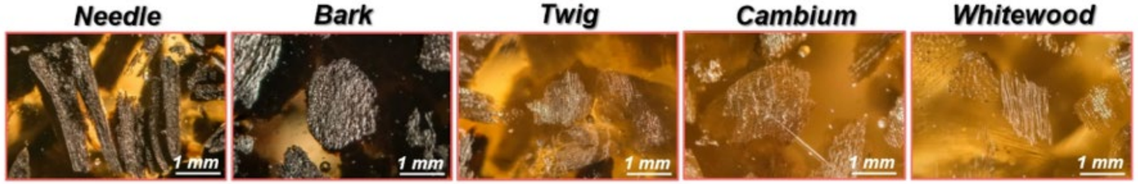


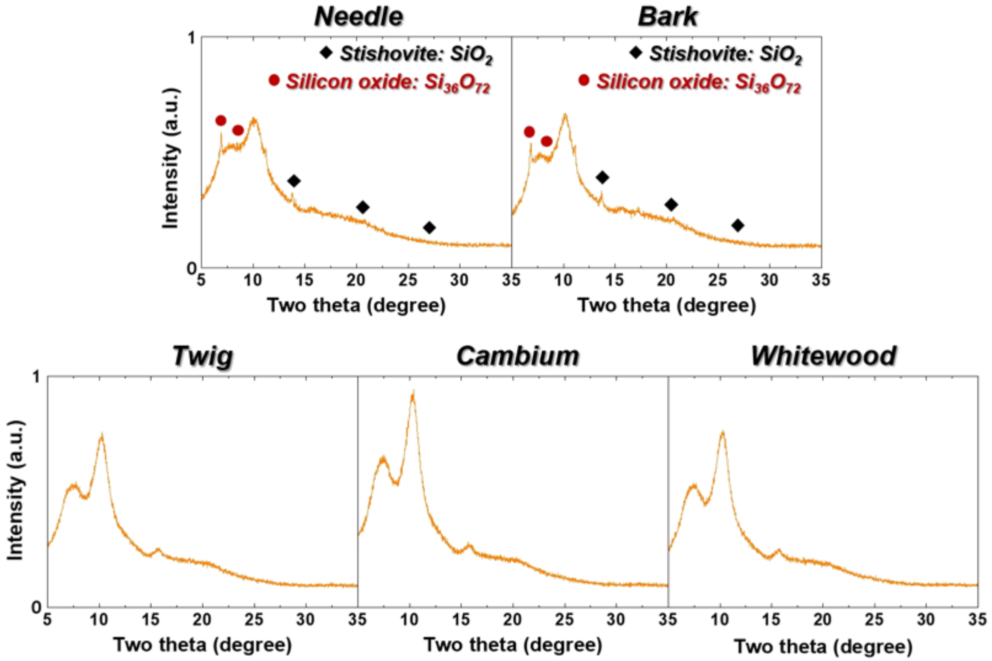
Characterization of intrinsic inorganics

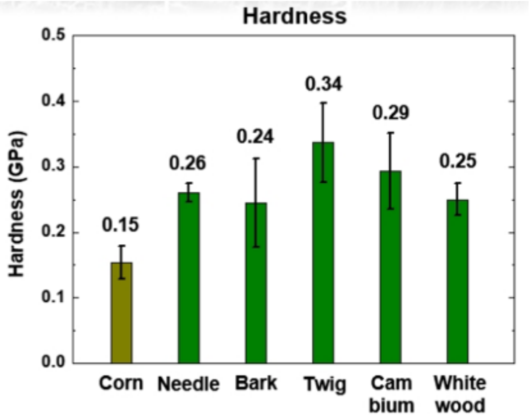
Tools

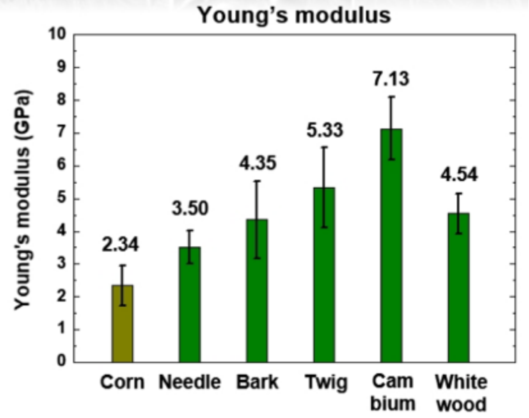
ORNL comprehensive characterization of intrinsic inorganics for pine anatomical fractions:

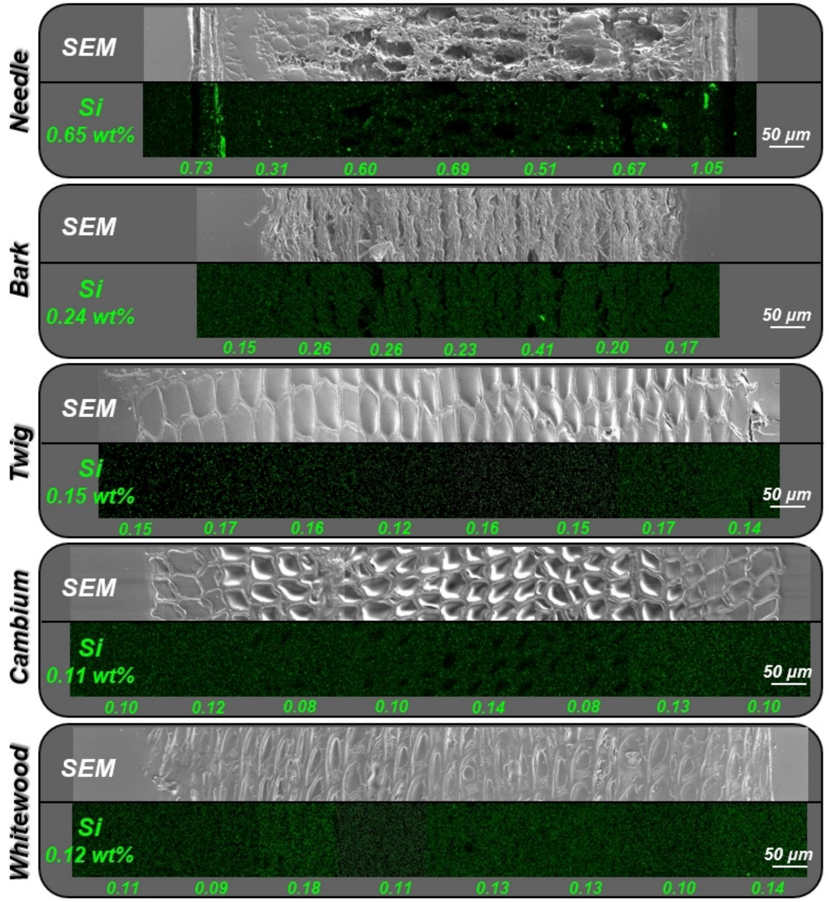
- Species identification by XRD
- Distribution inside biomass by EDS elemental mapping
- Mechanical properties by nanoindentation





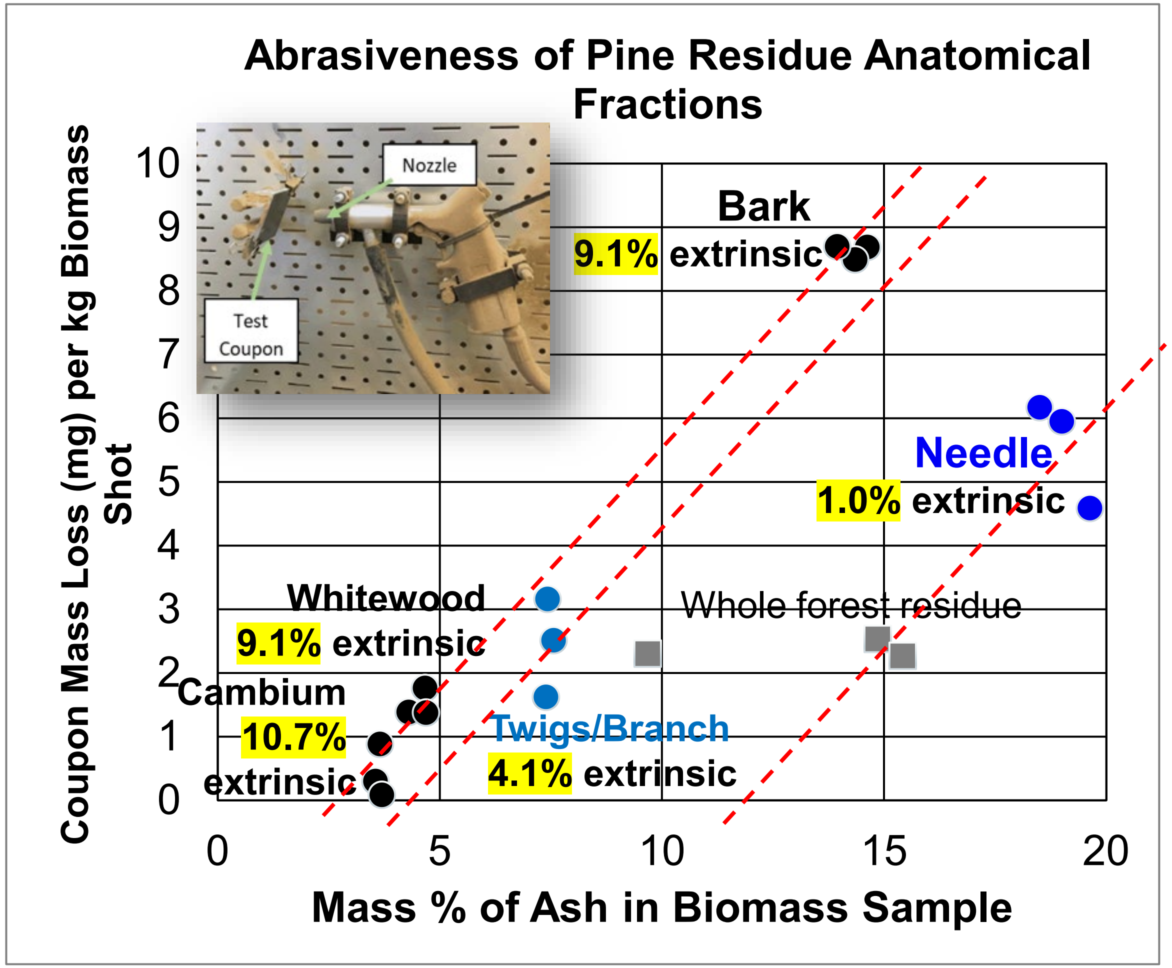






Contributions of macro-level anatomical fractions and inorganics to erosive wear

Knowledge

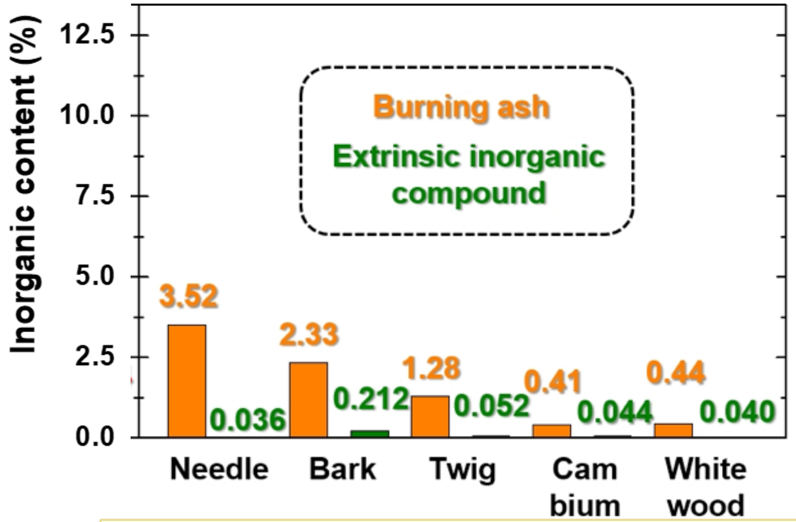


Blasting wear tests using coupons machined off actual hammers (low carbon steel)

Observations:

- Wear often increases along with the total ash content, *but not always*
- Wear is proportional to the percentile of extrinsic minerals in the total ash

Conclusions: Both intrinsic and extrinsic inorganic compounds are abrasive, but the extrinsic minerals are much more abrasive than the intrinsic inorganics.



