Identification of Critical Process Parameters for Knife Milling and Alternative Comminution Strategies

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Applied Materials Division

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Identification of Critical Process Parameters for Knife Milling and Alternative Comminution Strategies

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EXECUTIVE SUMMARY

An assessment of knife milling operations was performed to identify parameters that require consideration to model wear and degradation of knife blades. A quality-by-design (QbD) paradigm was followed to identify material and feedstock **attributes**, and processing **parameters** that impact the quality **attributes** of the blades used in the comminution of biomass into forms compatible with downstream operations. Based on analytical and experimental observations of knife and tool wear, a QbD model is proposed that considers three wear mechanisms (erosion, abrasion, and gouging) to predict volumetric wear of knife blades and sharpness. These factors, if properly applied, provide a science-based approach to predict the mechanical efficiency of the mill as a function of feedstock properties, knife blade material properties, and processing parameters (feed rate, speed, and design parameters).

1 BACKGROUND

The U.S. Department of Energy's Bioenergy Technologies Office supports activities to develop innovative technologies for converting biomass into usable products, fuels, and energy, including activities on Feedstock Supply & Logistics (FSL), Agal Biofuels, Sustainability, Analysis, and Conversion Technologies [1]. Recognizing the importance of pretreatment of biomass feedstocks on the development of value-added products [2–4], the Feedstock Conversion Interface Consortium (FCIC; <https://fcic.inl.gov>) develops first principles-based knowledge and tools to understand the effects of biomass properties and process variability on pretreatment operations required to transform biomass feedstocks from the physical state (coarse stalks, leaves, cobs bound up in bales) they are delivered to a biorefinery (e.g. ½ ton bales of corn stover) into loose product streams that are compatible with equipment used in low- or high-temperature conversion processes (Figure 1).

FIGURE 1 Illustration of physical form of corn stover feedstock in the field (left) and form required for conversion operations in a biorefinery

The FCIC is a collaborative and coordinated effort involving multi-disciplinary research teams representing nine national laboratories addressing different facets of research required to transform feedstock into forms that can be converted into useful bioproducts efficiently. It is organized into 8 collaborative tasks that address: feedstock variability, preprocessing, materials handling, materials of construction, high-temperature conversion, low-temperature conversion, crosscutting analyses, and data management [5]. The objective of the Materials of Construction task is to characterize, modeling, and test materials used in comminution of feedstocks to gain a fundamental understanding of failure and wear mechanisms, develop analytical tools to predict wear and establish material property specifications, select and evaluate candidate mitigations, and share the fundamental understanding and mitigations with the biomass industry. The knowledge and tools developed enable the rapid design and selection of materials that resist wear and maintain structural integrity, resulting in sustainable performance and improved product quality.

Task 1 currently focuses on issues related to wear and durability of components used in unit operations to pretreat feedstocks arriving from the field/forest to the entrance of biochemical or thermal reactors where the feedstocks are converted into useful products. Studies [6,7] have shown that mechanical wear can be significant, with wear clearly visible to the naked eye. The wear can add significant delays in processing feedstocks due to high downtimes to replace worn components, but also to clear jams that occur in milling units. Figure 2 illustrates different operations that are being considered for use to convert feedstock material into forms needed for low-temperature and high-temperature conversion processing. These operations include comminution/deconstruction (shredding, hammer milling, knife milling, rotary shearing) of corn stover and pine feedstocks, transport and binning (conveyors, augers, binning) of feedstocks, and conditioning/pretreatment (pug mill mixing, plug screw compressors, disk refining, and drying) of feedstock prior to entering chemical or thermal conversion units. Also shown in Figure 2, is a table that refers to CMA (critical material attribute), CPP (critical process parameter), and CQA (critical quality attribute) parameters that are used in science-based models to relate wear (CQA) to material properties (CMAs) of feedstock and materials of construction, and unit operational parameters (CPPs). The CMA, CPP, and CQA parameters are used to develop a quality-by-design, QbD approach to model the impact of feedstock and material properties, and, operational parameters on the quality (wear) attribute of critical components (e.g. hammers) during operation.

FIGURE 2 List of different operations used to pretreat biomass feedstocks prior to conversion to bioproducts, and typical QbD parameters required to model wear of comminution components.

