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Low-energy Comminution of Woody Biomass to Create Precision Feedstock Particles

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Abstract. *Under funding from DOE Office of Biomass Programs, engineers at Forest Concepts are working to apply low-energy comminution methods to produce improved biomass particle geometry and sizes optimal for biochemical and thermochemical conversion to liquid transportation fuels. Designs are constrained to concurrently achieve the DOE Uniform Feedstock Format criteria for bulk handling and flowability. The innovative comminution process independently controls shearing of biomass feedstocks parallel to the fiber orientation and cross-grain. Short-length cross grain shearing opens particles to high mass transport and eliminates fiber balls and other materials handling problems typically associated with hammer milling. The process is currently operating routinely at laboratory scale (200 kg/shift) on woody materials at a roundwood to 2mm cubic particle at a specific energy cost of approximately 150 MJ/odMg.*

Keywords. Comminution, woody biomass, feedstock, precision particle, low-energy

Introduction

Under partial funding from DOE Office of Biomass Programs, engineers at Forest Concepts are working to apply low-energy comminution methods to produce improved biomass particle geometry and sizes optimal for biochemical and thermochemical conversion to liquid transportation fuels. The existing predominant methods for comminution include rotary hammer mills, chippers and grinders of various designs. The attraction of such mass-flow comminution equipment is that they have high throughput and accommodate a wide range of feedstock forms. Major limitations for all these methods include high production of dust, excess production of overly fine materials, high power consumption, and random distribution of particle sizes. A less-recognized limitation is that resulting particles tend to have a high length-to-width/thickness ratio that negatively affects conversion efficiency and makes handling difficult. For many uses, the resulting material must be further processed by additional comminution equipment for second-stage grinding to a more optimal particle size. Forest Concepts aims to address these issues with a process that starts with roundwood and ends with small, highly uniform precision particles. The precision particles dimensions can be tailored to specific downstream conversion processes, unlike the industry standard comminution processes in use today. Additionally, processing from roundwood to our Crumbles™ precision particle consumes substantially less energy than standard comminution methods for similar size reduction.

Safety Emphasis

Processing woody materials is an inherently dangerous activity. Nearly all processing methods utilize either sharp or quick moving equipment. Our process involves a rotary veneer lathe and a rotary shearing head.

The centerless veneer lathe turns a log block via knurled rollers. A knife peals the surface layer of the block into veneer. To prevent injury strict operator locations were observed as well as cautious handling during core removal.

The infeed of the rotary shear must be open enough for materials to flow freely into the head. Consequently there are openings where operators could potentially get fingers, hands, or loose clothing engaged in the cutter head causing serious injury or death. To mitigate as much hazard as practical we built infeed chutes and conveyors to distance the operator from the processing head. Additionally multiple emergency stop switches were placed within reach of the processing head.

Standard personal safety gear including safety glasses and snug clothing were worn. Operators were trained on the machine including hazard avoidance. Lock out / tag out procedures were followed during data acquisition hardware connection as well as maintenance and configuration change activities.

Literature Review

Woody biomass is expected to provide a significant amount of cellulosic biomass to second generation biorefineries (Perlack et al., 2005). Wood is typically transported from forests and plantations in either roundwood logs or in chip form. Transport in log form consumes only the fossil fuel used in transport, while in-woods chipping requires an additional 30-50 MJ/Mg for converting raw logs into chips (Jones, 1981a, b). Both logs and chips are transported in specialized trucks or trailers, making long-haul transport increasingly expensive.

Wood must be mechanically processed into particle sizes and shapes that meet the feedstock specifications of each conversion process. When raw logs are delivered to a biorefinery or preprocessing center they are typically chipped, dried, and then ground to particle sizes appropriate for the intended end-use process. In the case of raw logs, there are often some energy savings that accrue from use of electrically powered industrial chippers rather than fossil fuel powered in-woods chippers. The subsequent milling of chips into feedstocks is identical for each pathway. Miao and others at the University of Illinois measured the specific energy for comminution of several biomass materials including willow wood into a range of particle sizes (Miao et al., 2010). The willow was processed by a Vermeer chipper to create raw material and then milled by knife or hammer mill to final screen size. Energy requirement to regrind willow chips to 1 mm size consumed more than 2,100 kJ/kg (2,100 MJ/Mg) and to regrind to 6 mm size consumed more than 200 MJ/Mg.