1.0% 9.1% 4.1% 10.7% 9.1%

% of extrinsic inorganic particles (>60 μm) in the 'total ash'

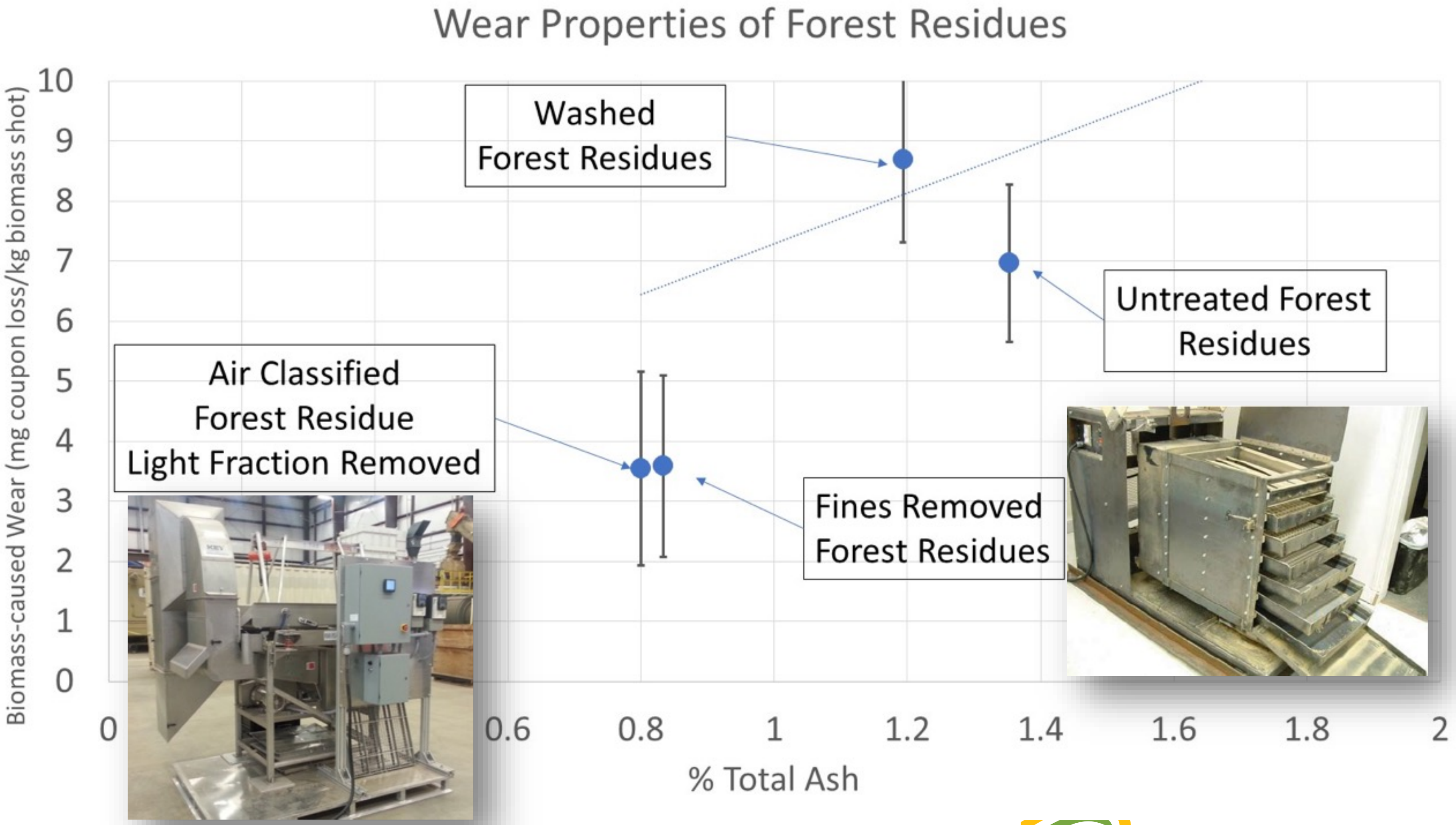
Feedstock modifications for ash reduction for hammer mill

Knowledge

fcic
FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

Effectiveness of Air classification, Size separation, and Water washing

Blasting wear tests using coupons machined off actual hammers (low carbon steel)



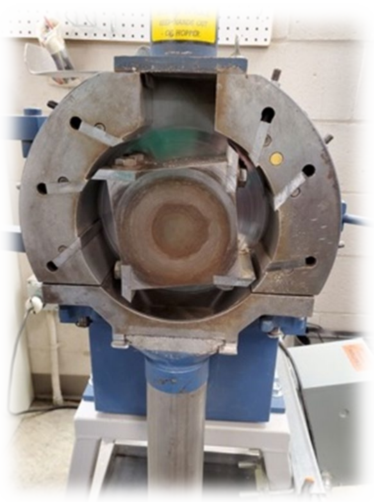
- **Air classification and size separation were effective in reducing erosive wear**
  - Removal of light fraction & fines
  - Modifications of forest residues led to 2X lower wear
  - Modifications of corn stover led to 4X lower wear
  - Cost: ~$0.84 per ton
- Water washing had little effect in wear behavior
  - Major extrinsic inorganic compounds are water insoluble
  - Washing moved the minerals around, not removing them

Transitioned from hammer mill to knife mill in FY20 Q4

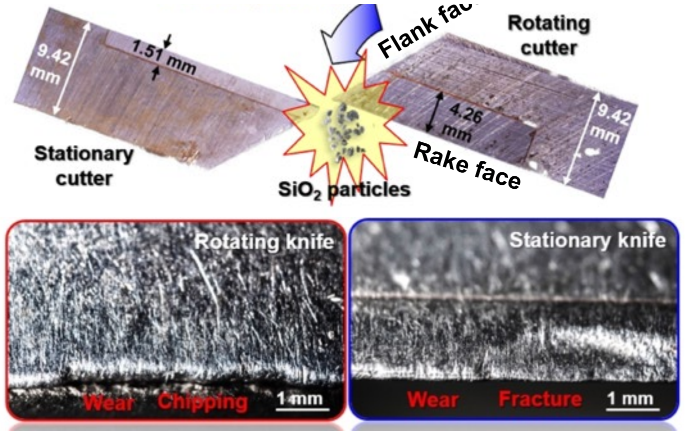
Knowledge

fcic FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

- **A good portion of results from the hammer mill work have been transferred to the knife mill study:**
  - Extrinsic and intrinsic inorganic species, mineral particle size & shape distributions,
  - Erosive wear model,
  - Feedstock modifications for ash reduction, and
  - Candidate alloys' wear resistance to 2-body abrasion.
- **Tribosystem analysis determined different wear mechanisms for knife mill**

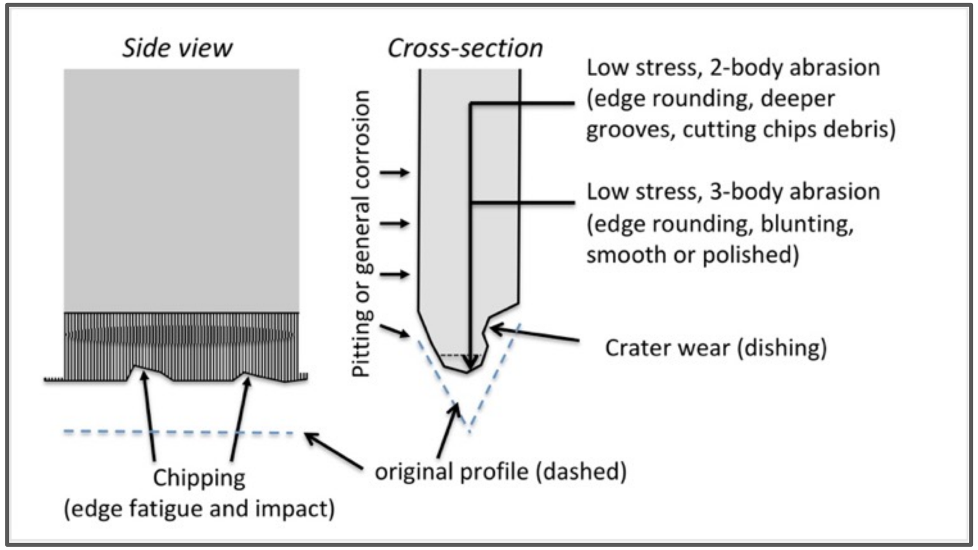


Knife Mill (Thomas Wiley Mill Model 4)



Hammer Mill: Blunt blades
Comminution mode: Crushing
Wear modes: Erosive wear (dominant) + Abrasive wear (secondary)

***Knife Mill*: sharp blades**
Comminution modes: Cutting + Crushing
Wear modes: 2-body/3-body Abrasive wear + Erosive wear (both important)



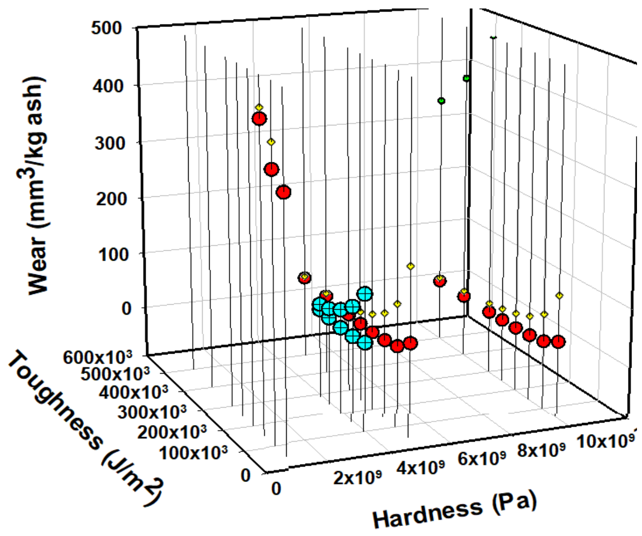
Selection of candidate coatings & surface treatments to mitigate wear

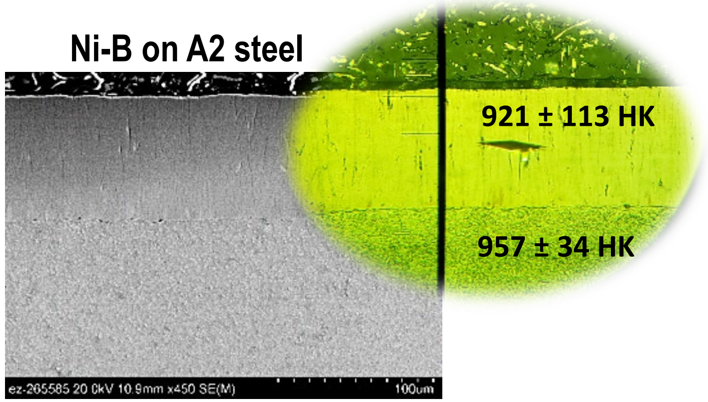
Knowledge

fcic FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

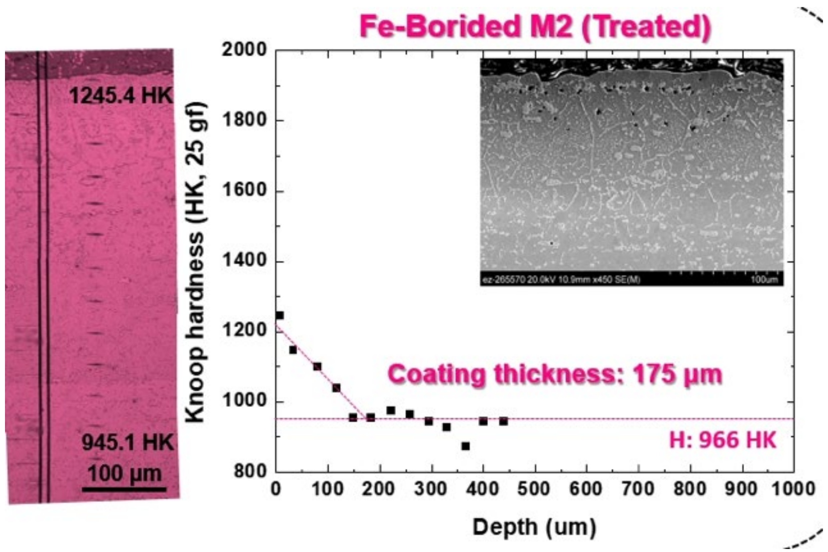
- **Abrasive** and **Erosive** wear can be mitigated by selecting tool materials with optimum mechanical properties
  - Increasing **hardness** – lowers **abrasive wear**
  - Increasing **fracture toughness and fatigue ductility** – reduces **erosive wear**

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





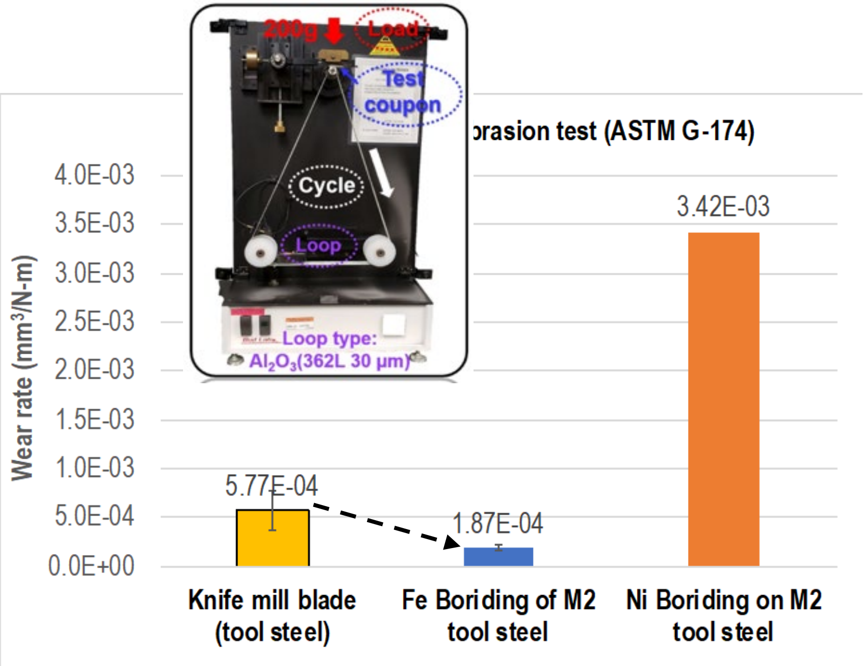
	Nickel Boriding (coating)	Iron Boriding (case hardening)	Diamond-like carbon (DLC) coating
Hardness	Up to 1200 HV	1200-1900 HV	1000-2800 HV
Thickness	Up to 100 µm	Up to 300 µm	Up to 100 µm
Microstructure	columnar	columnar	amorphous
Process [Manufacturer]	Autocatalytic deposition (EXO) **[UCT]**	Deep case boriding (DCB) **[IBC]**	Plasma-enhanced chemical vapor deposition (PECVD) **[NCT]** and **[C4E]**
Deposition Temperature	RT followed by crystallization at 385 °C	1000+ °C followed by heat treat/tempering	< 300 °C

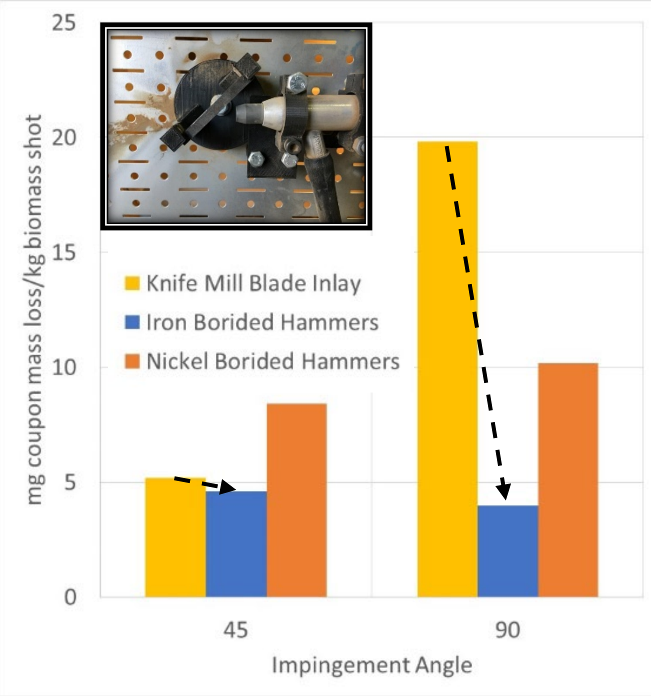


Improve tool life for knife mill using more wear-resistant surface treatments

Knowledge

- **Knife mill: 2-body/3-body abrasive wear + erosive wear (both important)**
- **Abrasion: Iron boriding showed 300% improved abrasion resistance in standard 2-body abrasion tests at ORNL**
- **Erosion: Iron boriding showed 10% and 400% improved erosion resistance at 45 and 90 degrees, respectively, in erosion wear tests at INL.**
  - More candidate coatings and surface treatments are being acquired and evaluated





