Improving knife milling performance for biomass preprocessing by using advanced blade materials

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Tomas Grejtak[1], Jeffrey A. Lacey[2], Miranda W. Kuns[2], Damon S. Hartley[3], David N. Thompson[4], George Fenske[5], Oyelayo O. Ajayi[5], Jun Qu[1,*]

[1]Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN USA
[2]Biological and Chemical Processing Department, Idaho National Laboratory, Idaho Falls, ID USA
[3]Operations Research and Analysis, Idaho National Laboratory, Idaho Falls, ID USA
[4]Biomass Characterization, Idaho National Laboratory, Idaho Falls, ID USA
[5]Applied Materials Division, Argonne National Laboratory, Lemont, IL USA

Abstract

Mechanical preprocessing of biomass, including size reduction, is a crucial step in converting biomass into biofuel. However, the feedstock inevitably contains abrasive intrinsic and extrinsic inorganics that may cause excessive tool wear in preprocessing. This work demonstrates that the performance of a knife mill can be significantly improved by applying a more wear-resistant blade material. A series of full-scale knife mill testing were performed for size reduction of forest residue using blades of tungsten carbide (WC-Co), iron-borided tool steel, and diamond-like carbon (DLC) coated tool steel. Blade material loss was quantified in correlation to the amount of feedstock processed and wear mechanisms were investigated via worn surface characterization. While the thin DLC coating was removed quickly, the WC-Co and iron-borided blades improved the tool life by 8X and 3X compared with the M2 tool steel blades (baseline), respectively, when compared with the commonly used tool steel blades. In addition, the in-situ throughput and power consumption measurements provided additional insights. The WC-Co and iron-borided blades maintained ~3X higher throughput than the baseline blades by the end of the test with lower normalized power consumption. The experimental results were then used as input for a techno-economic analysis, which demonstrated that the more wear resistant blades could reduce the knife milling cost by $2-3 per ton of biomass processed with downtime reduced by 65-85%.

Keywords

biomass size reduction, knife mill, blade wear, throughput

Corresponding Author

Jun Qu
phone: (865) 576-9304
email: qujn@ornl.gov

Nomenclature

gap_o	initial gap distance in mm;
gap_i	evolving gap distance in mm;
d	blade edge recession in mm;
V_{loss}	volume loss of the blade tip in mm^3;
ar	wear recession of a rotary blade in mm;
as	wear recession of a stationary blade in mm;
θ	blade tip angle in degrees;
w	blade width in mm;
V_r	volume loss of the rotary blade tip in mm^3;
V_s	volume loss of the stationary blade tip in mm^3;
A_u	blade tip area of the unworn blade in mm^2;
A_w	blade tip area of the worn blade in mm^2;
A	worn blade tip area in mm^2;
x	blade tip region used for determination of the worn area A in mm;
Z_u	height of the unworn blade tip along a region x in mm;
Z_w	height of the worn blade tip along a region x in mm;

1. Introduction

Biomass is a renewable source of energy that has a potential to reduce dependency on fossil fuels and, overall, positively impact the environmental sustainability[1–3]. The most common sources of biomass-derived energy are agricultural plants, forest residues, microalgae and municipal solid waste[3–5]. The biggest challenges that bio-energy faces in expansion include lowering the production cost and increasing in productivity[2].

Mechanical biomass preprocessing, such as size reduction, is an important step in converting biomass into biofuel[6]. Reducing biomass size results in densification which improves its handling, packing, transportation and biodegradability [7]. Traditionally, griding of biomass is enabled by specialized mills such as knife mill, hammer mill, ball mill, attrition mill or shredders[6], [8]. These pre-processing tools have certain advantages and disadvantages. Hammer mills offer specific benefits such as low cost or ability to process a wide range of biomass feedstock, however, they are not suitable for biomass with high moisture[9], [10]. Ball mills have been shown to be effective in preprocessing the biomass for fermentation and pyrolysis by decreasing the crystallinity of cellulose[11], [12] although controlling the particle size can be challenging[13]. Significant research efforts have focused on optimizing shredders. A new rotary bypass shear mill (Crumbler™) developed by Forest Concepts, LLC significantly reduces the power consumption and is well adapted for high moisture biomass[6], [14]. Disadvantages of rotary bypass shear mill are relatively low throughput and inability to reduce the biomass to < 1mm[6]. Knife mill is also used for biomass commination due to its favorable characteristics such as lower power consumption[15], improved particle flowability and narrower size distribution[16]. It is typically utilized for biomass with a moisture up to 15%[8]. In a knife mill, the biomass is ground by a shearing action between stationary and rotary knives[8] and the milling performance depends on many factors such as the number of knives, milling speed, particle size requirements, clearance (gap) between knives, and knife bevel angle[17], [18]. However, critical components of a knife mill are subjected to a high wear and damage caused by inorganic contaminants contained in biomass called ash [19]. These inorganics could either be an inherent part of biomass as they are contained inside of plants cell (intrinsic ash) or introduced by soil contaminant (extrinsic ash) during harvesting[20]. Studies showed that feedstock containing a high concentration of ash causes an excessive wear and damage of a ring and roller in ring die mills[21], screw press in briquetting extruder[22], grinder blades in hammer mills[10] and cutters in rotary shear comminution systems[14]. Comprehensive characterization of biomass ash by Lee et al.[23] revealed that the inorganic particles are dominated by quartz and their size ranges from smaller particles of ~tens of microns to larger particles of ~hundreds of microns. Experimental work by Lacey et al.[19] demonstrated that the wear of steel material increases with increasing ash content. Several methods have been developed to remove the ash from the biomass in order to minimize the impact of the inorganics on wear and damage of pre-processing tools such as mechanical separation (size separation and air classification) or chemical preprocessing (dilute acid leaching or water washing)[20]. However, additional biomass preprocessing increases the overall operation cost.

This paper demonstrates that the performance and durability of a knife mill for biomass preprocessing can be significantly enhanced by applying wear resistant blade materials. Our comprehensive analysis of the experiments performed on Eberbach knife mill include wear mechanisms of candidate blades, biomass particle size distribution, feedstock throughput, and power consumption. Moreover, a techno-economic analysis was conducted to elucidate the economic benefits from utilizing the advanced blade materials. This work demonstrates that applying more wear resistant blade materials significantly improves the durability and the performance of a knife milling operation and the findings from this work could be used as guidelines for improving the efficiency and reducing the cost for biomass preprocessing.

2. Materials and methods

2.1. Knife material

In order to select candidate materials for knife mill blades, bench-scale abrasive wear testing was conducted on a variety of steel alloys, composites, coatings, and surface treatments using the standard ASTM G174 loop abrasion test [24]. The results showed that iron boriding case hardening, diamond-like-carbon (DLC) coating, and tungsten carbide (WC-Co, C2 grade with submicron WC grains, containing 10 wt.% Co) have significantly higher wear resistance than the selected tool steels (hardened to HRC 60) that are typically used for knife mill blades, as shown in Table 1 and Figure S1; therefore, these materials were selected to fabricate candidate blades to be tested in an actual knife mill. Although iron borided D2 tool steel has very similar abrasion wear rates as the M2 tool steel, it was selected as a candidate surface treatment due its higher erosion resistance which was determined via sandblasting testing, (see supplementary Table S1). Moreover, monolithic D2 tool steel blade was available for iron boriding surface treatment at the time. Detailed experimental procedure of the loop abrasion wear test as well as sandblasting results are described in the supplementary. The baseline blades used in the knife mill testing were made of AISI M2 tool steel. One set of M2 tool steel blades was coated with a ~2 µm thick DLC coating via plasma-enhanced chemical vapor deposition (PE-CVD, TS NCT, Kennebunk, ME, USA). Another set of D2 tool steel blades was treated with iron boriding resulting in a ~175 µm hardened layer (IBC Coatings Technologies, Lebanon, IN, USA). The last set of the blades was assembled with WC-Co inserts (Eberbach Corporation, Belleville, MI, USA).