This approach was successfully applied to model erosive wear of stage 1 hammers used to shred corn stover bales [8, 9] at the Idaho National Laboratory (INL) Process Development Unit (PDU). However, in late Q3 of FY2020, concerns over the quality and variability of the size and shape of hammer-milled corn-stover, the production of fines, and the impact it had on milling productivity resulted in a decision to focus on knife-milling as the primary size reduction process. A review [10] comparing different milling processes (hammer, knife, attrition, and ball)

supports this decision and provides an excellent overview of knife-milling operations. The report presented here provides details on efforts to document the operational characteristics (process parameters) of proposed knife-milling operations and contrast them with hammer milling with the goal of developing a QbD approach to provide an analytical model of knife mill wear and degradation.

2 RESULTS

2.1 Overview of Biomass Preprocessing

Preprocessing of biomass feedstocks involves a number of unit operations that involve mechanical operations that can result in wear of components [11]. These operations include **bale processing** (deconstruction/shredding of corn stover bound up into square/rectangular, or round bales weighing approximately ½ ton), and **size reduction** operations to yield loose, free flowing biomass that can be readily treated by downstream pretreatment and conversion/digestion processes. Additional processing steps are often used remove rock, gravel, sand and non-ferrous metallic contaminants and to classify/separate the biomass by size and anatomical fractions prior to size reduction operations [12]. Figure 3 illustrates the flow diagram of major preprocessing operations used in the comminution of corn stover feedstock. The operations shaded in blue represent those sensitive to mechanical wear phenomena that can degrade performance and productivity.

FIGURE 3 Major unit operations used in the comminution of corn stover feedstock - adapted from ref [13] & [14].

An example of bale processing equipment is shown in Figure 4. The bale processing units under consideration for biomass-to-fuel applications are usually based on designs developed for industrial (e.g. recycling) or agricultural (dispersion of feed) shredding operations. Typical rotational speeds vary from 100 rpm for recycling industries, to 300-600 rpm for feed applications to 1300-1800 rpm for high power mills [16]. The functional heads that perform the shredding can be sawed-tooth shaped as illustrated in Figure 4, narrow hammers, augers, or tines. Care must be taken to select heads that avoid breaking bales into large flakes that often cause surging of flow and plugging of downstream operations [11].

Figure 5 shows examples of different size reduction technologies that are under consideration. These include hammer-milling, knife milling, and rotary-shear milling. Of those shown in Figure 5, hammer mills (and shredders) are most commonly used for biomass size-reduction because of their high capacities and low cost. However, issues related to poor operation with high moisture feedstock, generation of fines, and poor control of the biomass size is raising concerns about the ability of hammer milling to meet efficiency and productivity goals and has fallen out-of-favor, leaving knife milling and/or rotary-shear milling as the primary technologies for size-reduction. While knife mills and rotary shear mills may have lower throughput, they are not as sensitive to moisture, generate less fines, and produce product with a narrower size distribution [11].

The remainder of this report focuses on knife milling operations – in particular on the development of a QbD approach to analytically predict wear and degradation of knife mill blades as functions of feedstock properties, blade properties, and process properties. The comminution mechanisms for rotary shearing and knife milling are the same – shearing of biomass. The main difference is the geometry – knife mills involve shearing between sets of blades that interact along a linear path, while rotary shear involve shearing between sets of circular rotating blades. As a result, the models developed for knife milling operations (e.g. constitutive equations that relate volumetric wear to material, feedstock, and operational parameters, e.g. speed), should also be applicable to rotary shear operations.

FIGURE 4 Example of bale processing (shredding) equipment [15]

FIGURE 5 Different milling concepts for size reduction of biomass feedstock.

2.2 Knife Milling Geometry

Knife milling is used in a wide variety of industries for reducing the size of product to a desired size. Examples include **processing** of foods, pharmaceuticals, chemicals & additives, **recycling** of plastics & polymers, food & animal wastes, wood, rubber, and other industrial wastes, and **manufacturing** of wood products – e.g. wood planers, and chippers/canters used to fabricate board products from logs. Figure 6 shows a generic schematic of a knife mill adapted from ref [17]. Feedstock (from a shredder) enters at the top and is entrained in the milling/knife section that consists of a set of longitudinal knives mounted on rotating arms, and stationary knives. As the knives rotate, material trapped between the leading edges of the rotating knife and stationary knives is compressed and sheared. Fragments of sheared material that are small enough will fall through the sizing screen, otherwise they are transported back through the mill where they undergo further shearing.