Iron boriding may potentially significantly improve the knife life at a small add-on cost

Thomas Wiley Mill Model 4	Cost	Cost increase
Current tool steel knife set (10)	$2,150	Baseline
Fe-boriding a knife set (10)	$120*	~7%

**$12 per knife for a batch of 500 knives*

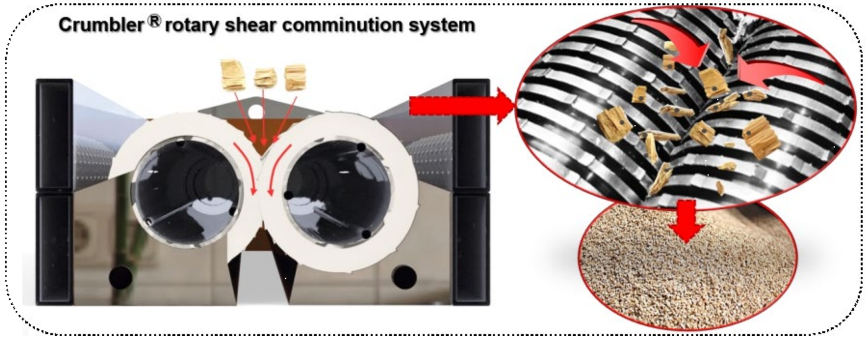
Knife blade prototyping and testing

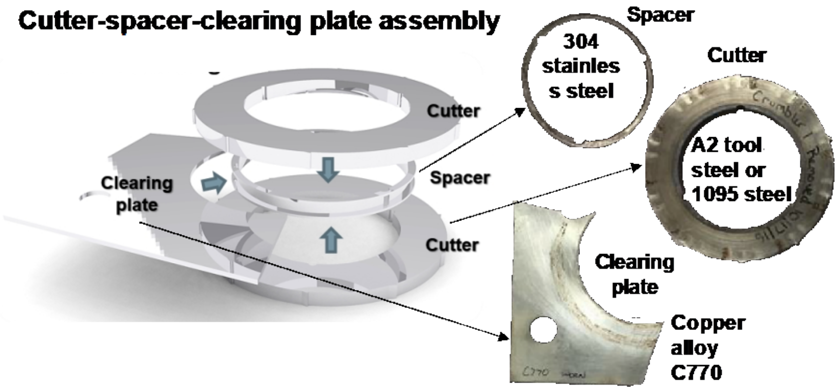
- INL is working with a knife mill OEM (Eberbach) to set up a state-of-the-art small knife mill (model E3803) and acquire commercial knife blades.
  - Six rotary and six stationary knifes, can operate at variable rotating speeds, and is equipped with a precise control of the gap between the rotary and stationary blades.
- ANL and ORNL are working with coating vendors (IBC, NCT, and C4E) to fabricate prototyping knife blades using candidate coatings.
- INL is planning knife mill tests to validate the improved tool life and performance of the prototype blades.

Blade materials	
Commercial (Eberbach)	Standard tool steel
	17-4H stainless steel
	WC-Co composite
Candidate	Iron boriding (IBC) of tool steel
	Thin DLC (NCT) on tool steel
	Thick DLC (C4E) on tool steel

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

- **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.**
- **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.**
- **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.





Distinguishing the wear mechanisms among biomass comminution systems

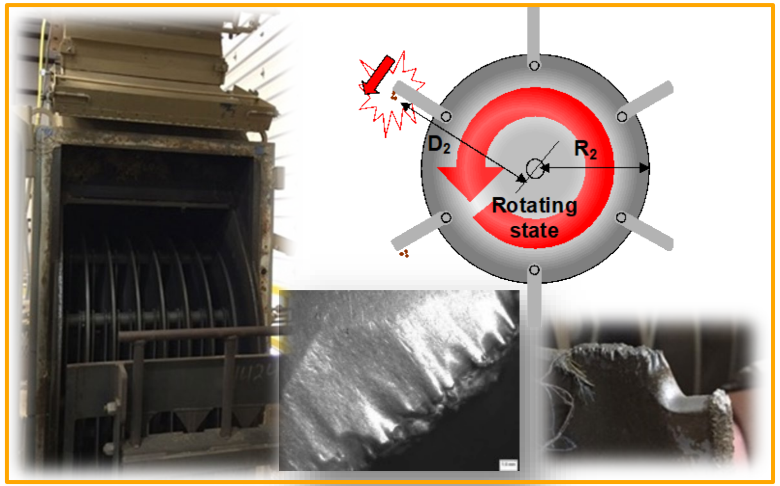
Knowledge

- **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**

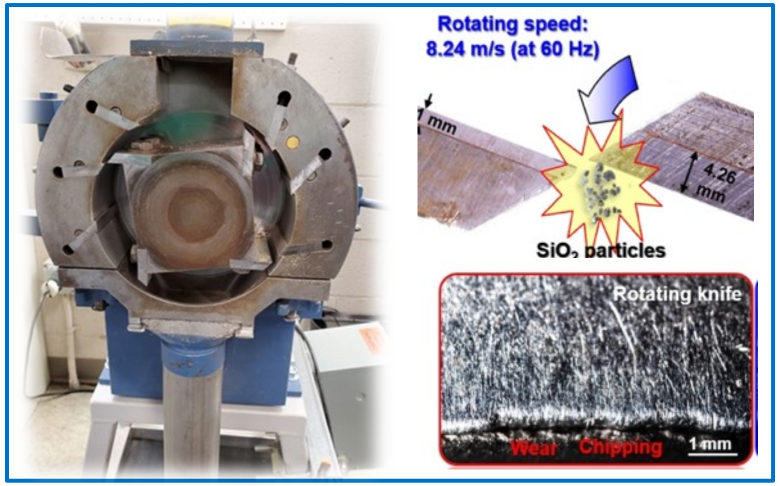
Erosive wear (dominant) + 2-body/3-body Abrasive wear (secondary)



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

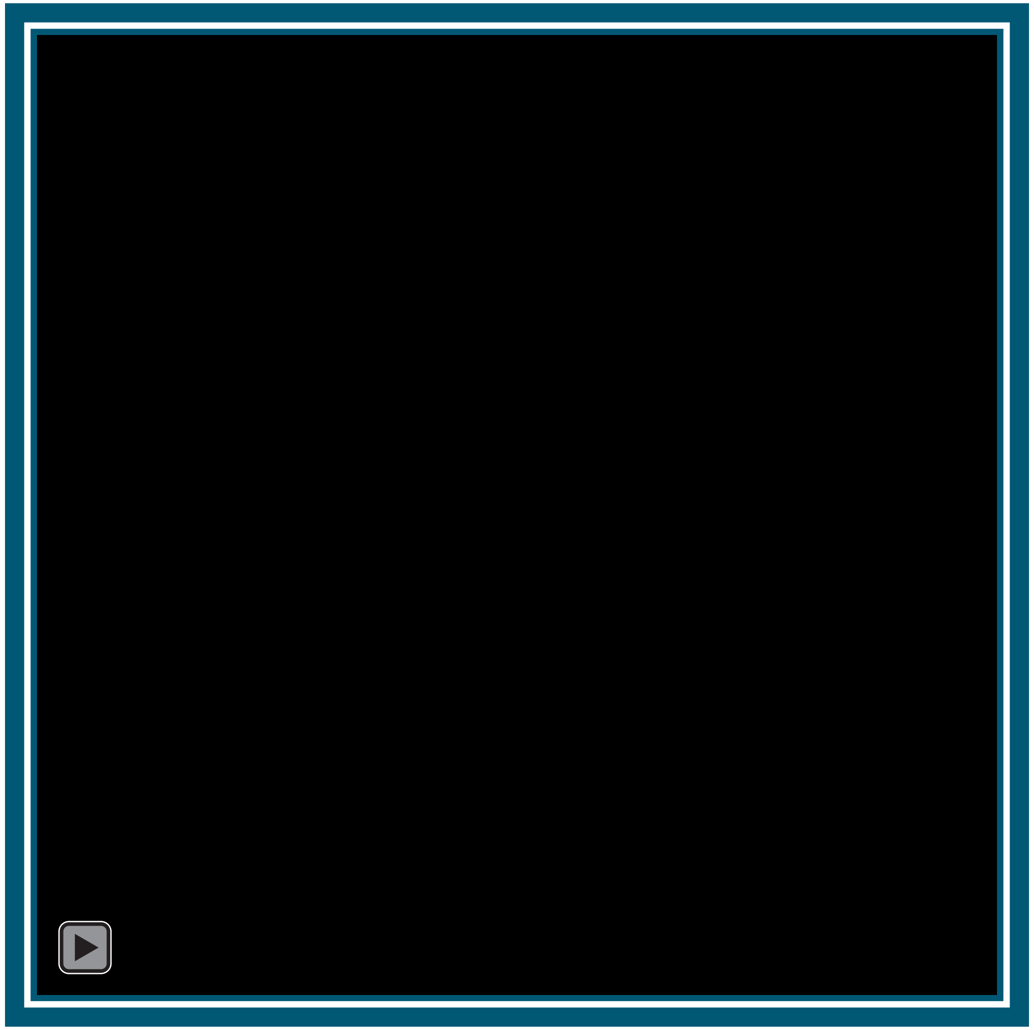
Sharp edges/corners @ low speed
→ **Cutting/Shearing**

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

Revealing the cutter-woodchip interface phenomena

- High-speed camera video clip catching the moment of the cutters shearing/crashing a woodchip on a Crumbler® at FC

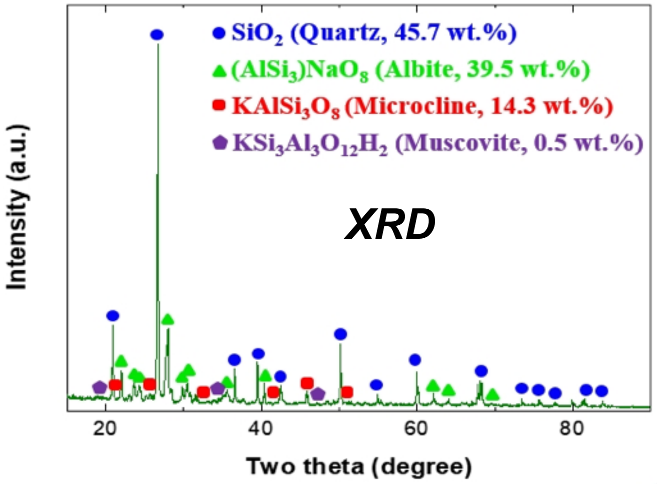
Photron Nova S12 high speed camera. Sample Record Rates: 1024 x 1024 @ 12,800 fps; Light Sensitivity: ISO 64,000 up to 500,000; Minimum Shutter: 200 ns

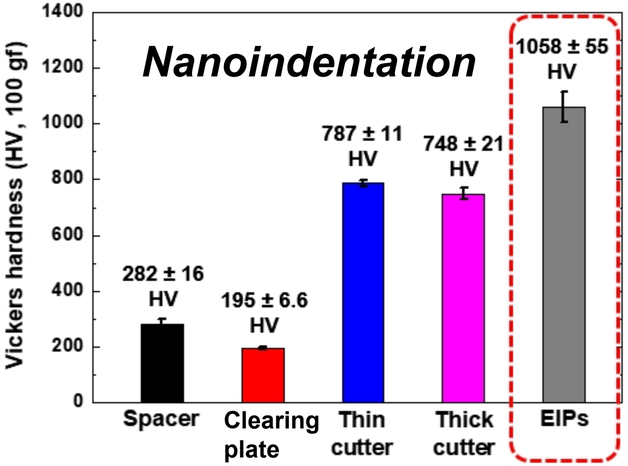


Extrinsic mineral particles of woodchips and their impact on cutter wear

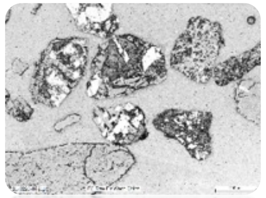
Knowledge

- **Extrinsic mineral particles**



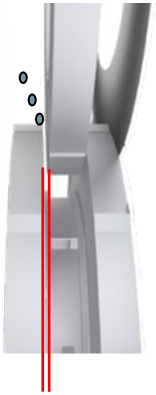


Extracted, mounted, and polished extrinsic inorganic particles



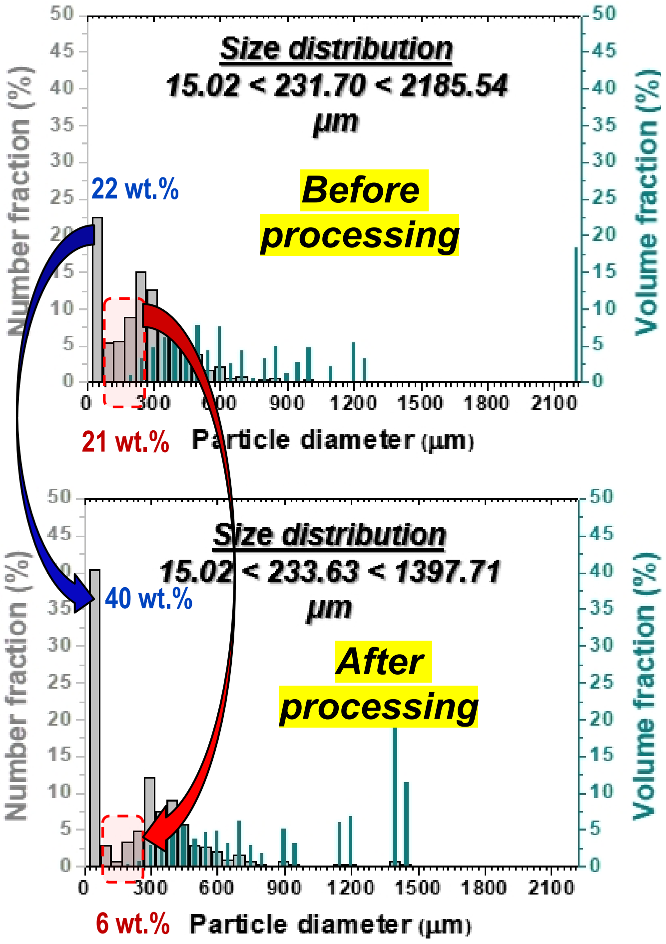
- **Extrinsic mineral particles cause 2-body/2-body abrasive wear**