Table 1. Properties of the selected blade materials

Blade material	Layer thickness (µm)	Vickers hardness (HV)	Wear rate (mm^3/(N-m))
M2 tool steel	-	983 ± 80	(5.3 ± 0.16)x10^{-4}
D2 tool steel	-	931 ± 110	(8.6 ± 0.66)x10^{-4}
DLC-coated M2 tool steel	~2	1380 ± 268	(5.3 ± 0.44)x^{-7}
Iron-borided D2 tool steel	~150	1569 ± 107	(5.6 ± 0.52)x^{-4}
WC-Co	-	1567 ± 108	(6.8E ± 0.84)x^{-5}

2.2. Feedstock material

The feedstock used for testing was based of material that is common for industrial use. Loblolly Pine horizontal 2" chipped material used in this study was obtained from FTX Consulting (Colleton, SC, USA) and stored outdoors until needed. The material was hand sorted into the following anatomical fractions: needles, bark, twigs/branches, cambium, and white wood. Twigs/branches were smaller in diameter and at least partially covered with bark. Cambium was defined as any wood chip that had a smooth surface where bark was once attached. White wood was defined as wood chips from the interior of the tree. The feedstock was first hammer milled using a ¼ inch (6.35 mm) screen and then dried to 11% moisture content before been placed into a super sack. The woodchip particle sizes varied between 0.1 and 4.5 mm with an average of 0.7 mm. The detailed particle size distribution is shown in Figure S2. On average, the feedstock contained approximately 8.8 wt.% of ash.

2.3. Knife mill testing

Experimental measurements to determine the wear properties of the candidate blade materials and their milling efficiency were performed on a commercial knife milling unit – Eberbach knife mill Model 3803 (Eberbach Corporation, Belleville, MI, USA), Figure 1. This knife mill configuration consists of six stationary (fixed) blades and six rotary blades mounted on a rotary shaft with a rotational speed of 800 RPM. Size of the screen was 2 mm. During experiment runs feedstock was loaded by rotating through three super sacks of biomass material. Biomass was loaded into a container, weighed and then metered into the grinder using an Eberbach cone feeder (auto feeder). The biomass was fed into the grinder to keep the hoper full and, as a result, different feed rates were observed, as shown in Table 2, because wear-resistant blades allowed higher feed rates. After four hours of run time the mill was stopped, clean, and left to cool down. The total amount of processed feedstock and processing time for each set of blades are shown in Table 2.

Three knife mill experiments were conducted, each using a different blade material: M2 tool steel blades with DLC coating, D2 tool steel blades with iron boriding, and WC-Co inserts mounted on tool steel bases. The cutting surface of the blades was approximately 4” (101.6 mm) wide and the cutting tip angle was 51°. Prior to the knife mill testing, each blade was sonicated with RBS 35 Detergent Concentrate (Thermo Scientific, Rockford, IL, USA) and dried in an oven at 80°C overnight.

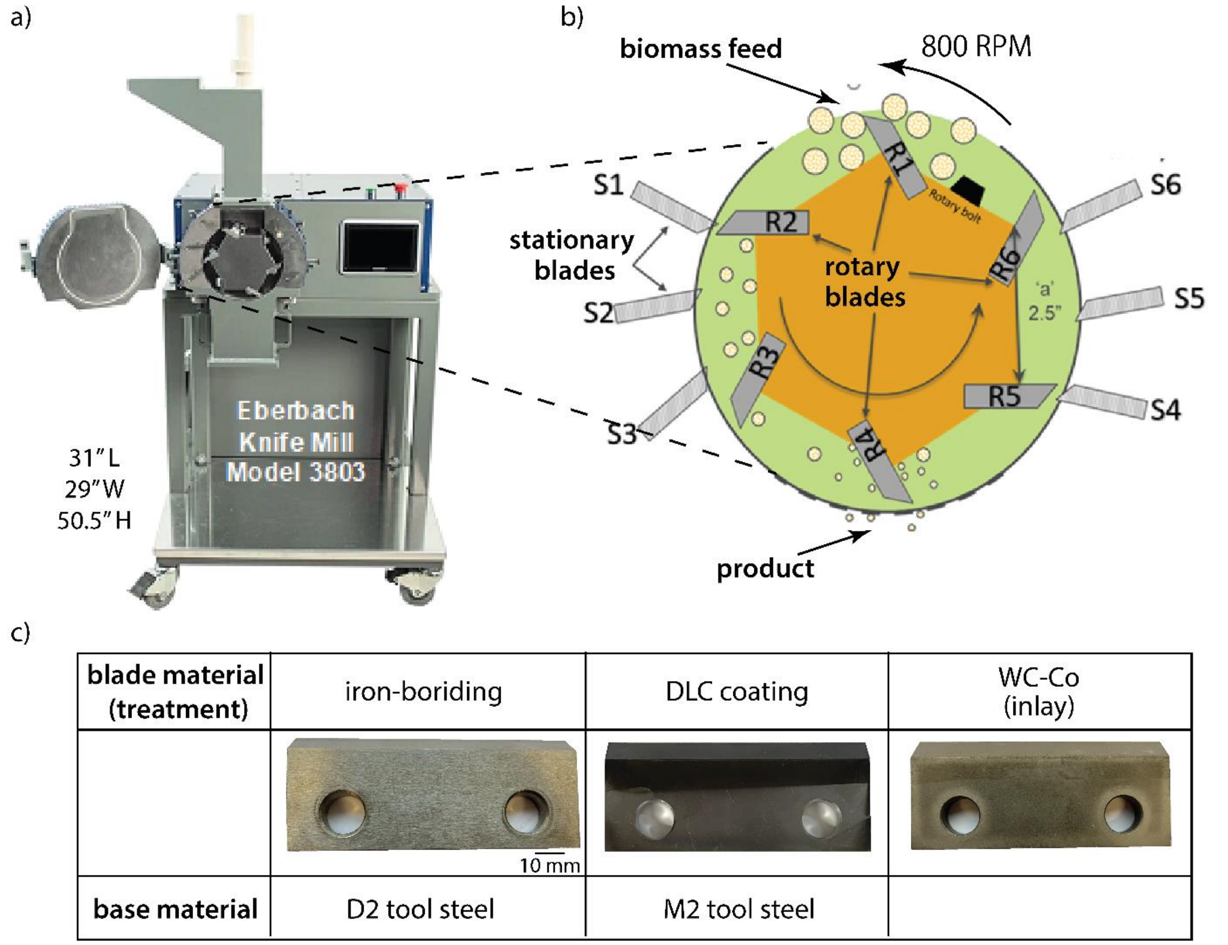

Figure 1. Experimental setup. a) Knife mill used in the experiments. b) Schematic of a milling procedure depicting an interaction between stationary, rotary blades and feedstock. c) Images of the blades.

Table 2. Total amount of feedstock processed and average feed rate for each blade material in the knife mill test.

Blade material	Amount of feedstock processed (kg)	Average feed rate (g/min)	Total milling time (hours)
DLC (M2 tool steel)	195	203	16
Iron-borided (D2 tool steel)	197	193	17
WC-Co (tool steel)	218	302	12

2.4. Wear measurements of blades

Wear performance of tested blade materials was determined by measuring the evolving gap between the stationary and rotary blades during knife milling using a feeler gauge, Figure 2. This method allows to determine the wear (linear) recession of a pair of rotary and stationary blades by tracking the increasing distance between the opposite blade tips. The gap was measured between each stationary and rotary blade pair and the resulting gap was determined as an average of a total of 36 measurements (6 stationary blades paired with 6 rotary blades). In order to determine a relative wear of the blades, the initial gap (gap_o) was measured prior to the testing. During the milling operation, the knife mill was paused at certain time intervals and the gap measurement was taken to determine the evolving gap (gap_i). The actual blade edge recession (d) due to wear is the difference between the evolving gap and the initial gap: $d = gap_i - gap_o$, which is then converted to a volume loss, V_{loss} as:

$$V_{loss} = (ar^2 + as^2) * tan(\theta) * \frac{w}{2}, \quad (1)$$

where *ar* and *as* are wear recessions of rotary and stationary blades, respectively, *w* is the width of the blade edge and θ is an angle of the blade tip. The values of *ar* and *as* in Eq. 1 were determined as ratios of average volume loss of the rotary, *Vr*, and stationary, *Vs* blades, respectively, over the sum of the average volume loss, *Vr*+*Vs*, measured with the 3D confocal microscope in Section 3.1, Figure 5b. More details about the gap measurement calculations are highlighted in the supplementary.