Experimental Procedure

Approach

Our driving objective is to design and build new generation, paradigm shifting, wood comminution equipment. The root level processing approach is to start with roundwood, create and industrial grade veneer, and process through our rotary shear “muncher.”

Industrial grade veneer is defined as a “low quality” veneer where surface checks and other finish defects are irrelevant. Veneering is a low energy, high yield process that precisely controls one dimension of a finished particle. As we are utilizing an industrial grade veneer, log blocks do not need any pretreatment before veneering. Virtually any moisture content can be processed.

Veneer making is a centuries-old process that is most often associated with the manufacture of toothpicks, match sticks, and plywood (Baldwin, 1995). The advantages of veneer as the primary breakdown product from small logs versus chips include:

- High transport density on trucks or rail. This enables cost effective delivery to more distant users.
- Shipping on common flatbed trailers or rail cars rather than specialized chip haulers.
- Veneer controls one dimension (thickness) of secondary products, thus reducing the complexity of further processing the material into precision feedstocks or value-added products.
- Veneer sheets naturally maintain the fiber orientation of a log with the grain direction across the sheet.
- Ease of palletizing or unitizing veneer sheets for handling, storage, and feeding into subsequent processes.
- Veneer manufacturing is a very low energy process for primary breakdown of roundwood.

Unlike logs or chips, veneer can be transported on conventional flatbed trucks, trailers and railcars. Green veneer has a transport and storage bulk density greater than 500 kg/m3 which maximizes the payload on all commercial forms of transport. The use of conventional modes of transport significantly increases the economical distance between a veneer producer and a woody feedstock end user. Banded stacks (aka units) of veneer are readily handled by forklifts further reducing the cost of storage and handling.

Our industrial grade veneer is then processed through our first generation rotary shear "muncher" while recording both torque arm and electrical based specific energy. The cutters on the muncher head are configurable into many particle lengths. For this report we will focus on a reference particle of approximately 1.6mm length, 2mm width, and 2mm thickness.

Figure 1. Nominal 2mm Crumbles® precision particles.

A major innovation that was developed as part of the project being summarized here is a method to process sheets of veneer cross-grain through a large paper-shredder like rotary shearing machine developed by Forest Concepts. The rotary shear machine consists of a pair of driven shafts upon which can be stacked nesting sets of cutter wheels. The width of each cutter wheel sets the length along the grain of particles sheared from sheets of veneer. A biomass feedstocks producer would have sets of cutters for each particle length desired by end users. Typical cutter widths range from 1.5mm to 6mm to produce a full range of particle sizes desired for biochemical, thermochemical, and densified solid biofuel products. In most cases the thickness of veneer produced from a lathe is set to correspond with a rotary shear cutter set to produce essentially cubic wood particles.

Our theories about how wood structural properties and natural modes of failure relate to shearing forces and energy were described by Lanning (Lanning et al., 2008). An objective of the project discussed in this paper was to further refine our mathematical models to include experimentally derived data from a purpose-built laboratory scale instrumented rotary bypass shear (aka WoodMuncher™ machine).

Materials from each run were sieved in our standard set of Gilson RoTap® sieves to plot the particle size distribution on both a wet and dry weight basis.

Comminution energy was calculated for each run and reported.

Materials

Hybrid poplar logs were obtained from Washington State University Puyallup branch's hybrid poplar stand on March 12, 2012. The logs were cut into roughly 8 to 10 feet long blocks. The logs were then stored uncovered outside in the Seattle, Washington area until further processing was done on May 28th, 2012.

Equipment

The initial breakdown into veneer of the logs was performed using Forest Concepts' short block centerless veneer lathe. The rotary veneer lathe used in these studies was a Model SWK130 centerless lathe made by Feixian Ruihao Machinery Making Co. of China. The lathe has a capacity of 100mm to 300 mm diameter by 1400mm long logs and can be set to produce veneer at any thickness between 0.5mm and 6.0mm. The core diameter is approximately 42mm.The lathe is powered by three drive motors from a common computerized control console.