New cutter | Slightly worn | Severely worn



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

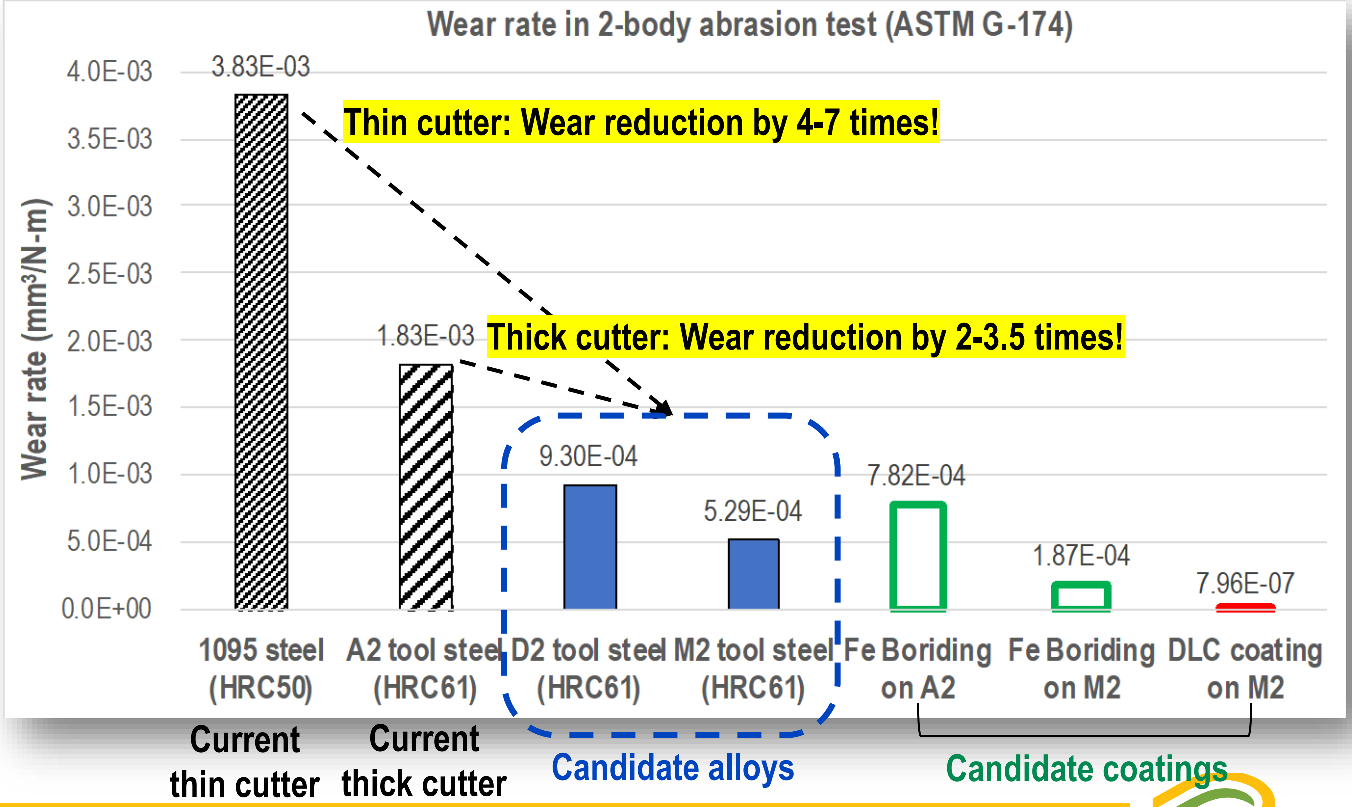
- **Mineral particles of 70-200 μm are trapped in the gap between cutters and crushed into smaller ones**
  - 70-200 μm-sized minerals decreased from 21 wt.% to 6 wt.%
  - <30 μm-sized minerals increased from 22 wt.% to 40 wt.%

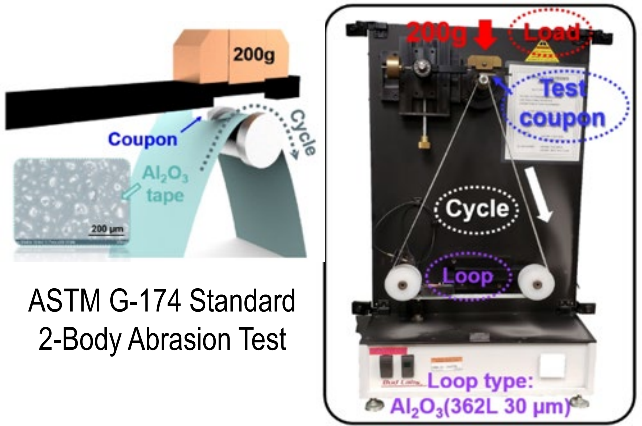


Improve cutter life by using more wear-resistant **alloys**

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*

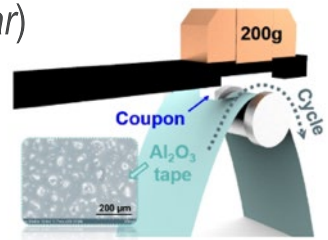
Improve cutter life by using more wear-resistant **coatings**

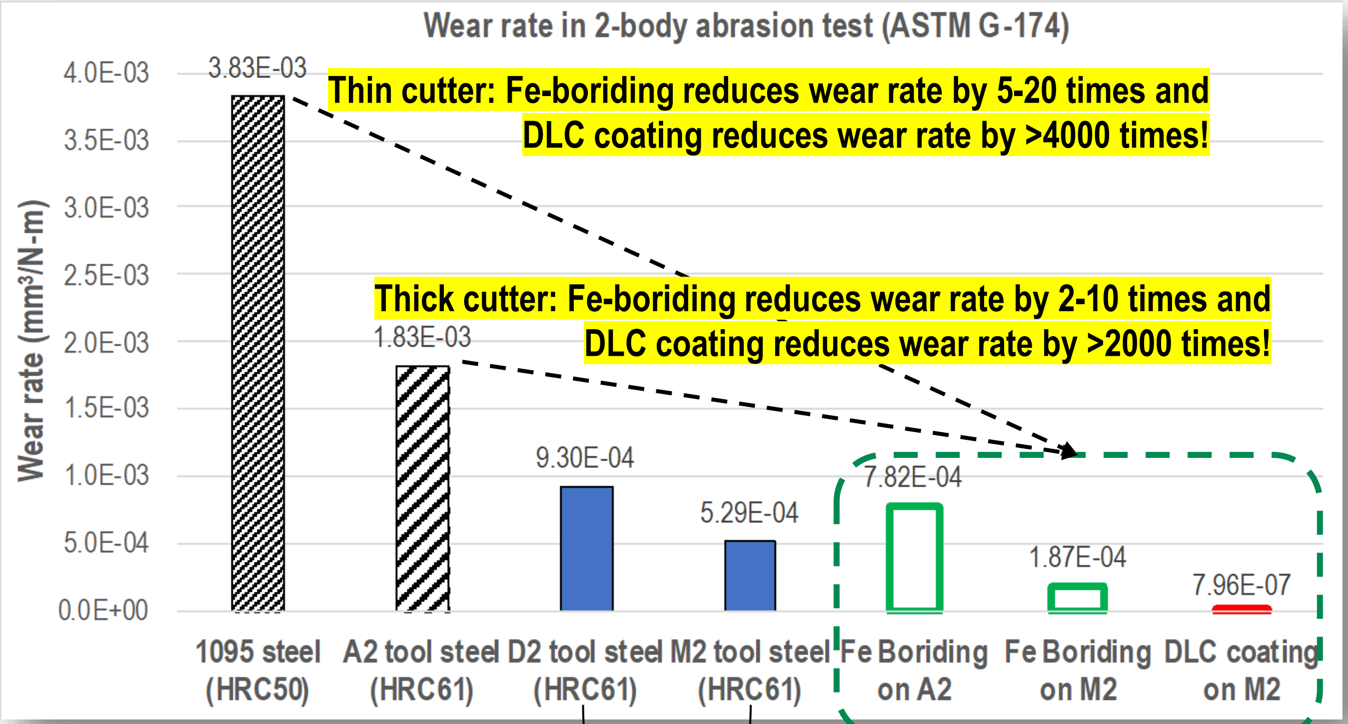
Knowledge

fcic
FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

- ***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**

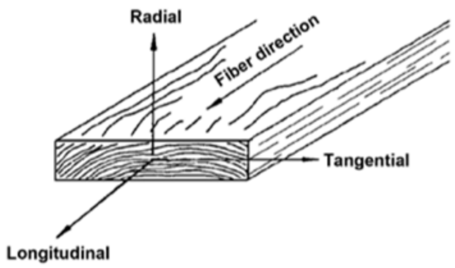
For thick cutter (3/16")		Wear rate ($x10^{-3}$ mm^3/Nm)	Potentially improved life	4.25"-dia. cutter cost*	Cutter cost factor
Baseline (A2 tool steel)		1.83	Baseline	~$40	Baseline
Candidate alloys	Fe-borided A2	0.78	~2x	~$52	~1.3x
	Fe-borided M2	0.19	**~10x**	~$88	**~2.2x**
	DLC-coated M2	0.0008	**>2000x**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

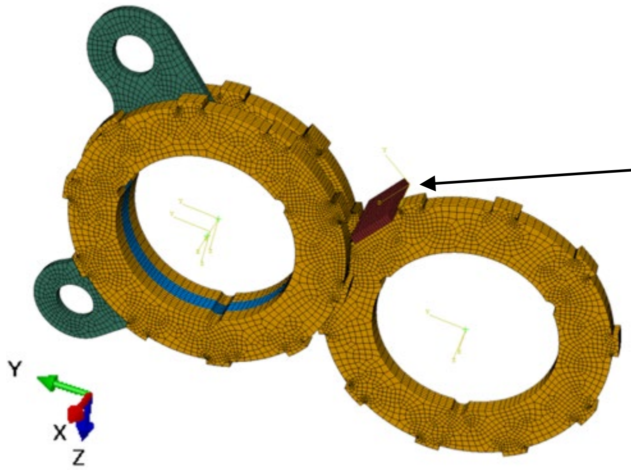
**Coating cost estimates based on batches of 100 parts*

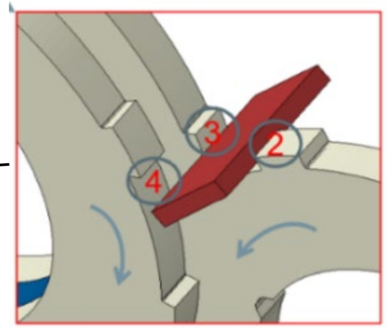
FEA modeling to calculate contact stresses at the cutting interfaces

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.**

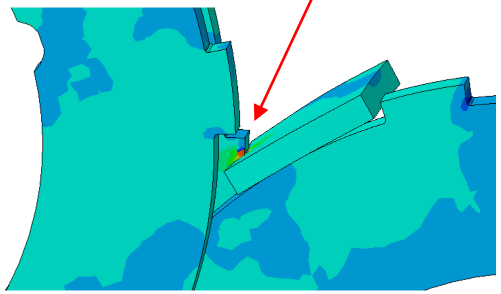


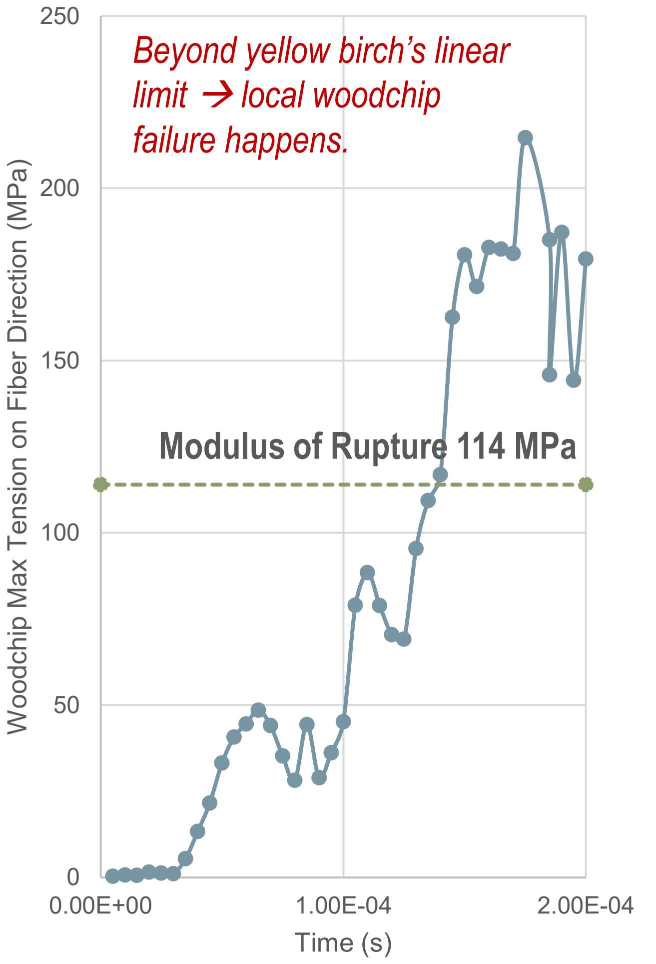




Time = 0.12 milliseconds

Contact pressure = 187.7 MPa





Stress of 3 mm thick woodchip on fiber direction

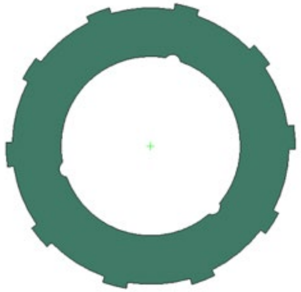
Wood – anisotropic mechanical properties

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

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.