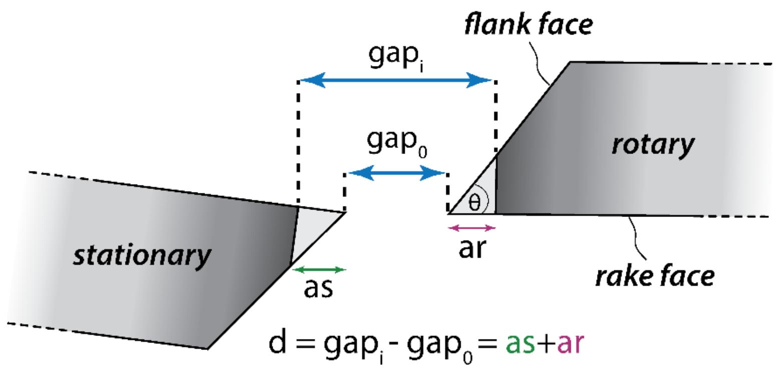

Figure 2. Schematic of a recessive gap measurement between a stationary and a rotary blade.

The volumetric loss of the blades was also determined by measuring the surface profile of the tips utilizing 3D laser confocal microscope (Keyence, VK-X1100, Itaska, IL, USA) which is illustrated in Figure 3. The tip 3D surface topography of all blades was measured before the milling and after the milling experiments, Figure S3. Five 2D surface profiles were then selected at five different locations along the blade. The unworn surface profile was aligned with the worn surface profile of the same blade. The areas of the unworn (A_u) and worn (A_w) blade tips were calculated by integrating their heights (Z_u) and (Z_w) over the region *x*. The worn area (*A*) was then determined as a difference between the unworn tip area, and the worn tip area:

$$A = A_u - A_w = \sum Z_u dx - \sum Z_w dx. \quad (2)$$

Five worn areas measured along the blade were averaged to estimate the final worn area. The volume loss was then calculated by multiplying the worn area by the blade width (*w*):

$$V_{loss} = A * w. \quad (3)$$

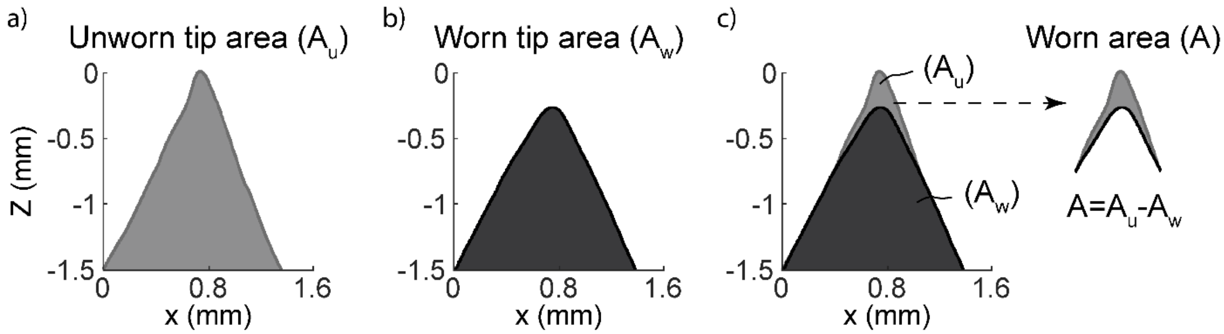

Figure 3. Determination of the wear of a M2 standard tool steel blade using 3D laser confocal microscope. a) Tip area of the middle section of an unworn blade, b) Tip area of the middle section of a worn blade after the knife mill test. c) Worn blade area determined as the differential between the unworn and worn blade tips.

2.5. Characterization of worn blades

The cutting edge, flank and rake faces of the blades were analyzed to identify the wear modes. Worn blade tips were imaged with optical microscopes (Olympus STM6, Tokyo, Japan; and Nikon Labophot-2, Tokyo, Japan) and a scanning electron microscope (FEI Quanta 400F, Hillsboro, OR).

2.6. Particle size distribution measurements

The evolution of the processed feedstock particle size during knife milling experiments was measured using a particle size and shape analyzer (Microtrac PartAn3D, Montgomeryville, PA USA). A dynamic particle analyzer provides a higher resolution and accuracy of a particle size measurement in comparison to a traditionally used sieve analysis[25]. Samples of processed feedstock from each of the three knife milling experiments were collected at several intervals: 1 kg, 100 kg and 200 kg of feedstock processed. A threshold of 500 µm was set to filter out clustered (bundled) particles. The evolution of the particle size distribution is represented via histograms and as a cumulative distribution.

2.7. Milling throughput measurements

Throughput, the amount of feedstock processed for a given period, was determined by monitoring the feedstock mass flow in 40 sec. and 60 sec. intervals. The throughput was measured for all blade materials during the knife milling experiments.

2.8. Techno-economic analysis (TEA)

A Discrete Event Simulation (DES) simulation model of the preprocessing system developed by Hartley et al. [26] was developed and employed to study the economic impact of using the wear resistant candidate blade materials in a knife mill. The TEA was modeled for an operation of 4 preprocessing lines, each sized at 600 dry U.S. short tons/day for a total throughput capacity of 2,400 dry U.S. short tons /day, for a milling period of 350 days, 24 hours/day. Each preprocessing line utilized four knife mills (JRS 14CHS) consisting of 36 rotating knives and 3 stationary knives each, for a total of 156 blades per preprocessing line (624 total blades in the system). The analysis was based on several inputs and assumptions which are summarized in Table 3. The cost in 2021$ of the blade's material was estimated based on inputs from Eberbach company and surface treatment suppliers. A single standard tool steel blade costs $350. DLC coating increases the blade cost by $8 and iron boriding costs $15 for treating each blade. A WC-Co insert costs $400, which increases the total cost of the knife to $750 each. The cost of the blade re-sharpening was estimated to be $42.50 for the standard tool steel blade or the WC-Co insert, based on input from a local machine shop. The 're-sharpening' cost of the iron-borided and DLC-coated blades includes the cost of resharpening the blade substrate and the reapplication of the surface treatment. The analysis also assumed a complete replacement of the blades after 3 re-sharpening because of the knife dimension requirements. The downtime cost for the blade re-sharpening or replacement was estimated to be 40.23 $/min. The modeled feedstock cost without knife mill downtime due to knife wear and replacement was 85.07 $/ton.

Table 3. Assumptions used in TEA model. Costs shown are in 2021$.

Blade material	Material cost ($/blade)	Re-sharpening cost ($/blade)	Downtime cost ($/min)	Base feed cost ($/ton)
M2 tool steel	350	42.50	40.23	85.07
DLC (M2 tool steel)	358	50.50	40.23	85.07
Iron-borided (D2 tool steel)	365	57.50	40.23	85.07
WC-Co (tool steel)	750	42.50	40.23	85.07

3. Results and Discussion

3.1. Wear properties of blade materials

Knife milling experiments showed that the WC-Co blades have the highest wear resistance (the lowest wear rate) among all tested blade materials, as compared in Figure 4. The blade volumetric wear loss, Figure 4b, was converted from the edge recession measurements, Figure 4a, using Eq. 1. At the end of the test, after ~220 kg of feedstock processed, the total volumetric loss of the WC-Co blade was ~0.65 mm^3 which is ~8 and ~2.5 times lower than that of the iron-borided blade, ~1.79 mm^3, Figure 4b. Both WC-Co and iron-borided blades exhibit a linear relationship between the blade volumetric loss and the amount of feedstock processed although the iron-borided blade had a slightly higher run-in wear, the initial ~40 kg of feedstock processed, Figure 4a.