Figure 6 Illustration of knife milling operations (adapted from [17]).

Images removed due to copyright policy – Please refer to references 18 and 19 for images of lab-scale and production scale knife-milling systems

FIGURE 7 Examples [18, 19] of lab-scale and industrial knife mills.

1 kg, while the industrial Jordan units are designed for continuous high-capacity operation. Other major manufacturers of knife milling equipment include Warren & Baerg, Vermeer, and Hay Buster [16].

Examples of actual knife milling equipment are shown in Figure 7 – one is a lab-scale unit (left), Wiley 4 mill [18], used for experimental small scale studies of knife milling operations, while the other is an industrial scale unit manufactured by Jordan reduction Solutions [19]. The Wiley mill is limited to processing small quantities of biomass, typically less than

2.3 Size Reduction Mechanism

Size reduction of biomass is not new – it has been used for millennia in the processing of grains for food. Size reduction (comminution) on an industrial scale, however, is relatively new. Recent reviews of biomass comminution identified several different mechanisms that can take place during size reduction operations [20, 21, 22, 23, 24]. These include cutting, shearing, tearing, impact stress, compression, and friction (as in disk refining – a form of shearing).

Figure 8 (adapted from ref [21]) illustrates mechanisms associated with knife milling operations. The top portions of Figure 8 illustrate the mechanisms involved in cutting, shearing and tearing, while the bottom images illustrate the resulting shapes.

Cutting is differentiated from shearing by the manner in which deformation occurs. During cutting, deformation and fracture occurs locally just ahead of the knife tip, while, with shearing, deformation occurs over the entire cross section of the biomass material. Sharp cutting tools (knives) typically have small wedge angles (less than 30°) that tend to concentrate forces just ahead of the tip. Shearing tools have large wedge angles (75 to 90°) that result in a deformation zone that extends over the entire cross section [23, 24]. The combination of tensile stress with torsion of the material results in tearing.

Figure 8 Illustration of comminution mechanisms associated with knife milling operations [21].

Mechanical wear of the leading edge of the knife tool (either cutting or shearing) will lead to blunting/rounding of the tip [25, 26]. Semi-intuitively, any process that rounds, or blunts the leading edge of a knife will decrease the average or peak Hertzian contact stress [27] imparted from the knife to the feedstock, thereby providing insufficient force to fracture/cut/shear the biomass feedstock. The worn cutting/shearing edges will therefore require a larger torque (power) to generate the required forces to fracture/shear the biomass feedstock. Alternatively, if the material does not undergo complete cutting, it will need clear the screen, and will recirculate back through the mill decreasing throughput and efficiency.

Examples of wear in knife milling operations can be found in recent articles prepared by Oak Ridge National Laboratory (ORNL) (Qu, Blau, and Keiser – [25, 26]). Additional examples of wear in milling operations utilizing tooling for wood working applications (wood planing, chipper/canter, timber cutting) are available in open literature [28, 29, 30, 31, 32]. Figure 9 shows a series of SEM images from an article [29] by Ghosh et. al. who studied knife edge recession (wear) of knives used in industrial chipper-canter operations to process small diameter logs into finished lumber. Four different wear mechanisms were observed – **abrasion (9a)**, **chipping (9b)**, **cracking (9c)**, and **deformation (9d)**. Ghosh also noted the

FIGURE 9 SEM micrographs of worn chipper-canter knives illustrating different modes of wear observed during operation: a - abrasion of rake face, b - edge chipping on chipper blade, c - cracking on canter blade, and, d - deformation of chipping knife [29 – with permission].

presence of a ‘denting/fracture’ mode wear on the tool edge attributed to sudden changes in the log density when knots, which are considerably denser than the surrounding material, are encountered.