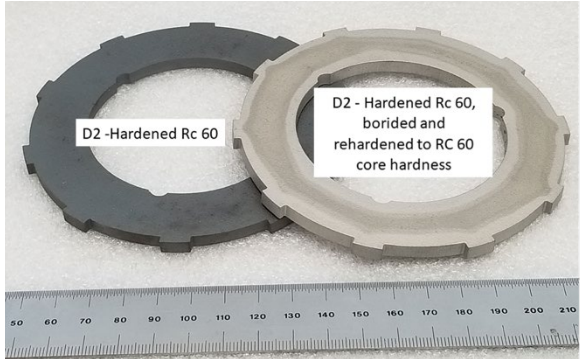


Case #	Cutter Thickness	Woodchip Size (mm)	Woodchip	Woodchip Modulus of Rupture (MPa)	Original Tooth Max Contact Pressure (MPa)	DZ Tooth Max Contact Pressure (MPa)
4	1/16" (1.6 mm)	6x6x6	Yellow Birch, 12%	114	**1249**	1038
5			Red Oak, 12%	75	**770**	627
6			White Cedar, green	29	397	486
13			Douglas-fir, 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

Cutter prototyping and testing

- ORNL and ANL are working with a cutter manufacturer (DST) and coating vendors (IBC and NCT) to fabricate prototype cutters using the DZ tooth design and candidate wear-resistant coatings.
- FC is planning to test the prototype cutters side-by-side with the baseline cutters on a rotary shear to validate the improved tool life and performance.

	Thick (3/16") cutter	Thin (1/16") cutter
Commercial (FC)	A2 tool steel	1095 carbon steel
Candidate	D2 tool steel (DST)	M2 tool steel
	Iron boriding (IBC)	Iron boriding (IBC)
	Thin DLC (NCT)	Thin DLC (NCT)

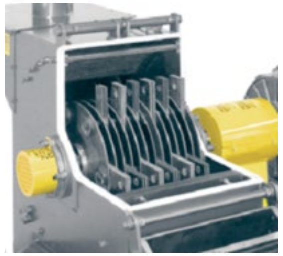


Thick (3/16") cutters

Thin (1/16") cutters

Analytical Solutions for Wear/Recession of Leading Edges – Dependence on Feedstock, Material, and Processing Properties

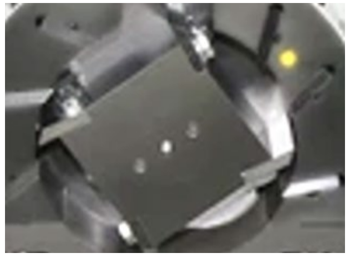
- **Hammer mill**



$$\Delta_{\perp} = \Delta Q_{erosion} * 2\pi r * \rho(r)$$

$$\Delta Q_{erosion} = \Delta Q_D + \Delta Q_C$$

- **Knife mill**



$$\Delta_{\perp} = \Delta Q_{abrasion} * \mathcal{X}$$

$$\Delta Q_{abrasion} = \frac{[(D/2)^2]}{2}(\alpha - \sin\alpha) * f(\Delta\theta, r)$$

- **Rotary Shear**

$$\Delta_{\perp} = \Delta Q_{abrasion} * \mathcal{X}$$

$$\Delta Q_{abrasion} = \frac{[(D/2)^2]}{2}(\alpha - \sin\alpha) * \mathcal{L}(\Delta\theta, r)$$

Feedstock Attibutes	
d	particle diameter
η	particle shape factor
ρ	particle density
β	Bulk modulus
E	Young's modulus
τ_s	Shear strength

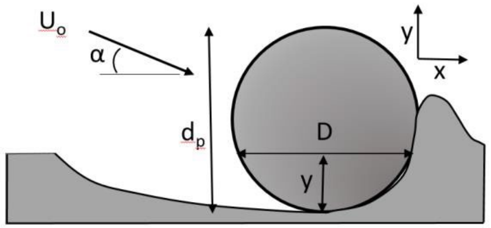
Material Attributes	
b	Manson-Coffin fatigue ductility exponent
ε_f	Manson-Coffin fatigue ductility coefficient
E	target material Young's modulus
H	target material hardness
K_c	critical stress intensity factor
R	target material fracture toughness

Process/Design Parameters	
U	particle impact velocity
α	particle impingement angle
ro	Outer radius of feedstock zone
ri	Inner radius of feedstock zone
L	Length of hammer mill zone
φ	Tool Leading Edge Angle
τ	Residence time
FR	Feed Rate
AC	Ash Content
N	Rotational Speed
No	Bale Ash Density
λ	Exponential constant

Mathematical Models of Erosion and Abrasion Relate Volume of Material Lost to Material Properties and Kinematic Conditions

General Types of Wear

Erosive Wear



$$\Delta Q_{erosion}\,(m^3/kg_{ash}) = \Delta Q_D + \Delta Q_C$$

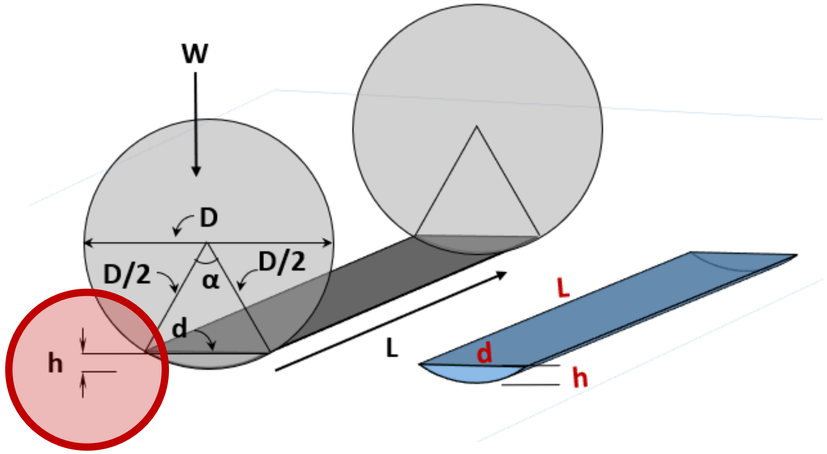
ΔQ_D = the volume lost to repeated deformation events arising from the normal component of a particle impacting a surface

ΔQ_C = the cutting component of wear arising from the horizontal motion of a particle

$$\frac{\Delta Q_C}{m_p} = C_c\,(1+f)[1-\exp(-200\alpha^2)]\,\frac{\left(\frac{\rho_p d_p^2}{\eta}\right)^{(1-f)/2}}{H^{\left(\frac{1+f}{2}\right)} R^{(1-f)}}\,U_0^{3-f}\cos^2(\alpha)\sin^{1-f}(\alpha)$$

$$\frac{\Delta Q_D}{m_p} = C_D\,\frac{\rho_p^{1/4b}}{\eta^{3/4b}\varepsilon_f^{1/b}H^{(1+1/4b)}}\,[U_0\sin(\alpha)]^{2+1/2b}$$

2-body/3-body Abrasive Wear



$$\Delta Q_{abrasion}(m^3/particle) = \frac{[(D/2)^2]}{2}(\alpha - \sin\alpha)\,x\,L$$

$$\alpha = 2acos\left[1 - {}^{2h}/_{D}\right]$$

$$h_e = \left[3W_e/\left(4E^*\sqrt{D^*/2}\right)\right]^{2/3}$$

$$h_p = Wp/[\pi\, D\, H\,]$$

Y. Ben-Ami, A. Uzi, and A. Levy, 2016, “Modelling the Particles Impingement Angle to Produce Maximum Erosion,” Powder Technology 301: 1032–1043.

Validation of Erosive Wear Model – Bench Scale Simulation

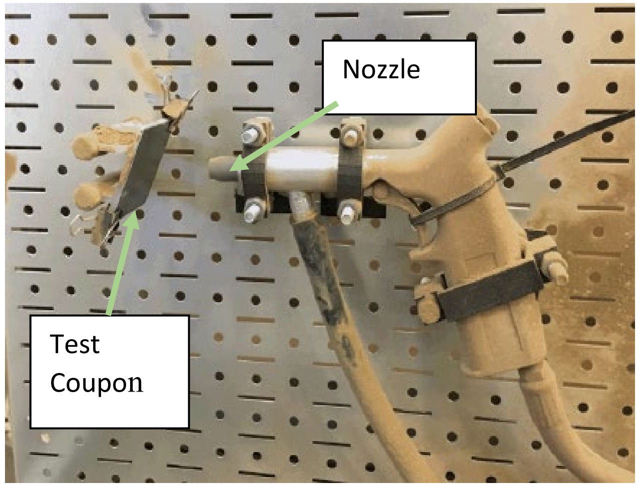
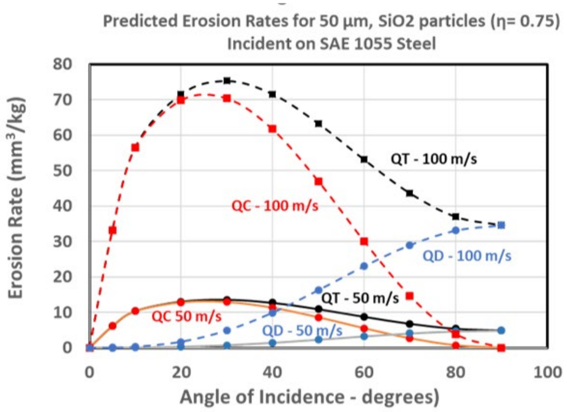


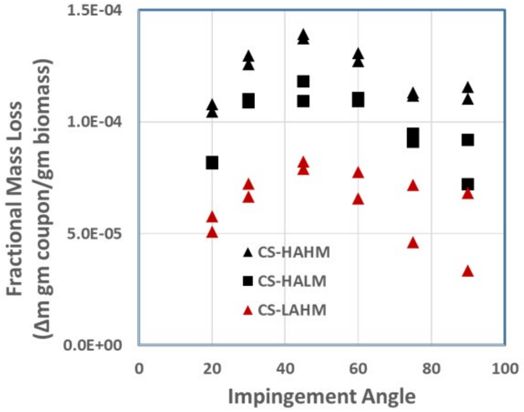
Photo of grit blaster nozzle used to simulate abrasive wear by biomass feedstock (courtesy INL [22])

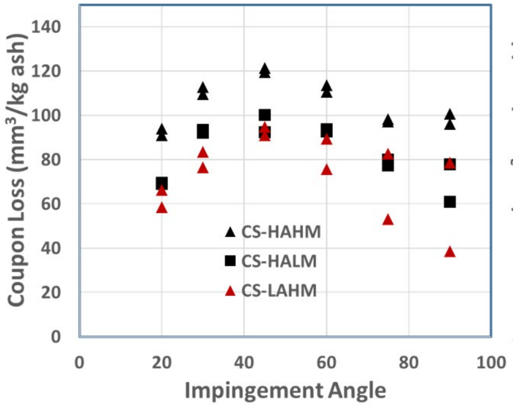
$$\frac{\Delta Q}{m_p} = C_D * \frac{\rho_p^{\left(\frac{1}{4b}\right)} * (U_0 \sin\alpha)^{\left(2+\frac{1}{2b}\right)}}{\eta^{\left(\frac{3}{4b}\right)} \varepsilon_f^{\left(\frac{1}{b}\right)} H^{\left(1+\frac{1}{4b}\right)}} + C_C(1+f) * (1-\exp(-200\alpha^2)) \frac{\rho_p^{\frac{1-f}{2}} d_p^{(1-f)}}{\eta^{\frac{1-f}{2}} H^{\frac{1-f}{2}} R^{(1-f)}} [U_0^{(3-f)} \cos^2(\alpha) \sin^{(1-f)}(\alpha)]$$

Ben-Ami erosion wear model

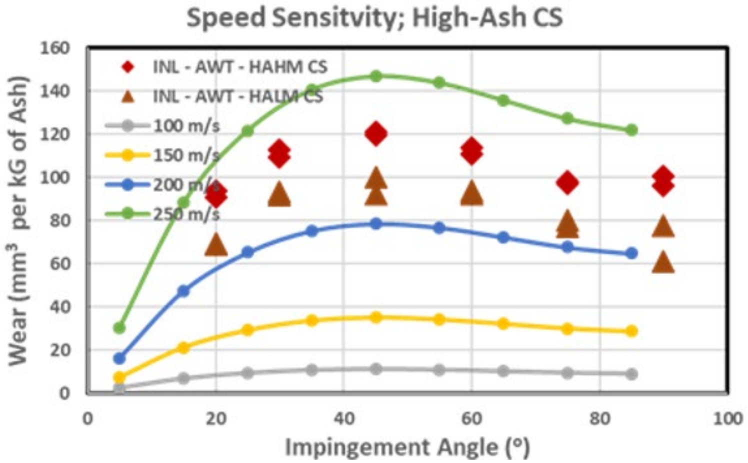


Predicted wear rate vs angle of incidence for 50 µm SiO2 particles





Comparison of predicted to measured wear at different particle speeds



George Fenske and Layo Ajayi, "An Analytical Model of Erosive Wear of Biomass Comminution Components", AN/AMD – 20/1