In contrast, the DLC-coated tool steel blades performed poorly. Although the bench-scale wear testing suggested a high wear resistance for the DLC coating, Table 1 and Figure S1, the coating on the blade tip was worn off quickly, after less than 50 kg of feedstock processed, based on visual inspection. By that moment, the DLC-coated blades had a similar wear rate to the iron-borided ones, which could be contributed to the DLC coating being partly present during that period. Since the blade tip was not protected by the DLC coating afterwards, the measured blade edge recessions and volumetric losses were assigned to the M2 tool steel substrate, which is used as the baseline in this work. A linear fit was made through all the volumetric loss data points of each blade material to determine the wear rate expressed as blade volumetric loss over amount of feedstock processed [mm^3/kg], Figure 4b. Remarkably, WC-Co had 8X lower wear rate than the standard tool steel while the iron-borided blade reduced the wear rate by 3X, as detailed in Table 4.

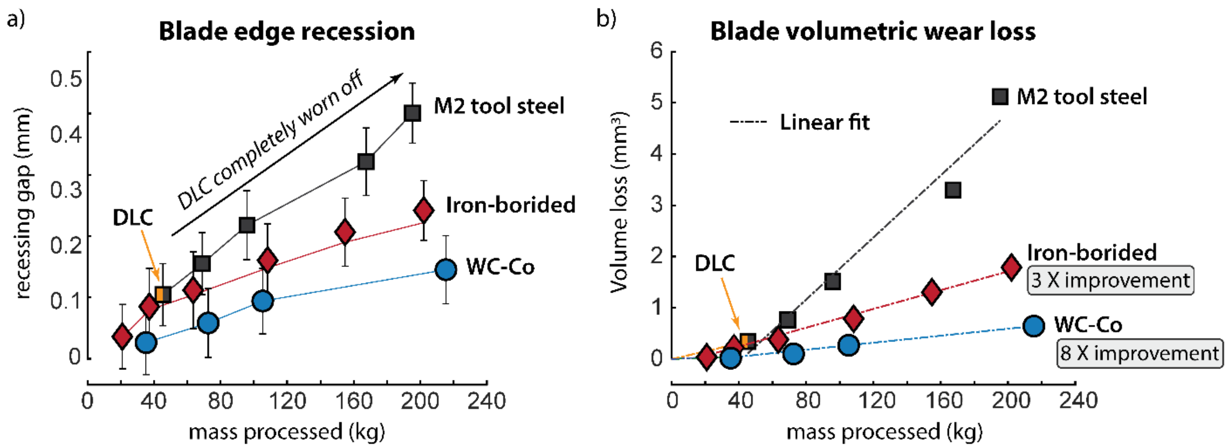

Figure 4. Wear performance of the three different sets of blades in the knife mill tests. a) Average recessing gaps of the blade tips over the amount of feedstock processed. b) Average volume losses of the blade tips converted from the recessing gaps over the amount of feedstock processed.

Table 4. Wear rates of blade materials in the knife mill tests.

Blade material	Wear rate (mm^3/kg)	Wear rate improvement (%)
*M2 tool steel	$3.0x10^{-2}$	baseline
Iron-borided D2 tool steel	$9.1x10^{-3}$	230
WC-Co	$3.6x10^{-3}$	730

**Note: wear rate of M2 tool steel after DLC coating was worn off.*

Comparison of unworn and worn surface profiles of the middle sections of selected stationary and rotary blades in Figure 5 and supplementary Figure S5, showed similar trends that were observed from the gap recession measurements in Figure 4. WC-Co blades had the lowest worn area followed by the iron-borided blade and the standard M2 tool steel blade, Figure 5(a-c). The volume loss of the blade tips of all tested knives determined from the worn area measurements, Eq. 2, is shown in Figure 5(d-f).

The trends in the volumetric loss of the blades are the same as those from the gap measurements, however, the values do not match, which is due to the differences in the measurement techniques. The calculation of the volumetric loss from the gap measurements intends to underestimate the wear because it does not include the wear on the flank and rake faces. Also, the edge chipping was ‘overlooked’ by the gap measurement because the feeler gauge touched on the tallest point.

Interestingly, both worn surface profiles and volumetric loss results suggest that the stationary blades worn more than the rotary blades for all three blade materials, Figure 5b. This trend is especially apparent in M2 tool steel blades in which the stationary blades had ~60% higher volumetric loss than the rotary blades. The abrasive wear of the rotary and stationary blades would be about the same because of the symmetry of the relative motion and force at the contact interface. Therefore, it is the erosion that made the difference between the rotary and stationary blades. If a particle has an elastic collision against a rotary blade, both the momentum and mechanical energy are preserved. Therefore, the velocity of the inorganic particle after a collision with the rotary blade would be roughly 2x of the velocity of the rotary blade (see derivation in Section 2 of the Supporting Information). If a particle has a perfect inelastic collision against a rotary blade, only the momentum is preserved and the particle would be stick onto the blade. As a result, the velocity of the particle would be same as the velocity of the rotary blade. Therefore, the velocity of a particle impacting a stationary blade would always be higher than a rotary blade speed. This explains why more wear was on the stationary blades than on the rotary blades.

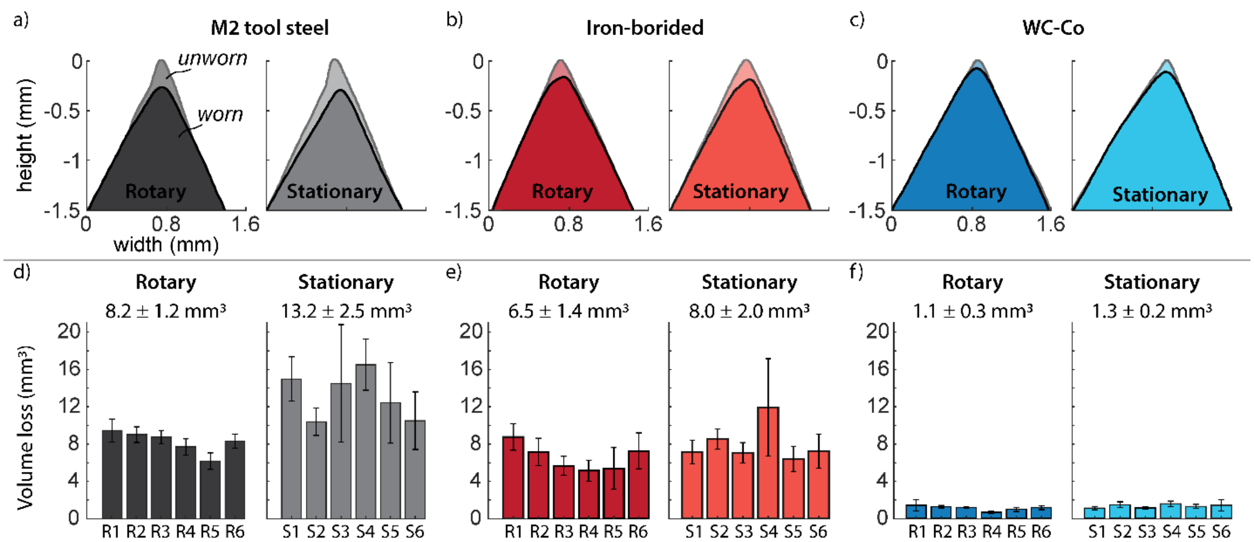

Figure 5. Wear of the blade tips measured with a 3D laser confocal microscope. Comparison of unworn and worn tips of the middle section of selected blades of a) M2 tool steel, b) Iron-borided knives, and c) WC-Co knives. Volumetric loss of the blades of knives d) M2 tool steel knives, e) Iron-borided knives, and f) WC-Co knives.

3.2. Worn blade morphology

Analysis of the worn blade tips after completion of the knife mill testing revealed underlying different wear mechanisms for the three blade materials, as shown in Figure 6 and Figure 7. The DLC coating was worn off from M2 tool steel baseline due to abrasion which is evident from the images of the flank face, rake face and cutting edge of the blade, Figure 6(a-c). The transition from the area covered by the residual DLC coating to the substrate exposed area on the rake face is relatively smooth without evidence of cracking or delamination, which indicates that the DLC coating on the blade tip was likely removed by abrasion and/or erosion instead of fracture or spallation, Figure S4.