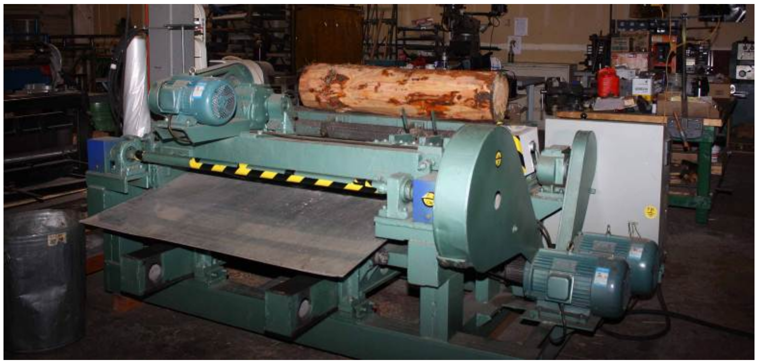

Figure 2. Short block centerless veneer lathe manufactured by FeiXian Ruihao Machinery.

The final breakdown of the veneer into Crumbles® precision particles was performed using Forest Concepts' research CrumbleMuncher. This rotary shear device is powered by a 10hp 3phase electric motor. The cutter head assembly has an approximately 130mm infeed width. Nominally 4" diameter cutters were used. The individual cutter width used for this experiment was 1.6mm (1/16 inch).

Energy usage load data was acquired for both breakdown operations. 3 phase electrical data was captured for each machine. Torque based load data was also captured for the CrumbleMuncher using the method described by Lanning (Lanning et al, 2011). Specific sensors include Fluke i400s current clamps and a Transcell Technology BSS-2K tension load cell. Measurement Computing USB-1616HS and AI-EXP48 data acquisition boards were used to connect the sensors to a LabView® coded program running on a Windows® based computer.

The LabView program captures:

- Each 3 phase leg's:
  - Instantaneous voltage
  - Instantaneous current
- Load cell excitation voltage
- Load cell voltage output

The capture rate was set at 960 samples per second per channel. From the captured data the program calculates:

- RMS voltage
- RMS current
- Electrical power factor
- Power factor corrected electrical power consumption

- Torque based power consumption

Energy data was analyzed using a proprietary Microsoft Excel® workbook that enabled calculation of the no-load and loaded energy and then applied those values to both the green and oven dry mass of a sample to compute the specific energy consumption in MJ/Mg.

Method

Three logs were randomly selected. An approximately ½ meter block was cut from each log. The block was then processed in the lathe. Electrical power consumption was recorded for each run. Torque based data was not recorded for the lathe as it is not equipped for such measurements.

Initial block length, diameter (4 places), mass, and moisture content were recorded. After processing, the core mass and usable veneer mass were recorded. A percent yield was calculated (veneer mass / block mass). Using an oven dry basis, the energy to process was calculated for the block and for the yield veneer (MJ/odMg).

The veneer was cut into 130mm wide strips in our shop band saw. This process is simply to fit the veneer into the research muncher and therefore the energy was not recorded as this saw would not be part of a production facility.

Four approximately 1 meter long veneer strips were randomly selected from each block’s veneer. Each block’s four strips constituted a single run for that block. Each strip’s initial length, width, thickness and moisture content were recorded. The strips were processed through our research CrumbleMuncher. Electrical and torque based power consumption were recorded.

Results and Data

The log blocks were processed using our veneer lathe and the electrical power consumption was recorded and corrected for power factor. Power consumption with respect to sample number (time in seconds times 960) is shown in the chart below for one block. The initial portion from sample 8,000 to sample 24,000 of the power consumed is from knife carriage positioning and partial block rotations as the knife makes first contact. Power consumption from lines 24,000 through 30,400 is from actual veneer production. The power from this region was used to determine the specific energy for veneer production. Table 1 shows the data from each of the three blocks. No load data was generated in a specific no load run and subtracted from the loaded run power consumption to determine specific power usage.