Validation of Erosive Wear Model – Hammermill Components

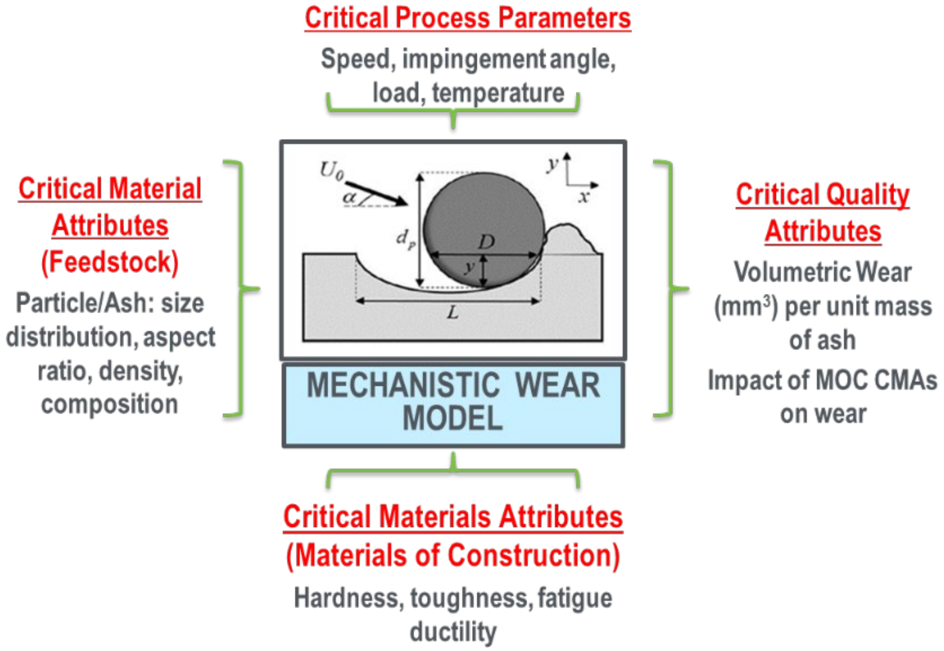
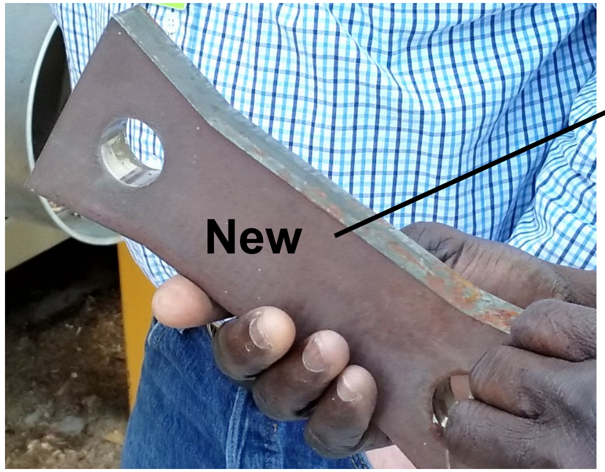
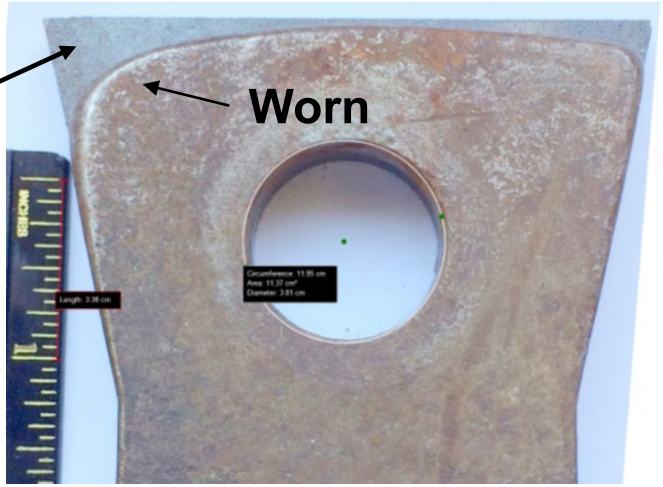


Illustration of QbD process for modeling component wear as functions of feedstock CMAs, hammer CMAs, and unit processing parameters, CPPs to wear (CQAs)

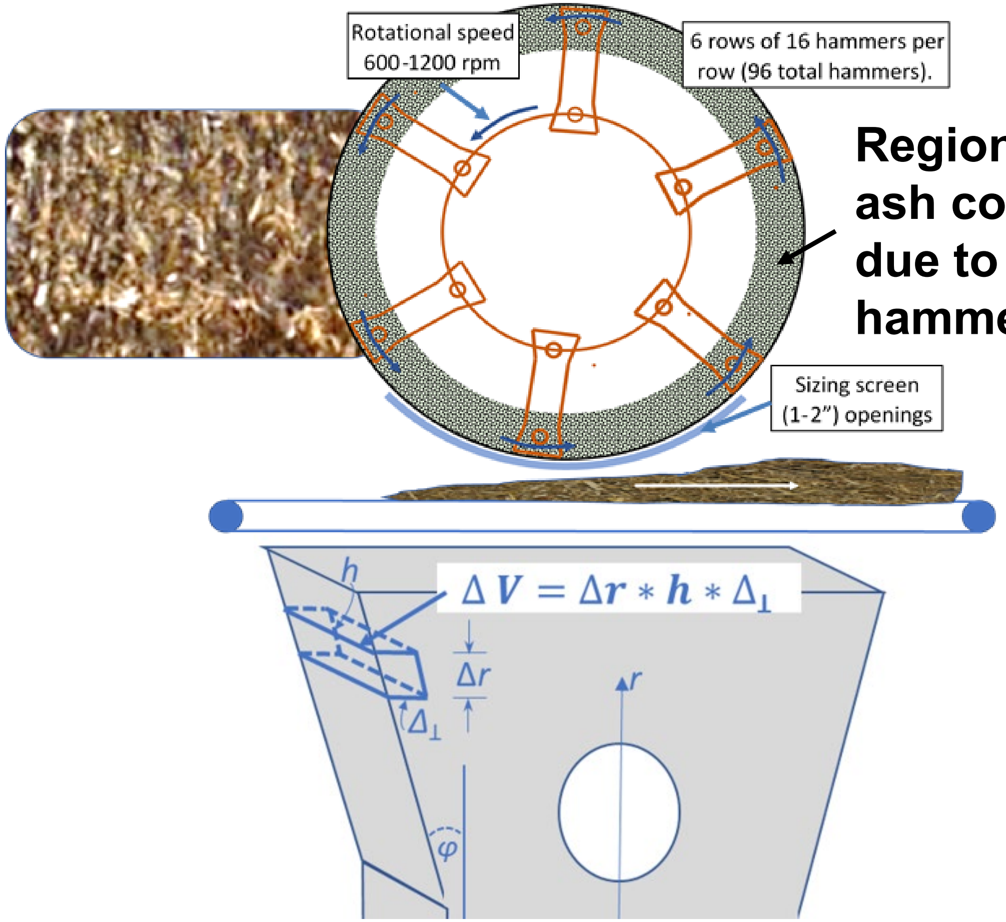
Illustration of the Vermeer Stage 1 hammer mill used to grind bales into loose feedstock.





George Fenske and Layo Ajayi, "Application of an Erosion Wear Model to Predict Wear of Hammer Milling Components",, AN/AMD – 20/2

Validation of Erosive Wear Model – Hammermill Components



Region where ash congregates due to rotation of hammers

Schematic of incremental wear volume on a stage 1 hammer.

$$\Delta V(m^3/rev) = \Delta Q_T * \Delta m$$

Δm = mass of particles that impact the leading edge of the hammer between r and r+Δr

$$\Delta m = \rho(r) * 2\pi r \Delta r h$$

$$\Delta V = \Delta Q_T * \rho(r) * 2\pi r \Delta r h$$

$$\Delta V = \Delta r * h * \Delta_{\perp}$$

Analytical Solution for Wear Recession of Hammer Face

$$\Delta_{\perp} = \Delta Q_T * \rho(r) * 2\pi * r$$

George Fenske and Layo Ajayi, "Application of an Erosion Wear Model to Predict Wear of Hammer Milling Componenets",, AN/AMD – 20/2

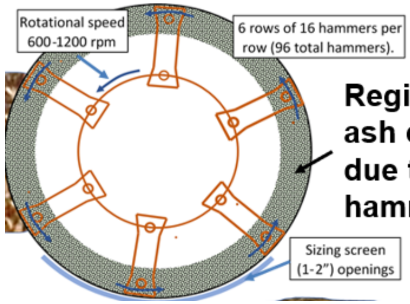
Engineering/QbD Modeling of Erosive Hammermill Wear

fcic
FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

Different Ash Density Assumptions

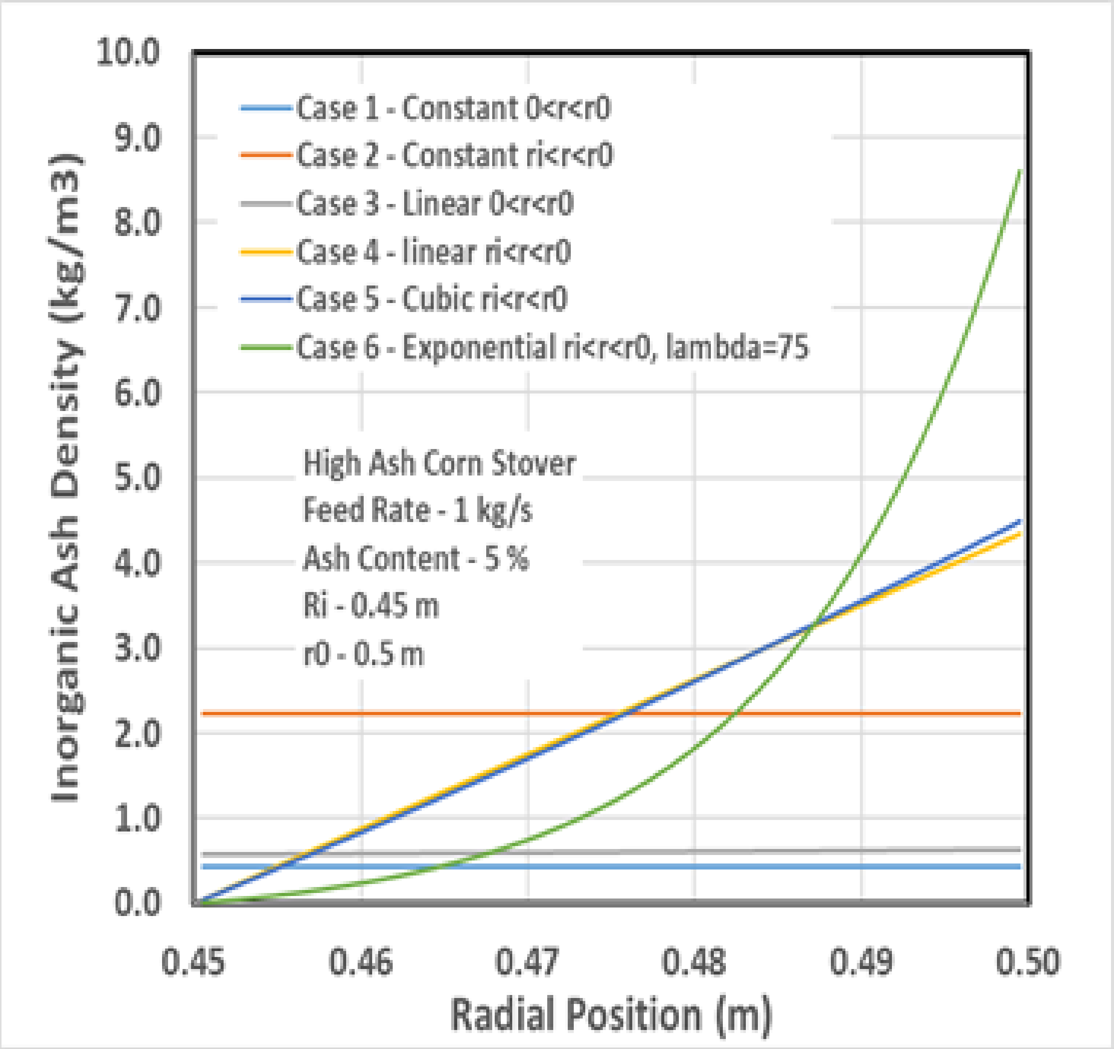
Case	Equation	Units	Region	A	C
1	$\rho(r) = C$	(kg_{ash}/m^3)	$0 < r < r_0$	0	$FR*\tau*AC/(\pi r_0^2 * L)$
2	$\rho(r) = 0$ $\rho(r) = C$	(kg_{ash}/m^3)	$0 < r < r_i$ $r_i < r < r_0$	0	0 $FR*\tau*AC/(\pi*L*(r_0^2 - r_i^2))$
3	$\rho(r) = Ar$	(kg_{ash}/m^3)	$0 < r < r_0$	$3*FR*\tau*AC/(2\pi*L*r_0^3)$	0
4	$\rho(r) = 0$ $\rho(r) = Ar + C$	(kg_{ash}/m^3)	$0 < r < r_i$ $r_i < r < r_0$	0 $(FR*\tau*AC)/(2\pi*L*(((r_0^3 - r_i^3)/3) + (r_i*(r_i^2 - r_0^2)/2)))$	0 $-A*r_i$
5	$\rho(r) = 0$ $\rho(r) = Ar^3 + C$	(kg_{ash}/m^3)	$0 < r < r_i$ $r_i < r < r_0$	0 $(FR*\tau*AC)/(2\pi*L*((r_0^5/5 - r_i^3 r_0^2/2) - (r_i^5/5 - r_i^5/2)))$	0 $-A*r_i^3$
6	$\rho(r) = 0$ $\rho(r) = Ae^{\lambda r} + C$	(kg_{ash}/m^3)	$1 < r < r_i$ $r_i < r < r_0$	0 $(FR*\tau*AC)/(2\pi*L*[[e^{\lambda r0}*((\lambda r_0 - 1)/\lambda^2) - e^{\lambda ri}\ r_0^2/2] - [e^{\lambda ri}*((\lambda r_i - 1)/\lambda^2) - e^{\lambda ri}\ r_i^2/2]]$	0 $-Ae^{\lambda ri}$