The wear modes of the substrate M2 tool steel (after DLC removal) are erosion on the rake face, Figure 6a, and abrasive wear on the flank face and cutting edge, Figure 6(b,c). The degree of wear of the rotating blade appears to be less severe than that of the stationary blade, Figure 6(a-c). In addition, cross-sectional SEM examination revealed a pronounced subsurface crack near the cutting edge of a stationary blade, which may be attributed to repeatable impact with the biomass feedstock leading to fatigue failure, Figure 7c.

The rake face of both the stationary and rotary iron-borided blades had significant chipping as a result of erosion near the tip, Figure 6d and Figure 7(d,e). The optical image, Figure 6e, of the flank face of the rotating blade shows evidence of abrasive wear in a form of pronounced scratches. The cutting edge in the borided blade shows pitting of the surface layer at different scales, Figure 6f. Similar to the M2 tool steel blade, a possibly fatigue-induced subsurface crack was also observed just below the cutting edge of the iron-borided D2 tool steel blade (still in the zone of iron boriding), Figure 7f.

WC-Co blades had the lowest surface damage. The optical images show much less significant erosion with a smaller-scale pitting and chipping on the rake face, Figure 6g, and abrasion with shorter and shallower scratches on the flank face, Figure 6h, compared with the iron-borided blades. The SEM images, Figure 7(g-i), revealed that WC-Co particles are extruded, removed or pushed away by erosion, micro-fracture and chipping of the WC-Co grains.

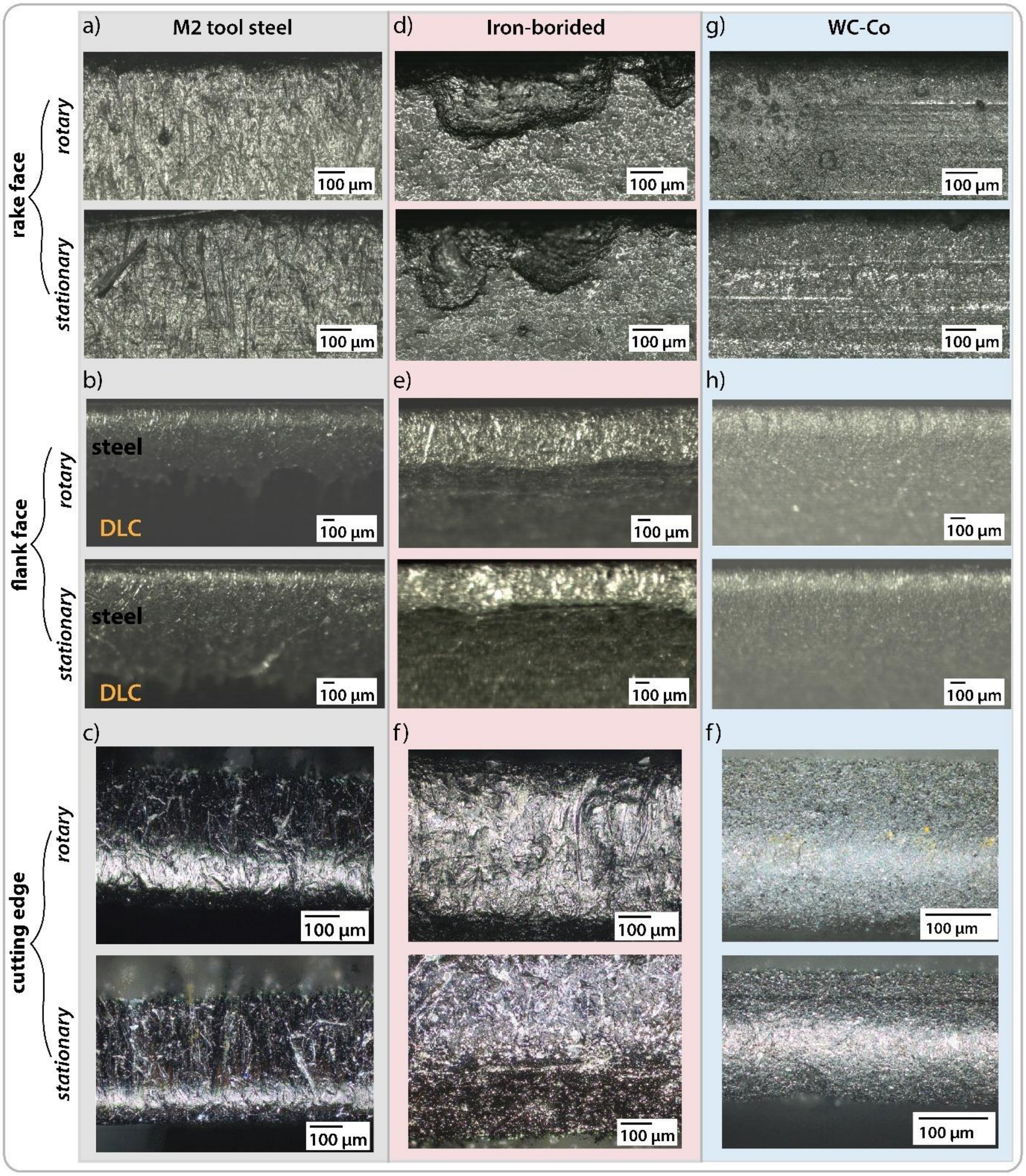

Figure 6. Optical images of worn blade tips of (a-c) DLC-coated M2 tool steel, (d-f) Iron-borided D2 tool steel, (g-f) WC-Co.