In a separate article [30] on wear of chipper-canter tools, Heidari et. al. observed **micro-ploughing, chipping, impact, cracking, and deformation**, with abrasion, chipping, and cracking being the dominant modes of wear along the edge. Tribochemical wear was also observed, but not along the knife edge.

The ORNL studies [26] identified a number of damage modes that contribute to wear of knives used in biomass milling operations. These include **impact wear** along knife edges (exemplified by edge breakage and/or chipping), **sliding wear** arising from firmly-embedded, hard, abrasive particles (2-body abrasion), **abrasive wear** (3-body) by loose hard particles, **polishing wear** by small loose particles, and **tribochemical/corrosion**. Figure 10 [26] summarizes the different wear modes proposed by ORNL. Two-body abrasion is dominant for new blades, but as wear occurs, and the clearance between the two blades (stationary and rotating) opens up, movement of loose particles between the blades along the cutting edge can lead to enhanced 3-body wear.

FIGURE 10 Summary of active wear modes in knife mills [courtesy ORNL - 26].

2.4 QbD Modeling of Wear Processes in Knife-Milling

A quality-by-design (QbD) approach is being by the FCIC to organize and understand how the different unit operations associated with harvesting, transporting, storing, preprocessing, pretreating, and conversion of biomass feedstocks affect each other and overall value chain. Task 1.3 of the Materials of Construction task is adopting the QbD approach and is developing analytical tools to predict wear, establish material property specifications, and select and evaluate candidate wear mitigation approaches. This approach, shown in Figure 11 [35], applied an analytical model of wear due to erosion to predict wear of components used in **hammer** milling operations. The QbD model makes a simple assumption that the volume of material removed is the product a volumetric wear rate (volume of material removed per unit mass of incident ash) and the amount of ash (mass) impacting the component. The volumetric wear rate is dependent on ash properties, material properties and process parameters (Equation 1):

$$\Delta V_T = \Delta Q_T * \Delta m \quad (1)$$

where:

ΔV_T volume eroded per revolution of the hammer (m^3/rev)

ΔQ particle erosion wear rate ($\text{m}^3/\text{kg}_{\text{ash}}$) – Ben-Ami model [36]

Δm mass of particles that impact the leading edge of the hammer, Δm is dependent on the local density of ash.

The approach used in Equation 1 separates the analysis into two parameters, the first, ΔQ , relates the volumetric wear rate to **material attributes** (MAs), and **process parameters** (PPs), while the second, Δm , provides unit-specific **process parameters** (speed, impingement angle). A constitutive equation developed by Ben-Ami et. al. [36] was used to model the impact of input and process parameters on wear. The constitutive equation developed by Ben-Ami is of the form shown below [9, 36].

FIGURE 11 QbD process used to model wear of hammer mill components as functions of feedstock properties, hammer properties, and operational process parameters [35].

$$\Delta Q_T = \Delta Q_D + \Delta Q_C \quad (2)$$

where:

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

and,

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

Material attributes include properties of the feedstock such as the density, size and shape of biomass ash particles, and composition (which determines particles mass density of individual particles, ρ_p), and properties of the comminution component (in particular **hardness, H, fracture toughness, R, and Coffin-Manson fatigue ductility parameters – ϵ_f and b**). Process parameters include operational specific parameters such speed/rotational speed, U, geometrical dimensions, biomass feed rate, ash content, ash residence time, and run time (total number of revolutions) that are used to calculate the total mass of ash that impacts a local segment of the

component. With appropriate assumptions for the density, ρ , of inorganic ash within a specific mill, particle residence time, geometrical shape and dimensions, the QbD process was able to analytically predict changes in the shape of the leading face of rotating hammers. A list of material attributes, process parameters and quality attributes required and developed for the hammer mill QbD analysis are given in Table 1. A similar QbD approach is currently being developed to model mechanical wear of critical components used in shredding and knife milling operations. The process parameters are highly specific to unit operation and geometry of the contact zone and it highly likely that a new set of process parameters will be required to analyze wear and degradation/blunting of the knife edges. degradation of knife mill components.