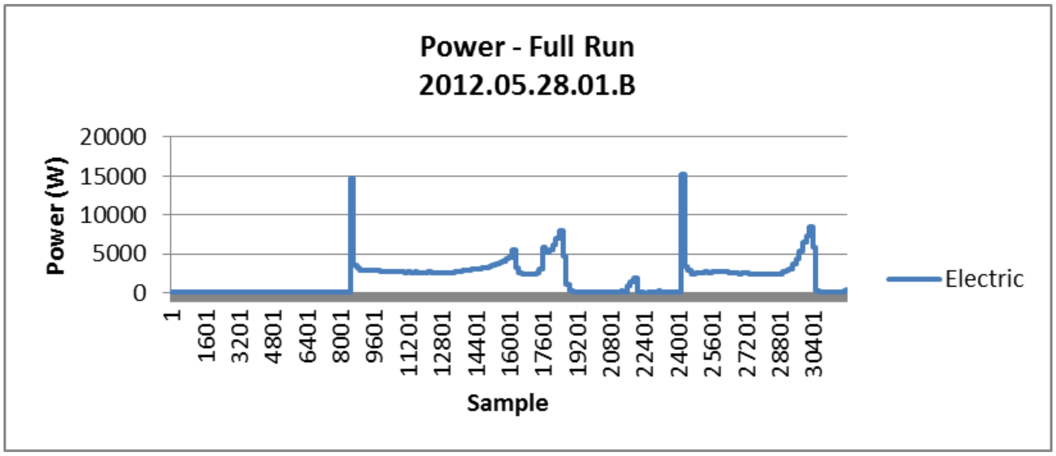

Figure 3. Typical power consumption load data for a veneer run. All points upto 24,000 are for carriage positioning. Veneer making starts at sample 24,000 and continues through sample 30,400.

Table 1. Summary table of power consumption for each of four log blocks processed in the veneer lathe.

Veneer	*2012.05.28.001.A*	*2012.05.28.001.B*	*2012.05.28.001.D*	*2012.05.28.001.E*
MJ/odMg (block)	*9.73*	8.45	8.58	8.66
MJ/odMg (yield)	*10.62*	10.86	11.022	18.88
Yield %	*91.60%*	77.87%	77.81%	45.84%
MC %	*51.32%*	51.32%	50.42%	47.21%

Specific power consumption to produce veneer was calculated for both the raw block mass and the veneer yield (usable veneer) mass. As we want to know the power consumed in relation to a finished product, we used the specific energy per veneer yield for combined consumption calculations. Sample 2012.05.28.001.E exhibited a high yield based veneering specific energy, due to the unusually low yield.

Test strips were cut from each veneer set and processed through our CrumbleMuncher. Both electrical and torque based power consumption were recorded as shown in the figure below. No load data was taken from the first portion of the run, lines 1 through 11,000. The test strips were then fed into the CrumbleMuncher and the power consumption was recorded, as seen in the spikes below. Specific power consumption was calculated by taking the average power for each test strip and subtracting the no load power.

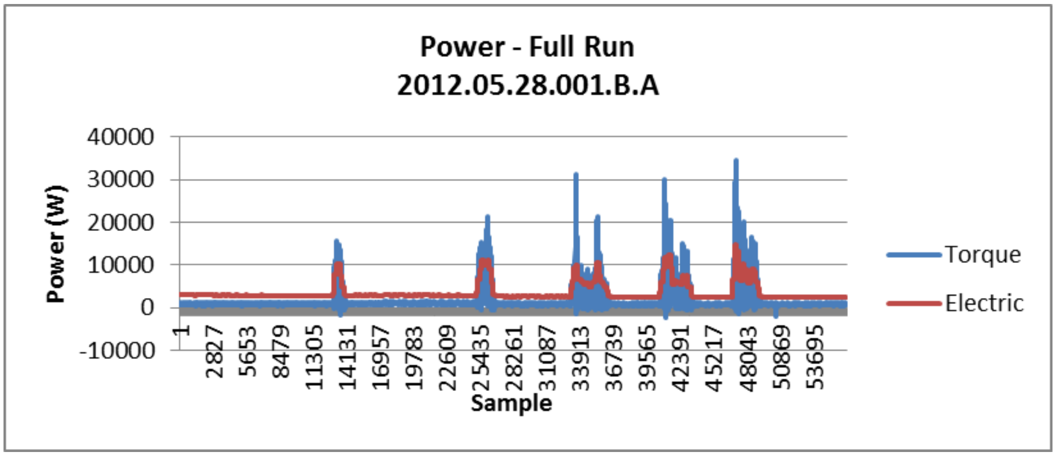

Figure 4. Typical CrumbleMuncher power consumption load data. The spikes in power consumption represent the veneer pieces being processed. Note that there are five spikes when only four veneer pieces were used. The first piece broke during feeding and is accounted for in spikes one and two.