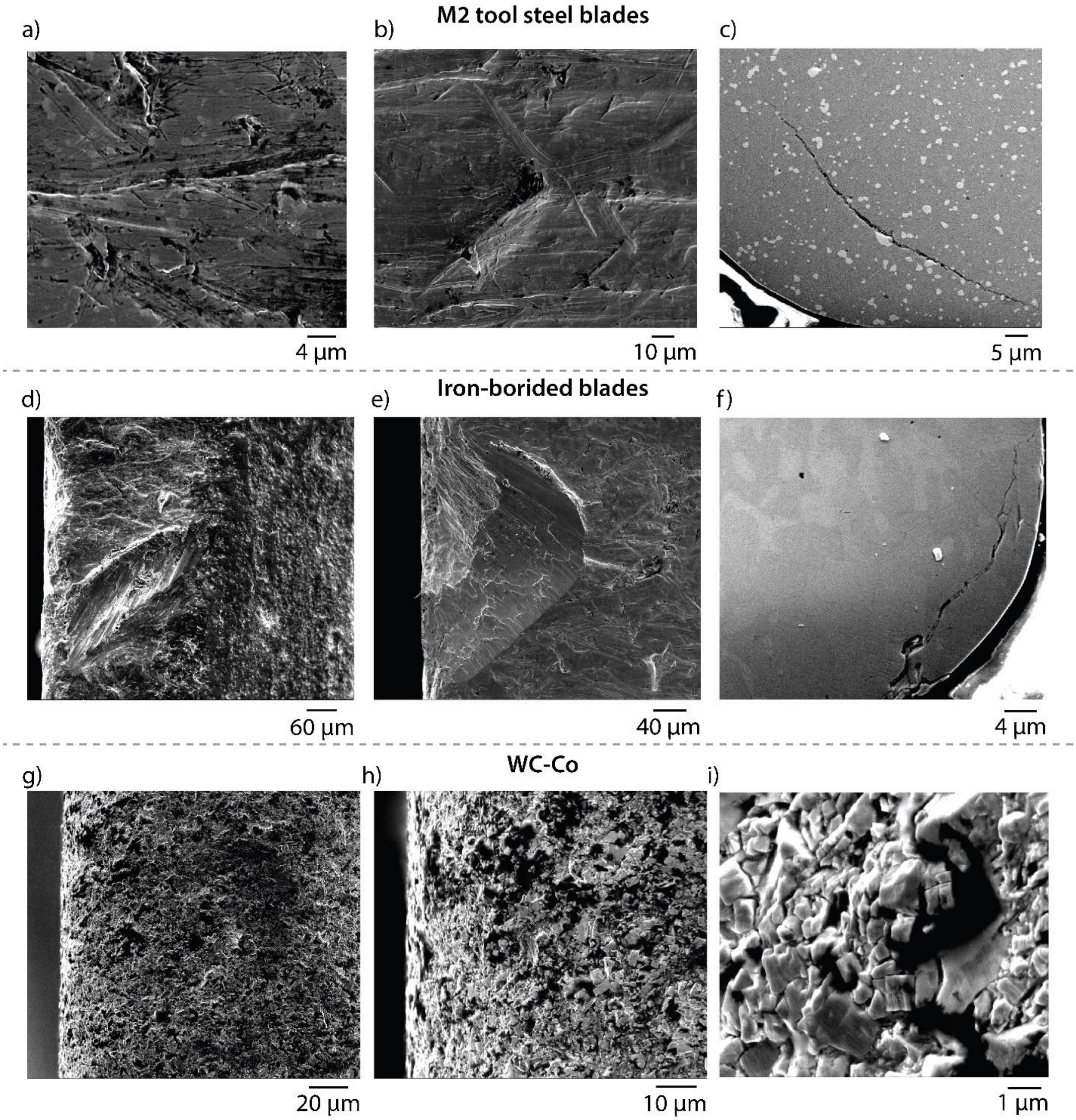

Figure 7. SEM images of worn blade tips. (a-c) M2 tool steel. (d-f) Iron borided. (g-i) WC-Co.

3.3. Particle size distribution

A comprehensive particle size analysis revealed that the biomass particle sizes after the knife mill testing are in a range of 10 – 160 µm, Figure 8. While the overall particle size distributions (PSDs) appear to be similar for the three blade materials, some differences were observed. For the M2 tool steel, the initial 1 kg of feedstock processed likely corresponds to the DLC coating before it being worn off. As expected, milling with worn blades (after 100 kg and 200 kg of feedstock processed) resulted in more smaller particles (<50 µm) but less medium sized particles (50-120 µm) for the M2 tool steel and iron-borided blades, Figure 8 (a,b). This is because worn blades would rely more on impact-induced fracture than on cutting in the particle size reduction. Such a trend was not present for the WC-Co blades, instead Figure 8c shows little change in PSD after 1, 100, or 200 kg of feedstock processing. This suggests that the blades were still sharp and cutting the woodchips effectively by the end of the knife mill test, which can be confirmed by the blade morphology in Figure 6 above.

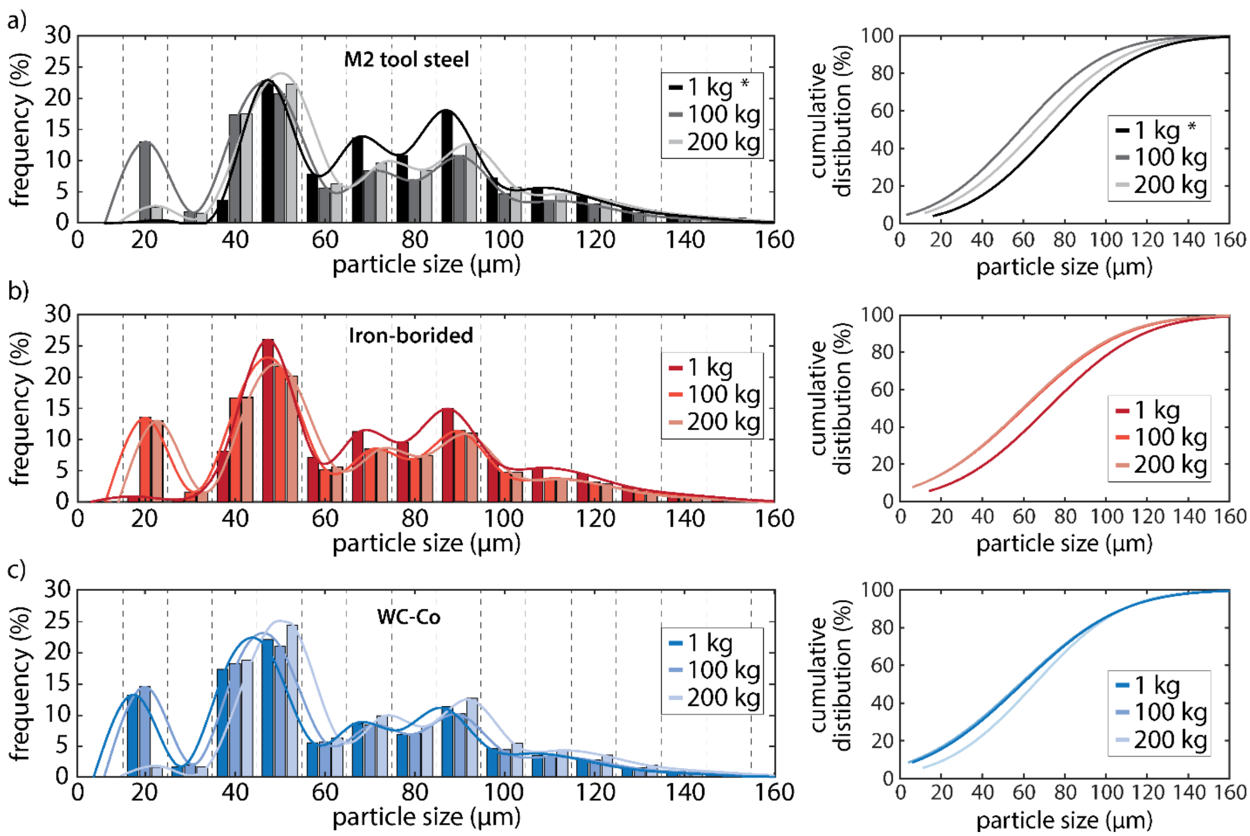

Figure 8. Evolution of particle size distribution and cumulative distribution for blades of a) M2 tool steel (*initial 1 kg of feedstock processed with the DLC coating before being worn off), b) Iron-borided, and c) WC-Co.

3.4. Knife milling feedstock throughput and power consumption

Figure 9a compares the throughput during the knife mill tests of the three sets of blades. Throughput was determined by measuring the amount of feedstock processed over a certain time interval. The more wear-resistant WC-Co and iron-borided blades evidently increased the throughput. By the end of the test, the throughput for these two wear-resistant blades was around 5-6 g/s, about three times higher than that (<2 g/s) for the M2 steel blades. This could be attributed to the improved wear resistance that better retained the sharpness of the blades.

The throughput was expected to start at the highest level at the beginning of milling when the blades are the sharpest and the blade gaps are the smallest, and then gradually decrease with the amount of feedstock processed due to wear. However, except the throughput for the DLC coated blades showed a quick drop before the coating was worn out (0-40 kg), the throughputs had an increasing trend initially for the iron-borided (0-130 kg) and WC-Co (0-140 kg) blades as well as for the M2 steel blades right after the DLC coating was removed (45-95 kg), as shown in Figure 9a. This is counter-intuitive. It is hypothesized that the increase in throughput was due to chipping of the blade cutting edge as observed in Figure 6 (a,d,g). Chipping could actually increase the localized contact pressure against the feedstock to provide more efficient size reduction. In the meantime, the cutting edge was becoming thicker or blunter due to abrasive wear. Therefore, edge chipping and thickening, each as part of the blade wear process, were likely competing in determining the throughput. Based on that, the throughput may be categorized into three stages during the knife mill test: (Stage 1) throughput initially rose because edge chipping increased the contact pressure against the feedstock outweighing the edge thickening (blunting), (Stage 2) throughput decreased when edge chipping became less significant because the edge was getting thicker and its effect was overshadowed by blunting, and (Stage 3) throughput dropped to a trendless lower level when the gap between the rotary and stationary blades was so large that the milling process was no longer sensitive to the edge sharpness. Linear fits were made through the data points in each stage to highlight the trends.