2.5 Physical Model of Knife Milling

Based on observations of knife blade wear presented above and knife mill geometries, a physical model of knife edge wear can be proposed as shown in Figure 12. Shredded biomass feedstock containing variable amounts of inorganic ash enters the mill (ranging from a few percent to upwards of 10%). The mill contains two sets of knife blades (stationary and rotating). The stationary blades are mounted on the outer periphery of the milling drum, while the rotating blades are mounted on an internal hub/drum that rotates at speeds ranging from 600 rpm to 1800 rpm depending on the size of the mill. Shredded material fed into the mill is trapped between the leading edge of a stationary blade/tool and a rotating blade as they come in close proximity to one another. The gap between the two blades at closest approach is on the order of a $\frac{1}{2}$ to 1 mm. Materials trapped between blades is compressed, held firmly and undergoes size reduction by cutting, shearing, or tearing (Figure 8). Material that is sufficiently small will pass through openings in the sizing screen and exit the mill. Material too large to pass through the screen rotates back through the mill. Hard, particulate matter in the form of extrinsic inorganic mineral ash moving freely, or, attached to the external surfaces of pieces of organic feedstock, as well as intrinsic biogenic ash species [37]. These particles, if sufficiently hard, can erode and alter the shape (sharpness) of the leading edge and open the gap between rotating and stationary blades – resulting in a decrease in the force and stresses applied at the pinching point. Wear of the blades can occur by a number of interactions between inorganic mineral compounds, and knife edge surfaces and are summarized in Table 2. For **rotating blades**, the dominant mechanisms include erosion, gouging (a form of erosion), and abrasion. For **stationary/fixed blades**, the dominant mechanisms include gouging,

TABLE 1 List of feedstock attributes, material attributes, process parameters, and quality attributes used to model wear of hammers

Symbol	Attribute
Feedstock Properties	
d	particle diameter
η	particle shape factor
ρ	particle density
Hammer Properties	
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 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	Hammer Leading Edge Angle
τ	Residence time
FR	Feed Rate
AC	Ash Content
N	Rotational Speed
No	Bale Ash Density
λ	Exponential constant
Output (Quality Attribute)	
ΔQ	Wear Rate ($\text{mm}^3/\text{kg}_{\text{particles}}$)

FIGURE 12 Illustration of biomass cutting/shearing during biomass knife milling. Hard abrasive inorganic and biogenic particles impact leading edges of knives resulting in erosive and abrasive wear.

TABLE 2 Dominant wear mechanisms on knife mill blades

Rotating Knives	Stationary Knives
Erosive wear of rake face and leading edge by extrinsic inorganic particles	No erosion – fixed blades do not move and impact ‘free’ inorganic particles
Gouging/macro-deformation (erosion) by large inorganic particles (much larger than the knife edge thickness)	Gouging/macro-deformation (erosion) by large inorganic particles (much larger than the knife edge thickness)
Abrasive wear by inorganic particles adhering to organic biomass particulates	Abrasive wear by inorganic particles adhering to organic biomass particulates
Abrasive wear by intrinsic biogenic particles interior to organic biomass particulates	Abrasive wear by intrinsic biogenic particles interior to organic biomass particulates

and abrasion. **Erosion** of rotating knives that operate at speeds sufficient to create high speed impacts between the blade tip and ‘free’ inorganic particles, occurs continuously during each 360° rotation of the knife hub. Erosion is not considered for stationary blades since the blade is fixed, not moving, and hence does not generate a relative speed/velocity between the blade and the free inorganic particles sufficient to induce erosion. Gouging (a form of impact/erosive wear) occurs at the tip of a blade where the particle size, mass, and velocity are sufficient to deform/chip the thin region along the blade tip. **Gouging** of rotating blades can occur continuously, while gouging of the fixed blades takes place when blade tips are in close proximity to one another. **Abrasion**, a process where material is removed or displaced by hard particles sliding along a surface, occurs on the rake face and leading edge of rotating and stationary blades. The particles can be inorganic particles that adhere to surfaces of organic biomass particulates, or intrinsic biogenic particles inside of organic particulates. Abrasion can occur on both rotating and stationary blades on rake faces and leading edges.