L = mill drum length (1.5 m)
λ = exponential constant - set to 75

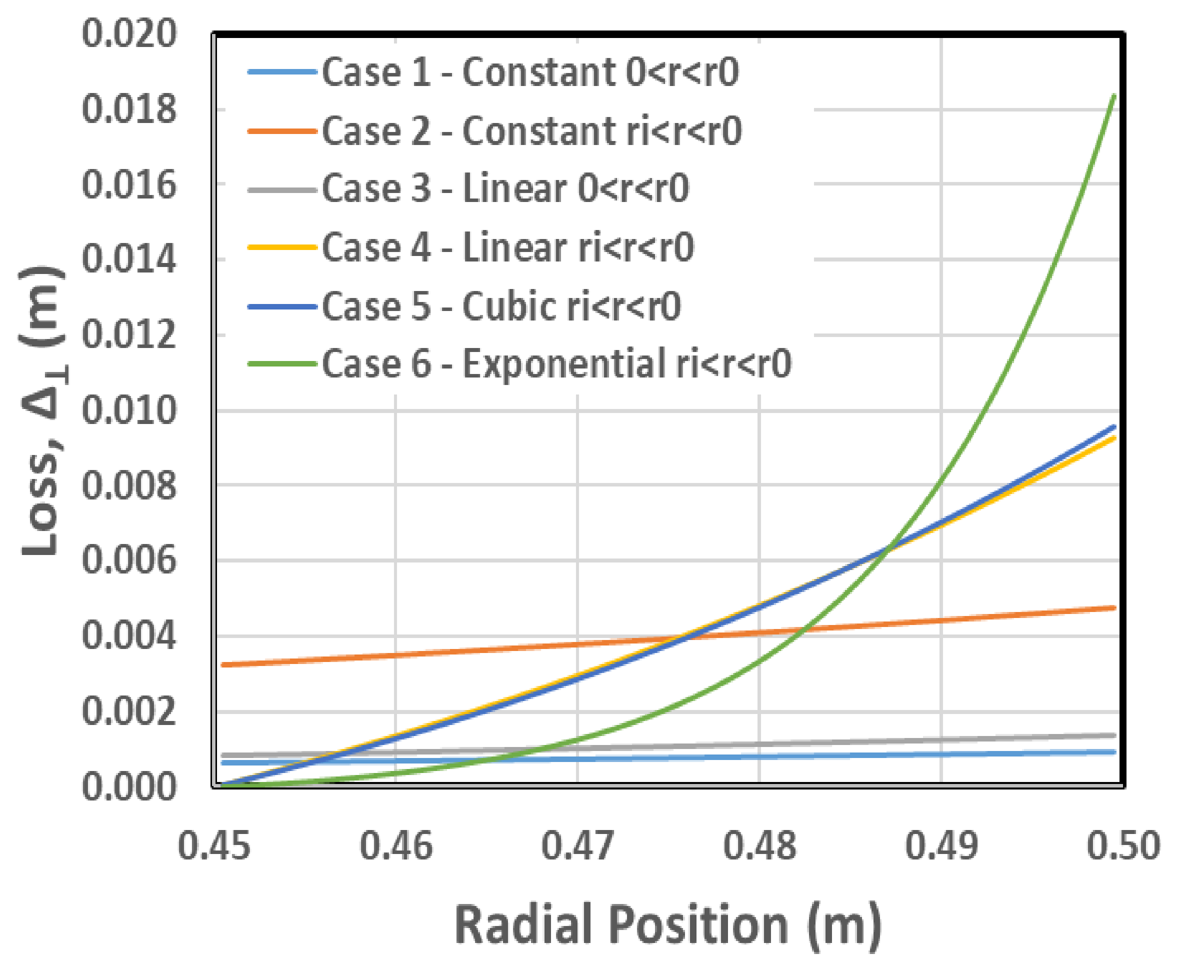


Region where ash congregates due to rotation of hammers

Total mass in the rotating mill is equal to FR * AC * τ



Analytical Predictions of Hammer Wear



- Experimental observations indicate wear is essentially limited to outer 5 cm of the hammer. In this region the hammer angle (of the fresh hammer) remains constant at 75^o.
- The model predicts the recession is proportional to the ash density which is a function of position (radius)

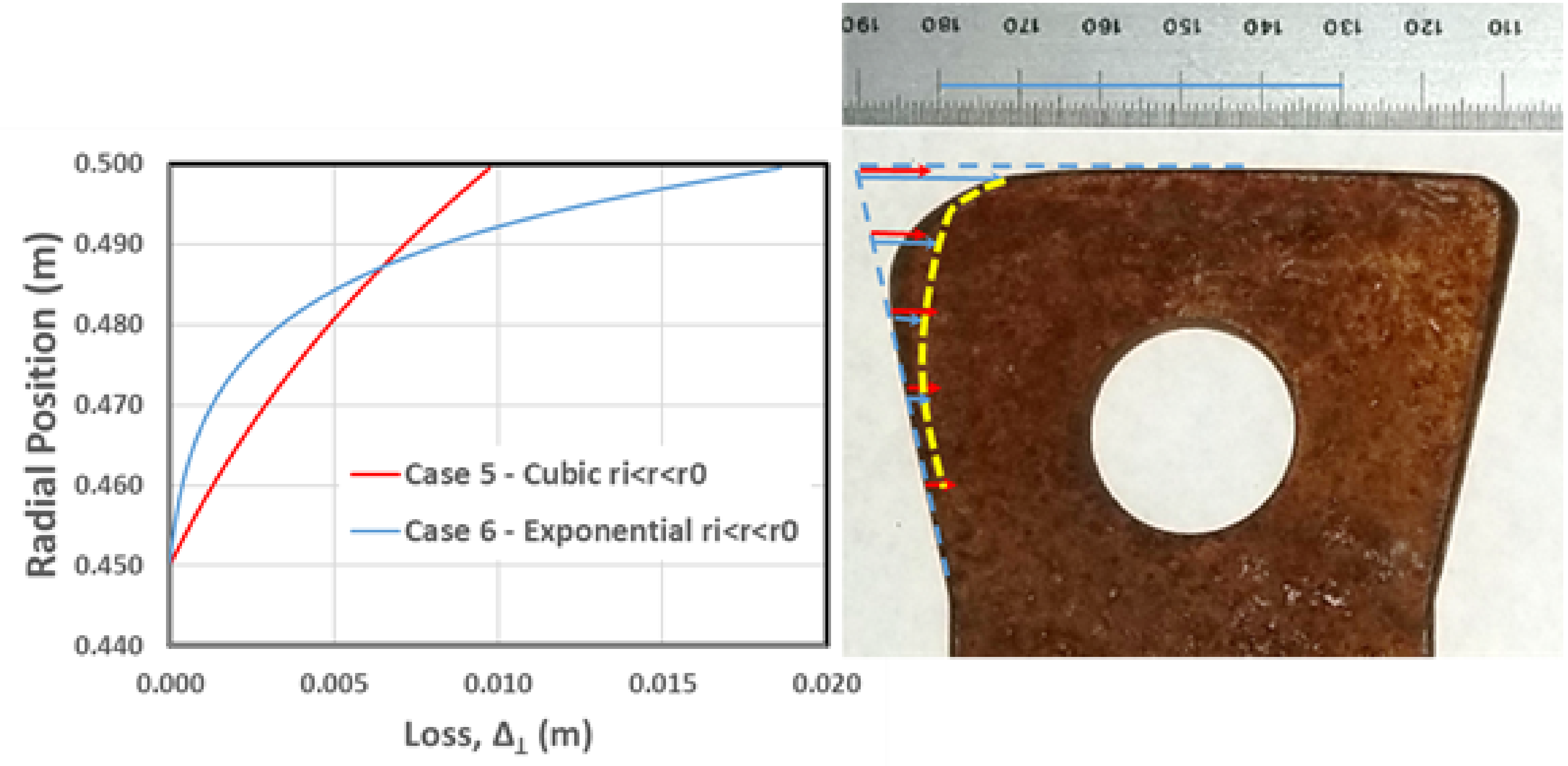
$$\Delta_{\perp} = \Delta Q * \rho(r) * 2\pi * r$$

Analytic Predictions of Hammer Wear

Sufficient flexibility in model parameters for reliable simulation of erosive wear.

Potential applications include:

- Impact of hammer design (hammer face angle)
- Impact of rotational speed on hammer wear
- Impact of material properties (hardness, toughness, fatigue ductility) on wear and recession
- Impact of feedstock variability (ash content, ash size and shape) on wear



Comparison of predicted shape with actual shape of a worn. Yellow line (right) illustrates projected shape for the exponential particle density distribution.

Application of Erosion Wear Model

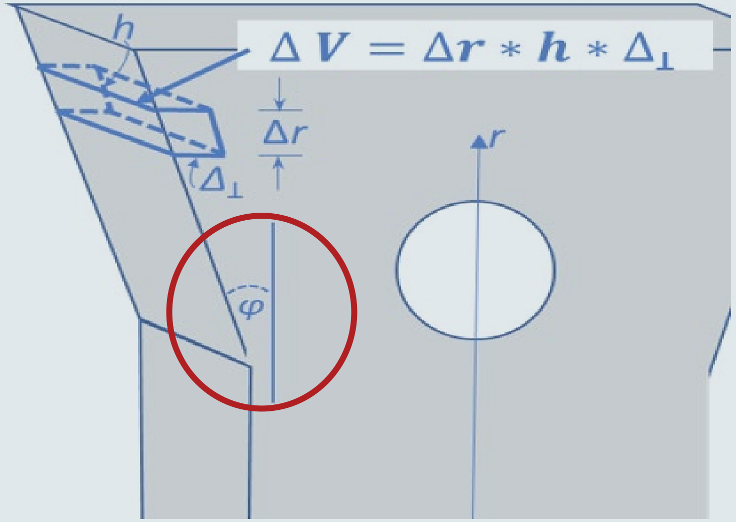
Impact of material properties (hardness, toughness, fatigue ductility) on wear and recession

Fracture Toughness	ϵ = 0.5			ϵ = 1.0		
	4 GPa	8 GPa	12 GPa	4 GPa	8 GPa	12 GPa
5 kJ/m^2	0.168	0.102	0.077	0.056	0.034	0.025
10 kJ/m2	0.104	0.063	0.047	0.034	0.021	0.016
20 kJ/m2	0.064	0.039	0.029	0.021	0.013	0.010
30 kJ/m2	0.048	0.029	0.022	0.016	0.010	0.007
40 kJ/m2	0.040	0.024	0.018	0.013	0.008	0.006
50 kJ/m2	0.034	0.021	0.015	0.012	0.007	0.005

Impact of rotational speed on hammer wear

Rotational Speed (rpm)	Hammer Recession $\Delta_\perp$ (mm)
600	4
750	9
900	18
1050	33
1200	55

Impact of hammer design (hammer face angle)



Face Angle ϕ (deg)	Hammer Recession $\Delta_\perp$ (mm)
0	18
15	18
30	18
45	16
60	13
75	8

Pivot to Knife Milling
Physical Modeling of Knife Milling

Knife mill: abrasive wear + erosive wear (both important)

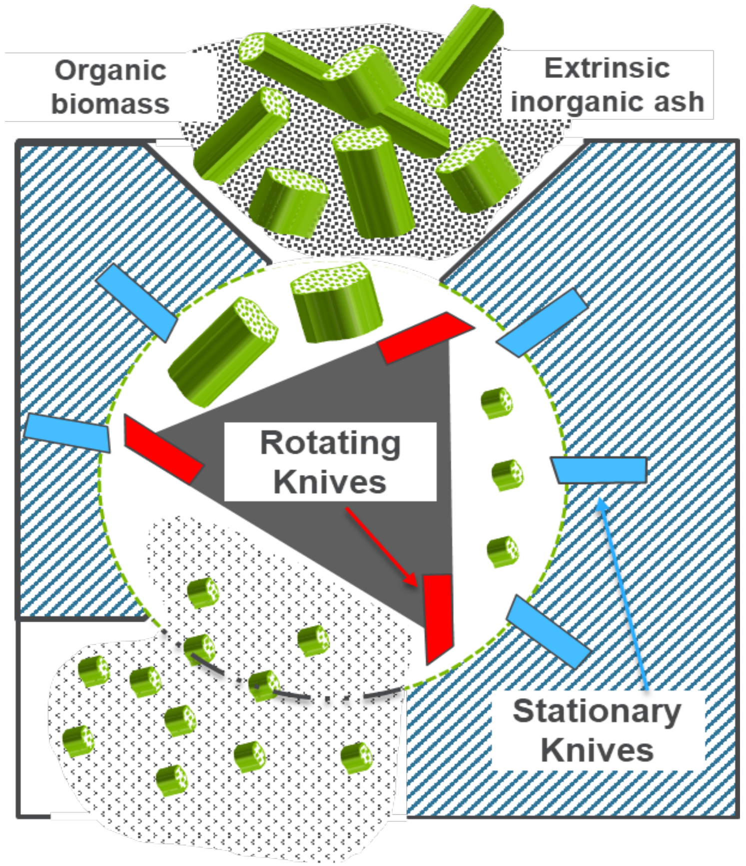
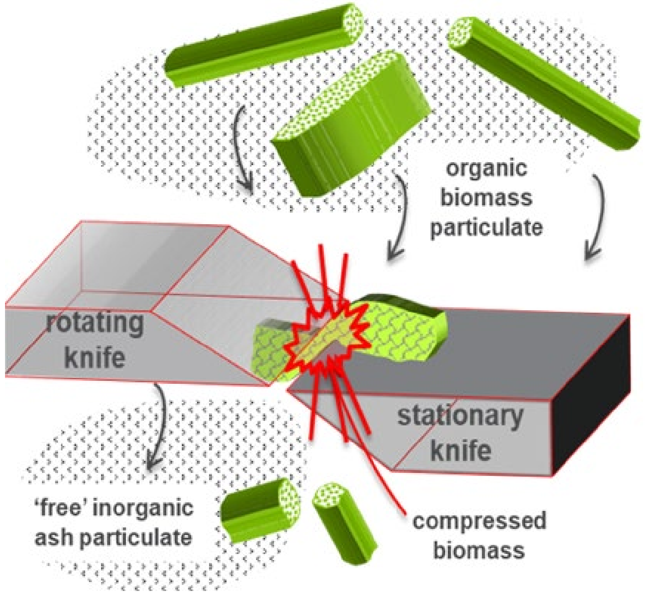
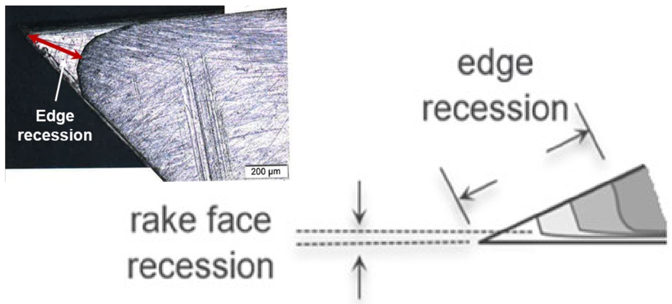