From Figure 9a, it appears that the M2 steel blades already reached the third stage because of their higher wear rates, but the iron-borided and WC-Co blades were still in the second stage by the end of the tests. The initial throughput for the DLC-coated M2 tool steel blades was ~7 g/sec and decreased to ~2 g/sec by the time the coating was worn off (~45 kg feedstock). The throughput of the uncoated M2 tool steel blades initially increased to ~7.5 g/sec (Stage 1, 45-95 kg) but then quickly decreased to ~2 g/sec after processing ~120 kg feedstock (Stage 2) and maintained at that level to the end of the test (Stage 3). The WC-Co blades started with a high throughput of ~8 g/sec and slowly increased to ~9 g/sec after processing ~140 kg feedstock (Stage 1), and then saw the throughput decreasing to ~5 g/sec by the end of the test (Stage 2). The iron-borided blades started with a lower throughput, ~3 g/sec, compared with other blades. A possible reason is that the substrate steel blades went through a blasting process to remove surface oxides in preparation for iron boriding and thus were not as sharp as other two types of blades. The throughput for the iron borided blades increased along with the amount of feedstock processed and reached a peak of ~7.5 g/sec after processing ~130 kg feedstock (Stage 1) and slowly decreased to 5-6 g/sec by the end of the test (Stage 2).

Power consumption was recorded during each knife mill test (excluding the periods when the knife mill was paused or no biomass feedstock was fed). It is understood that the recorded power consumption counts both the active power used for feedstock size reduction and all the passive resistances that unfortunately could not be easily separated. The power consumption is also directly related to the throughput, and thus the measured power consumption was normalized by the corresponding throughput (kW/(g/sec)), basically the energy consumed per unit feedstock mass, Figure 9b. The results clearly demonstrate that the normalized power consumption was lower with the improved wear resistance of the blades. Normalized power consumption of knife milling operation using the WC-Co blades was not only the lowest among all blade materials but also the most consistant. In contrast, the normalized power consumption was on average the highest and the most inconsistant when using the standard tool steel blades.

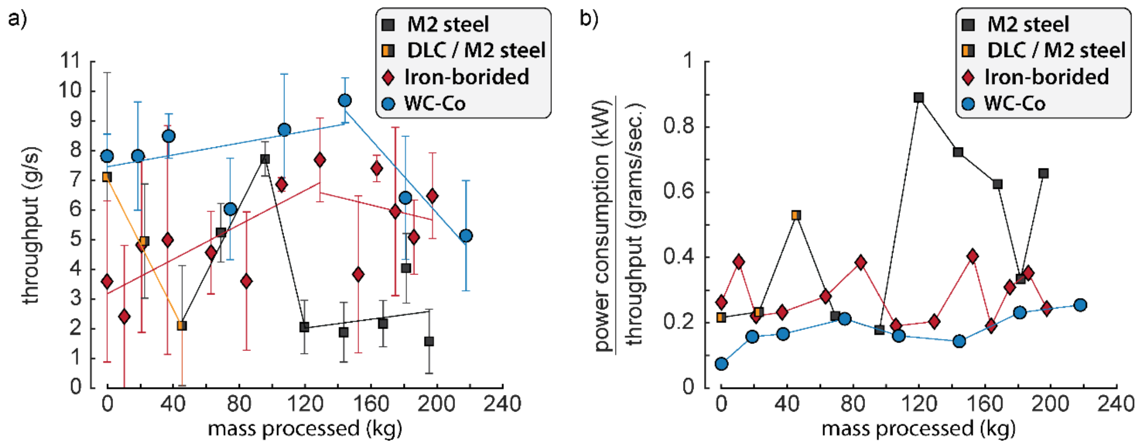

Figure 9. Knife milling performance using different blade materials. a) Feedstock throughput during the test; b) Power consumption normalized by throughput during the test.

3.5. Techno-economic analysis (TEA)

The knife milling results were used as inputs in a TEA, as illustrated in Figure S6, to demonstrate the economic feasibility of replacing the standard tool steel blade with the more wear resistant WC-Co or iron-borided blades. The TEA results are summarized in Table 5. This analysis consists of several assumptions which are listed in Table 3. Certain inputs are independent to the blade material such as downtime cost or base feedstock cost. The most important inputs are those that are material-specific which are the blade cost, blade re-sharpening cost, and blade durability. The cost of the knife milling using different blade materials was simulated for a system of four preprocessing lines, each containing four full-size commercial knife mills (JRS 14CHS) with each mill consisting of 39 knives (36 rotating knives and 3 stationary knives) for a period of 350 days (50 weeks), 24 hours/day. First, it is imperative to determine the number of failures for different blade materials. In this analysis, a failure means a blade requires re-sharpening or replacement due to wear. When the blades are re-sharpened 3 times, they will be replaced by a new set. Based on the field experiences with knife mill operation, the standard tool steel blades need to be resharpened after 100 tons of ash had passed through the mill (estimated from the vendor, Rawlings Manufacturing, Missoula, MT, USA per personal communication). Applying iron-boriding surface treatment and WC-Co inlay would enable the blades to process 326 and 746 tons of ash, respectively, before replacing them, Figure S7. This finding is especially important for knife milling dirty biomass with a high content of ash. Improving the wear resistance of the blades allows to process larger amount of ash which would decrease the downtime associated with less frequent replacement of the blades. More detailed information about TEA can be found in the supplementary.

For the tool steel DES simulation (with stochastically-sampled ash contents from a distribution), this resulted in failures roughly every 2 weeks which is an equivalent of approximately 104 failures in a 50-week period for the 4 sets of four knife mills (Table 5). The improvement in the tool life for the other blade materials is based on the knife mill testing results in Table 4. The reduced number of modeled failures were 32 and 12 for the iron-borided and WC-Co blades, respectively. The reduction in the blade failures automatically increased the amount of produced feedstock and decreased the downtime. The highest reduction of the downtime cost per amount of biomass pre-processed is achieved with the WC-Co blades ~ 0.20 $/ton, which is significantly lower than the downtime cost using the standard blades, 1.37 $/ton. The downtime cost for the iron-borided blades was determined to be 0.47 $/ton. Lower frequency of the blade failures also reduces their overall cost. Re-sharpening and replacing WC-Co blades would cost only $1.10 per ton of biomass pre-processed and $1.84 with iron-borided blades. This is significantly lower than the cost of the standard blades, $4.22. The total milling cost determined as a sum of knife cost, downtime cost and feedstock cost was the highest for the M2 tool steel blades, 75.71 $/ton, followed by the iron-borided blades, 72.44 $/ton and the WC-Co blades, 71.42 $/ton. The analysis clearly demonstrates that the knife milling operation cost is notably reduced by applying more wear-resistant blade materials.

Table 5. TEA of different blade materials simulated for an operation of four sets of four knife mills (total 16 mills) each containing 39 knives based on knife mill testing results.

Blade material	Initial knife cost ($)	# of failures	Biomass produced (ton)	Downtime (min)	Knife cost ($/ton)	Total cost ($/ton)
M2 tool steel	54,600	104	486,052	16,672	4.22	75.71
Iron-borided D2 tool steel	56,940	32	486,832	5,760	1.84	72.44
WC-Co inlay + tool steel	117,000	12	499,048	2,496	1.10	71.42

4. Conclusions

This study demonstrates that applying wear resistant blade materials can significantly enhance the durability and performance of a knife mill for biomass pre-processing. The knife wear rate, worn blade morphology, biomass particle size distribution, feedstock throughput, and power consumption were measured for three different blade materials: DLC-coated M2 tool steel, iron-borided D2 tool steel, and tungsten carbide-cobalt composite. Knife milling experiments showed that the tungsten carbide inserts provided 8X wear performance improvement, followed by iron-boriding surface treatment with a 3X wear reduction when compared to the commonly used tool steel blades. In contrast, the thin DLC coating was worn off quickly and thus is not suitable for the knife mill application. The improved durability of tungsten carbide blades is attributed to a high resistance against both erosion and abrasion while the iron-borided blades showed significant edge chipping and spalling. The enhancement in the wear resistance of the blades also resulted in a higher throughput and a lower normalized power consumption, but had less impact on the particle distribution of the processed biomass. Techno-economic analysis predicts that using the tungsten carbide or iron-borided blades could potentially reduce the overall operational cost of a knife mill despite their higher cost when compared to the standard tool steel blades.