2.6 Mathematical Models of Wear

The QbD approach identified to model wear and blunting of knife milling blades follows the approach developed for predicting wear of hammermill hammers (Equation 1) where the volumetric wear per revolution is proportional to a wear rate (volume per unit mass) and the mass of erodent material. The process involves two steps:

- Development of constitutive relations that relate volumetric wear to feedstock properties, material properties, and generic process parameters (speed, impingement angle) – ΔQ
- Derivation of engineering formula to calculate the mass of material (in this case inorganic mineral ash) that a knife surface is exposed per revolution of the knife mill – Δm .

The constitutive equations depend on the wear mechanism: erosion, abrasion, or gouging. Equations for erosive processes that have already been developed for QbD analysis of hammer mill wear will be used for the knife wear analysis. Table 1 provides a list of critical material properties required to calculate the erosion rate (volume per unit mass of ash), and includes attributes such as the particle size, density, and shape, material hardness, toughness, and fatigue ductility. Constitutive equations for abrasive wear and gouging are not yet available for analysis of knife wear, however, numerous models [38] are available in the open literature and will be adapted for the knife blade analysis.

Engineering calculations of the mass of particles incident on the knife edges will be specific to the geometry of the knives and mill. Table 1 provides a list of critical process parameters that are needed to determine the density and speeds of particles impinging on the leading face of the stage 1 hammer mill used in the INL PDU facility. The list includes information on the feed rate, the ash content of the feed material, geometry of the hammer, residence time of particles in the mill, and rotational speed.

Examples of the QbD approach to model results of wear simulation studies of erosion by corn stover and pine feedstocks have been reported previously [35]. The same approach was recently used to predict changes in the shape of actual hammers used to mill corn stover at the INL PDU [9].

TABLE 3 Summary of QbD Wear Model for Knife Milling

$\Delta V = \Delta Q * \Delta m$			Eq 1
Hammer-Milling			
	$\Delta Q_{erosion}$	Ben-Ami erosion model [36]	Eq. 2-4
	Δm	based on generic horizontal hammer mill design	[9]
Knife-Milling			
<i>erosion</i>		erosion operable over 360° of rotation	
	$\Delta Q_{erosion}$	Ben-Ami erosion model [36]	Eq. 2-4
	Δm	based on a TBD horizontal knife mill design - comparable to hammer milling - focus on 'free' floating extrinsic inorganics	TBD
<i>abrasion</i>		abrasion operable when roating/fixed knife edges are in close proximity	
	$\Delta Q_{abrasion}$	Archard wear abrasion model [38]	TBD
	Δm	engineering relations under formulation	
<i>gouging</i>			
	$\Delta Q_{gouging}$	physical model under development	TBD
	Δm	engineering relations under formulation	TBD

For knife milling, three different forms of constitutive relationships will be applied – erosion abrasion, and gouging. Table 3 summarizes the QbD approaches that have been developed for hammer-milling, and those that are, or will be developed, for knife-milling and the status of development. The overall volumetric wear (per revolution) will be given as:

$$\Delta V_{Knife} = \Delta V_{erosion} + \Delta V_{abrasion} + \Delta V_{gouging} \quad (5)$$

keeping in mind that each mechanism on the right-hand side of Equation 6 is not active over the entire rotation cycle – erosion occurs over the entire 360° of rotation, while abrasion and gouging occur only when blade tips are in close proximity to one another.

Selection of a constitutive equation for abrasive wear is not complete, we expect it will follow a general Archard type constitutive model. In its simplest form, the Archard equation relates the volume worn from a surface (V) to the load (W) applied to the ash/mineral particles, sliding distance (L), and material hardness (H):

$$V = K * \frac{W \times L}{H} \quad (6)$$

where K is a parameter dependent on the wear mechanism – 2-body/3-body abrasion of ductile or brittle materials, and the presence of fatigue, corrosion, or oxidation, and material attributes and process parameters. K can be predicted analytically [38], or, more commonly determined experimentally. For example, a well-known solution for K for adhesive wear [39] yields K= 1/3. For abrasive wear of ductile and brittle materials, analytical solutions for K depend on particle

shape, as well as toughness and elastic modulus [38]. Effort is currently underway to determine which analytical solution for K is applicable for modeling abrasive wear. When completed, the results from the analytical modeling will be compared to ongoing labscale wear tests at Argonne and Oak Ridge to validate the analytical values of K . This process will follow the QbD process illustrated in Figure 13 for modeling knife wear with appropriate changes to the process parameters to accommodate the test conditions and geometries used during the labscale simulation studies.