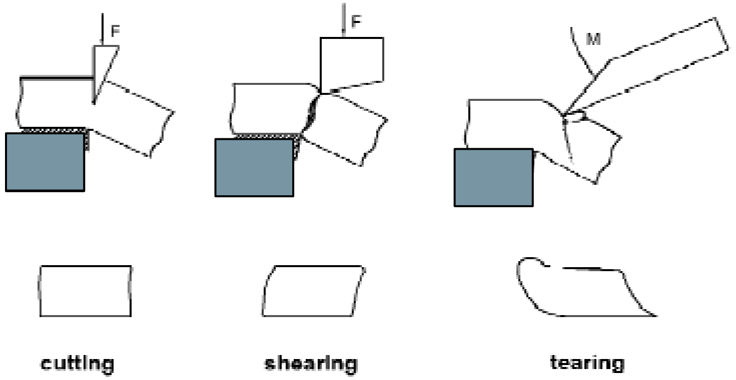
Illustration of knife milling operations

Size reduction during knife milling



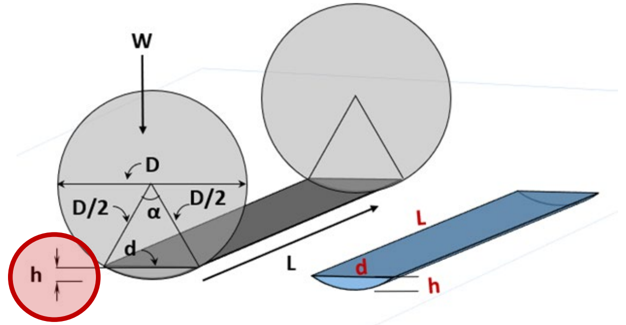


Abrasion/erosion of knife edge opens gap between knives and changes the process of deformation from cutting to shearing to tearing



First Step in Calculating Abrasive Wear

For a given particle size and load, calculate indentation depth and wear volume produced per unit sliding distance

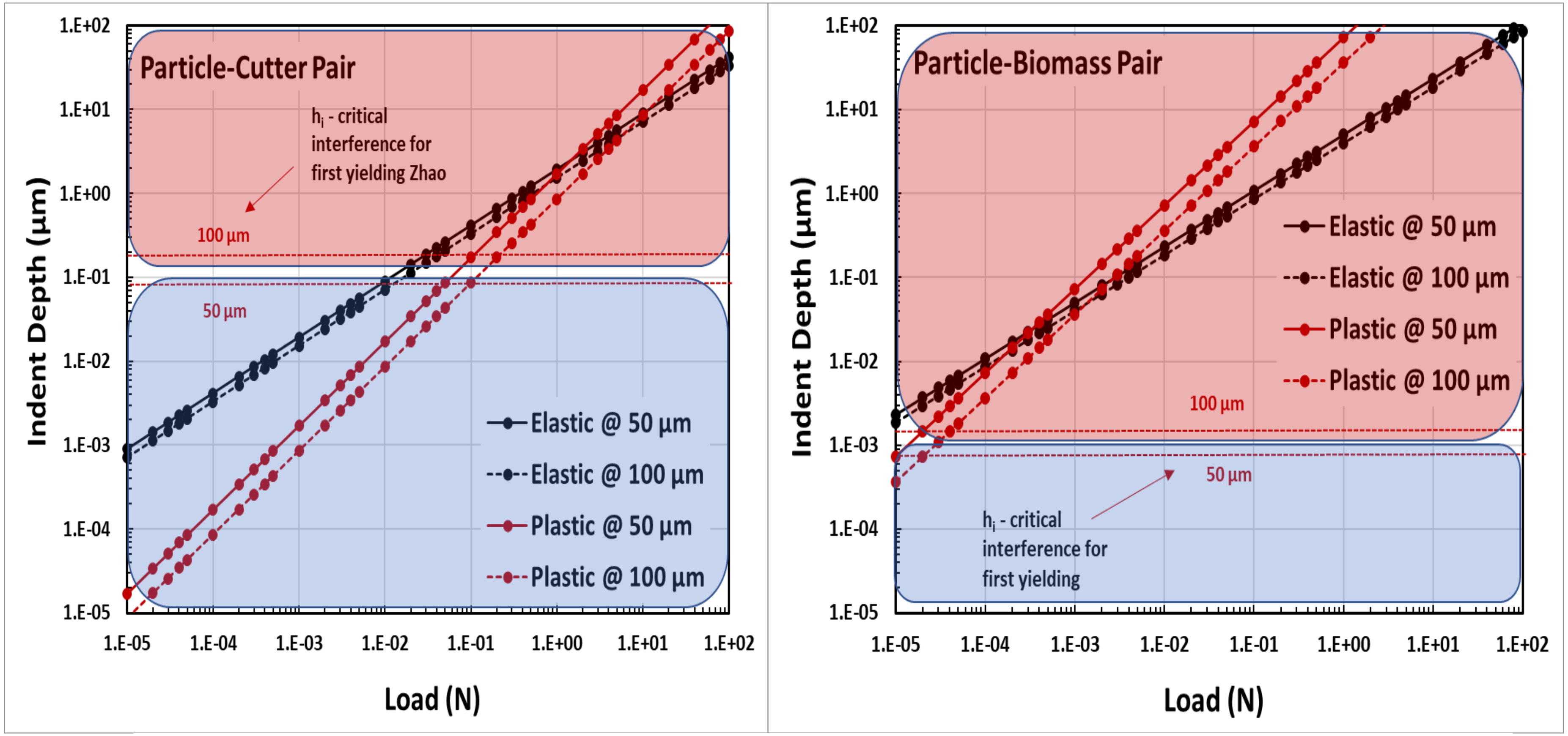


$$\Delta Volw(m^3/particle) = \frac{[(D/2)^2]}{2}(\alpha - \sin\alpha)\ x\ L$$

$$\alpha = 2acos\left[1 - {}^{2h}/_{D}\right]$$

$$h_e = \left[3W_e/\left(4E^*\sqrt{D^*/2}\right)\right]^{2/3}$$

$$h_p = Wp/[\pi\ D\ H\ ]$$

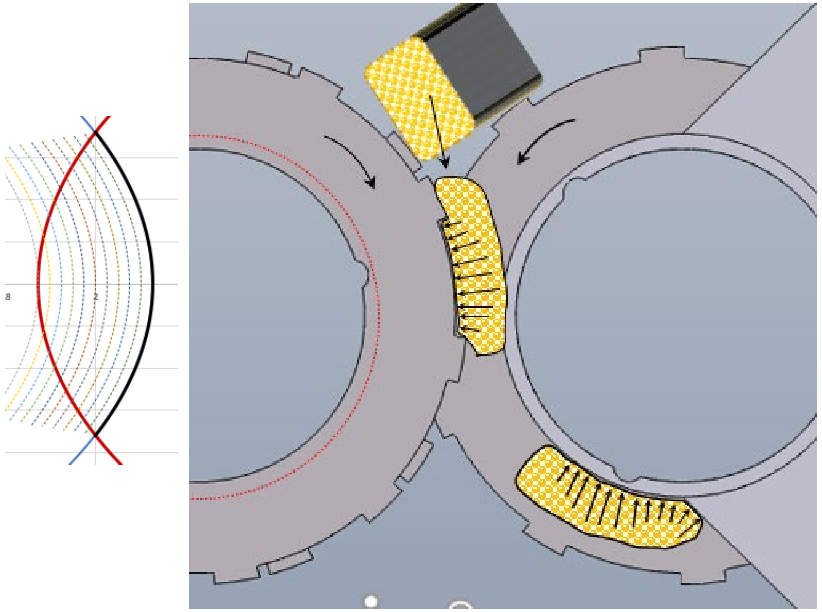


Calculated indentation depths as a function of load for elastic and plastic behavior

Second Step: Apply Processing Parameters to Model Kinematics of Components

Engineering Equations – relating constitutive wear rate to processing parameters

- **Work in-progress**
  - Calculate average load, W, applied to particles based on chip strength and ash content and chip size



$$\Delta V(r \rightarrow r+\Delta r) = \Delta Q_{ab}(m^3/particle) * \#(particles)$$

$$\Delta V = \frac{[(D/2)^2]}{2}(\alpha - \sin\alpha) * \mathcal{L}(\Delta\theta, r) * \mathcal{X} * 2\pi r \Delta r$$

$\#\,\text{particles} = \mathcal{X}(particles/m^2) * \Delta a$

$\Delta a = 2\pi\, r\Delta r$

$\#\,\text{particles} = \chi(particles/m^2) * 2\pi\, r\Delta r$

$\mathcal{X}$ = density of particles per unit area

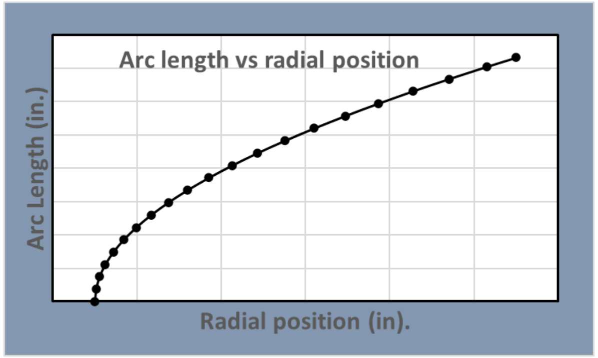
$$\Delta V(r \rightarrow r+\Delta r) = \frac{[(D/2)^2]}{2}(\alpha - \sin\alpha) * 2\pi r\mathcal{L}(\Delta\theta, r) * \mathcal{X} 2\pi r \Delta r$$

$$\Delta V(r \rightarrow r+\Delta r) = 2\pi r \Delta r \Delta_{\perp}$$

$$\Delta_{\perp} = \frac{[(D/2)^2]}{2}(\alpha - \sin\alpha) * 2\pi r\mathcal{L}(\Delta\theta, r) * \mathcal{X}$$

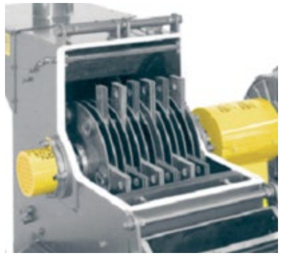
$$\alpha = 2\cos^{-1}\left(1 - \frac{2h}{D}\right)$$

$\mathcal{L}(\Delta\theta, r)$ = relative sliding distance between counter rotating cutters



Applications of Analytical Models

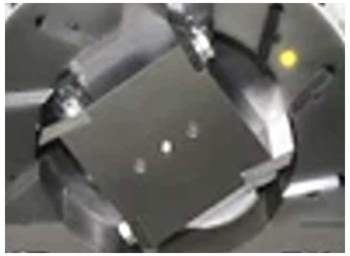
- **Hammer mill**



$$\Delta_{\perp} = \Delta Q_{erosion} * 2\pi r * \rho(r)$$

$$\Delta Q_{erosion} = \Delta Q_D + \Delta Q_C$$

- **Knife mill**



$$\Delta_{\perp} = \Delta Q_{abrasion} * \mathcal{X}$$

$$\Delta Q_{abrasion} = \frac{[(D/2)^2]}{2}(\alpha - \sin\alpha) * f(\Delta\theta, r)$$

- **Rotary Shear**

$$\Delta_{\perp} = \Delta Q_{abrasion} * \mathcal{X}$$

$$\Delta Q_{abrasion} = \frac{[(D/2)^2]}{2}(\alpha - \sin\alpha) * \mathcal{L}(\Delta\theta, r)$$

- **Biomass Conversion**
  - Predicting wear & sharpness of components - maintenance & replacement
  - Predicting performance (efficiency & quality)
  - Design of components shape & selection of materials of construction
  - Techno-economic analysis – ROI
  - Impact of feedstock variability on wear & performance

- **Wear in Alternative Comminution (Sizing) Operations**
  - MSW – design of comminution systems
  - Polymer/plastic recycling
  - Battery recycling
  - Ore processing
  - …..

Summary and Future Work

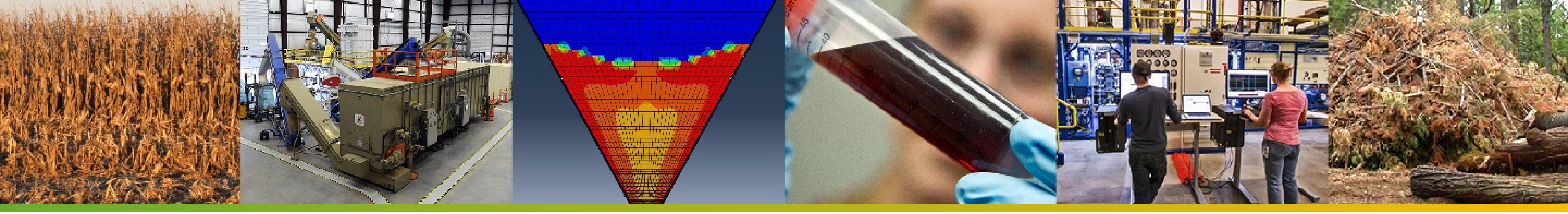
Technical Approach: ORNL, ANL, and INL, in collaboration with industrial partners (Forest Concepts, Eberbach, and coating vendors), are working on various biomass size reduction systems to

- fundamentally understand their wear mechanisms,
- develop advanced tool materials and/or designs,
- fabricate and test prototype high-performance tools, and
- generate predictive wear models.

Impact: Provide fundamental understanding of the wear mechanisms and recommend mitigations for improved economics by increasing the throughput and tool life and reducing the downtime and power consumption.

Future Work:

- Complete the current studies for knife mill and rotary shear with demonstration of improved economics and
- Identify other biomass processing systems that experience wear issues and apply the materials approach to address them.



Thank you

energy.gov/fcic

fcic
FEEDSTOCK-CONVERSION
INTERFACE CONSORTIUM