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References

[1] M.-A. Perea-Moreno, E. Samerón-Manzano, and A.-J. Perea-Moreno, "Biomass as Renewable Energy: Worldwide Research Trends," *Sustainability*, vol. 11, no. 3, p. 863, Feb. 2019, doi: 10.3390/su11030863.

[2] A. Tursi, "A review on biomass: importance, chemistry, classification, and conversion," *Biofuel Research Journal*, vol. 6, no. 2, pp. 962–979, Jun. 2019, doi: 10.18331/BRJ2019.6.2.3.

[3] J. Cheng, *Biomass to renewable energy processes*. CRC press, 2017.

[4] T. Bridgwater, "Biomass for energy," *J Sci Food Agric*, vol. 86, no. 12, pp. 1755–1768, Sep. 2006, doi: 10.1002/jsfa.2605.

[5] S. V. Vassilev, D. Baxter, L. K. Andersen, and C. G. Vassileva, "An overview of the chemical composition of biomass," *Fuel*, vol. 89, no. 5, pp. 913–933, 2010, doi: 10.1016/j.fuel.2009.10.022.

[6] O. Oyedeji, P. Gitman, J. Qu, and E. Webb, "Understanding the Impact of Lignocellulosic Biomass Variability on the Size Reduction Process: A Review," *ACS Sustain Chem Eng*, vol. 8, no. 6, pp. 2327–2343, Feb. 2020, doi: 10.1021/acssuschemeng.9b06698.

[7] Z. Miao, T. E. Grift, and K. C. Ting, "Size Reduction and Densification of Lignocellulosic Biomass Feedstock for Biopower, Bioproducts, and Liquid Biofuel Production," in *Encyclopedia of*

Agricultural, Food, and Biological Engineering, Second Edition, CRC Press, 2010, pp. 1–4. doi: 10.1081/E-EAFE2-120051298.

[8] L. Kratky and T. Jirout, “Biomass Size Reduction Machines for Enhancing Biogas Production,” *Chem Eng Technol*, vol. 34, no. 3, pp. 391–399, 2011, doi: 10.1002/ceat.201000357.

[9] L. J. Naimi, “A study of cellulosic biomass size reduction,” *Thesis, University of British Columbia*, 2016, doi: doi.org/10.14288/1.0224813.

[10] S. Roy, K. Lee, J. A. Lacey, V. S. Thompson, J. R. Keiser, and J. Qu, “Material Characterization-Based Wear Mechanism Investigation for Biomass Hammer Mills,” *ACS Sustain Chem Eng*, vol. 8, no. 9, pp. 3541–3546, Mar. 2020, doi: 10.1021/acssuschemeng.9b06450.

[11] J. H. Lee, J. H. Kwon, T. H. Kim, and W. Il Choi, “Impact of planetary ball mills on corn stover characteristics and enzymatic digestibility depending on grinding ball properties,” *Bioresour Technol*, vol. 241, pp. 1094–1100, 2017, doi: https://doi.org/10.1016/j.biortech.2017.06.044.

[12] A. S. da Silva, H. Inoue, T. Endo, S. Yano, and E. P. S. Bon, “Milling pretreatment of sugarcane bagasse and straw for enzymatic hydrolysis and ethanol fermentation,” *Bioresour Technol*, vol. 101, no. 19, pp. 7402–7409, Oct. 2010, doi: 10.1016/j.biortech.2010.05.008.

[13] J. M. S. Eng, K. Km, and H. Motjotji, “The Effect of Ball Size Diameter on Milling Performance,” *Journal of Material Science & Engineering*, vol. 04, no. 01, pp. 4–6, 2014, doi: 10.4172/2169-0022.1000149.

[14] K. Lee, D. Lanning, L. Lin, E. Cakmak, J. R. Keiser, and J. Qu, “Wear Mechanism Analysis of a New Rotary Shear Biomass Comminution System,” *ACS Sustain Chem Eng*, vol. 9, no. 35, pp. 11652–11660, Sep. 2021, doi: 10.1021/acssuschemeng.1c02542.

[15] S. Mani, L. G. Tabil, and S. Sokhansanj, “Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass,” *Biomass Bioenergy*, vol. 27, no. 4, pp. 339–352, 2004, doi: 10.1016/j.biombioe.2004.03.007.

[16] S. Paulrud, J. E. Mattsson, and C. Nilsson, “Particle and handling characteristics of wood fuel powder: effects of different mills,” *Fuel Processing Technology*, vol. 76, no. 1, pp. 23–39, Apr. 2002, doi: 10.1016/S0378-3820(02)00008-5.

[17] V. S. P. Bitra, A. R. Womac, C. Igathinathane, and S. Sokhansanj, “Knife Mill Comminution Energy Analysis of Switchgrass, Wheat Straw, and Corn Stover and Characterization of Particle Size Distributions,” *Trans ASABE*, vol. 53, no. 5, pp. 1639–1651, 2010, doi: 10.13031/2013.34886.

[18] L.J. Naimi, S. Sokhansanj, X. Bi, C. J. Lim, A. R. Womac, A. K. Lau, S. Melin, “Development of Size Reduction Equations for Calculating Energy Input for Grinding Lignocellulosic Particles,” *Appl Eng Agric*, vol. 29, no. 1, pp. 93–100, 2013, doi: 10.13031/2013.42523.

[19] J. A. Lacey, J. E. Aston, S. Hernandez, M. Intwan, V. S. Thompson, K. Lee, J. Qu, “Wear and Why? How Ash Elements Can Help Define Wear Profiles of Biomass Feedstocks,” 2019. doi: 10.13031/aim.201901446.

[20] J. A. Lacey, J. E. Aston, and V. S. Thompson, “Wear Properties of Ash Minerals in Biomass,” *Front Energy Res*, vol. 6, no. NOV, pp. 1–6, Nov. 2018, doi: 10.3389/fenrg.2018.00119.

[21] Z. Chen, G. Yu, X. Yuan, Q. Wang, and J. Kan, “Improving the Conventional Pelletization Process to Save Energy during Biomass Densification,” *Bioresources*, vol. 10, no. 4, pp. 6576–6585, Aug. 2015, doi: 10.15376/biores.10.4.6576-6585.

[22] R. M. Singh, “Study on Wearing of Screw of Biomass Briquetting Extruder,” *Nepal Journal of Science and technology Vol 2*, no. October, pp. 83–86, 2000.

[23] K. Lee, S. Roy, E. Cakmak, J. A. Lacey, T. R. Watkins, H. M. Meyer, V. S. Thompson, J. R. Keiser, J. Qu, “Composition-Preserving Extraction and Characterization of Biomass Extrinsic and Intrinsic Inorganic Compounds,” *ACS Sustain Chem Eng*, vol. 8, no. 3, pp. 1599–1610, Jan. 2020, doi: 10.1021/acssuschemeng.9b06429.

[24] “ASTM G 174 Standard test method for measuring abrasion resistance of materials by abrasive loop contact,” *ASTM Annual Book of Standards,* vol. 3, pp. 735–739, 2014, doi: 10.1520/G0174-04R17.

[25] H. Wei, T. Zhao, Q. Meng, X. Wang, and B. Zhang, “Quantifying the Morphology of Calcareous Sands by Dynamic Image Analysis,” *International Journal of Geomechanics*, vol. 20, no. 4, Apr. 2020, doi: 10.1061/(ASCE)GM.1943-5622.0001640.

[26] D. S. Hartley, D. N. Thompson, L. M. Griffel, Q. A. Nguyen, and M. S. Roni, “Effect of Biomass Properties and System Configuration on the Operating Effectiveness of Biomass to Biofuel Systems,” *ACS Sustain Chem Eng*, vol. 8, no. 19, pp. 7267–7277, May 2020, doi: 10.1021/acssuschemeng.9b06551.