FIGURE 13 Illustration of QbD approach under development to analytically model mechanical wear of knives used to mill biomass.

Figure 13 illustrates the knife wear processes that are/will be modeled and the material attributes and process parameters that will affect the quality attributes of biomass exiting the mill. A summary of the attributes and parameters that will be incorporated into the QbD model is presented in Table 4. The list in Table 4 is preliminary and is based in part on the parameters that were considered in the QbD model of hammer milling operations. The table also indicates which of the three wear mechanisms (erosion, abrasion, gouging) will require input for each attribute. Since erosion processes have already been modeled (for hammer milling applications), the list is well established. The lists for abrasion and gouging are preliminary and will depend on the constitutive models selected for abrasion and gouging which are still under development.

TABLE 4 List of feedstock attributes, material attributes, process parameters, and quality attributes required to model wear of knife blades

Symbol	Attribute	Erosion	Abrasion	Gouging
Feedstock Properties				
d	particle diameter	•	•	TBD
η	particle shape factor	•	•	TBD
ρ	particle density	•	•	TBD
β	Bulk modulus	NA	•	TBD
E	Young's modulus	NA	•	TBD
τ_s	Shear strength	NA	•	TBD
Knife Properties				
b	Manson-Coffin fatigue ductility exponent	•	Maybe	TBD
ϵ_f	Manson-Coffin fatigue ductility coefficient	•	Maybe	TBD
E	target material Young's modulus	•	Probable	TBD
H	target material hardness	•	•	TBD
K_c	critical stress intensity factor	•	Probable	TBD
R	target material fracture toughness	•	Probable	TBD
Process Parameters				
U	particle impact velocity	•	Probable	TBD
α	particle impingement angle	•	TBD	TBD
ro	Outer radius of feedstock zone	•	•	TBD
ri	Inner radius of feedstock zone	•	•	TBD
L	Length of hammer mill zone	•	•	TBD
φ	Tool Leading Edge Angle	•	•	TBD
τ	Residence time	•	•	TBD
FR	Feed Rate	•	•	TBD
AC	Ash Content	•	•	TBD
N	Rotational Speed	•	•	TBD
No	Bale Ash Density	•	Maybe	TBD
λ	Exponential constant	•	•	TBD
Output (Quality Attribute)				
ΔQ	Wear Rate ($\text{mm}^3/\text{kg}_{\text{particles}}$)	•	•	TBD
Δ_l	Rake face recession	•	TBD	TBD
ER	Edge Recession	TBD	TBD	TBD

3 CONCLUSION

The objective of Task 1.3 is the development of a semi-mechanistic models of wear capable of predict wear and degradation of mechanical components (e.g. hammers and knives) used in the comminution of biomass feedstocks into forms compatible with conversion processes. The task originally focused on modeling hammer milling operations, but following a change in direction in FY20 Q3, the task shifted its attention to knife milling operations. Analysis of the wear phenomena observed to occur in sibling operations such as wood planning, recycling, agricultural feed processing, etc., indicates the QbD approach developed for hammer milling [9] does not capture all of the wear mechanisms present in knife mills, nor does it capture differences in processing parameters.

An updated QbD approach was developed for knife milling operations based on designs of commercial knife mills under consideration for evaluation at INL and the National Renewable Energy Laboratory (NREL). Effort is currently underway to develop constitutive equations to calculate volumetric wear rates per unit mass of erodent (inorganic ash) for erosive, abrasive, and gouging wear modes. Engineering equations will be formulated in FY21 to determine the mass of erodent that impact knives during each revolution of a blade. Together, the wear rates and mass flux will be used to calculate the volumetric wear, recession of the cutting edge – information that can guide development of codes to predict milling efficiency and performance.

4 FUTURE DIRECTIONS

- Development and selection of constitutive equations for abrasion and gouging wear phenomena
- Formulation of engineering equations to predict flow/impact of biomass chips and ash incident on knife edges
- Formulation of engineering equations to model forces between biomass chips and knife surfaces/edges as chips are compressed/pinched in the cutting zone.

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