As can be seen in the data, the electrical based power is smoother than the torque based. This phenomena is due to the rms averaging function of the data acquisition program that takes 160 samples and converts them into a single rms sample that is then repeated 160 times to correlate with the time and torque samples. The torque samples are raw instantaneous samples and have no smoothing applied. Additionally, the load cell reacts substantially faster than electrical circuit's slight changes in processing power. The table below summarizes the CrumbleMuncher processing energy.

Table 2. Summary table of power consumption for crumbling process through CrumbleMuncher.

Crumbles	*2012.05.28.001.B.A*	*2012.05.28.001.D.A*	*2012.05.28.001.E.A*
MJ/odMg Elect	131.22	137.89	138.43
MJ/odMg Torque	127.25	129.14	129.21
MJ/odMg Average	129.23	133.52	133.82

Individual sample veneering and munching energies were added to get a total specific energy to process nominally 1.6mm cubic particles from roundwood to finished particle. The average specific energy (yield), including sample 2012.05.28.001.E, was 145 MJ/odMg.

Table 3. Cumulative specific power consumption from log to Crumble® precision particle.

Combined	*2012.05.28.001.B.A*	*2012.05.28.001.D.A*	*2012.05.28.001.E.A*
MJ/odMg	140.09	144.54	152.70

Sieve size analysis was preformed on the produced Crumbles® particles using Forest Concepts' standard fine particle sieve set. As we have seen in previous size analyses of these particles, the distribution grouping is relatively tight. This experiment targeted a nominally 1.6mm particle. As shown in the chart below, more than 70% of the particles were less than 3.175mm and greater than 1.18mm.

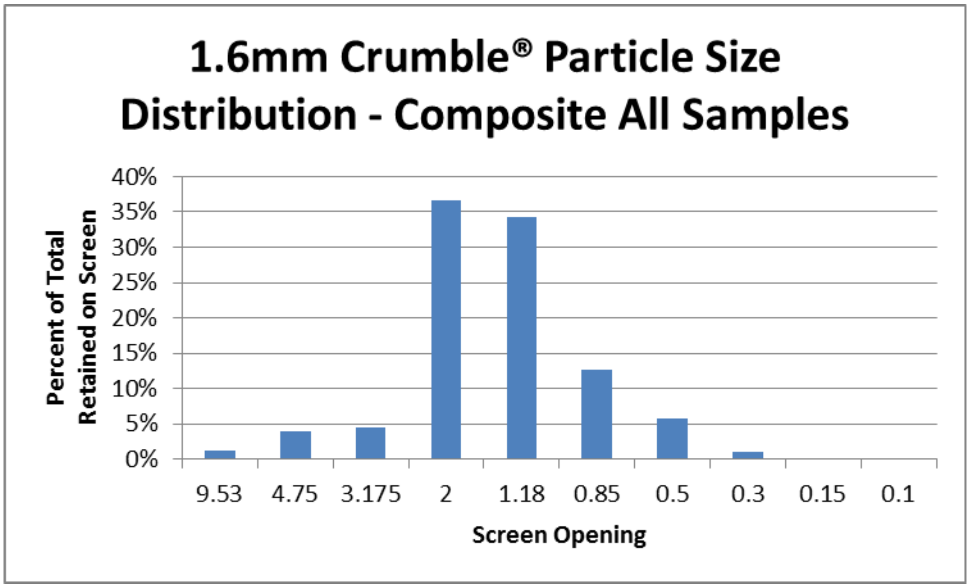

Figure 5. 1.6mm (2mm nominal) Crumble® precision particle sieve size distribution directly after manufacture.

Discussion and Conclusion

Previous work by others, discussed earlier, suggests that the energy require to process roundwood to chips and chips to small particles was on the order of 40MJ/Mg and 2000MJ/Mg, respectively. At this scale we can conclude that total processing energy was on the order of 2000MJ/Mg. The Forest Concepts' roundwood to industrial veneer to precision particles consumed approximately 150MJ/Mg. As seen in this example, our new process uses a small fraction of the energy, less than 10%, traditional small particle size reduction processes consume. Lower energy consumptions translate directly into better economics for biofuels producers, and ultimately benefits biofuels users.

Our veneering and crumbling process utilizes high moisture raw feedstocks, which eliminates the costly drying step that most hammer mills require. Preliminary data suggests that if low moisture content Crumbles® particles are required, the small, uniform Crumbles® precision particles dry much quicker reducing dryer capital and operating cost. Forest Concepts will be examining this phenomenon under an additional DOE SBIR research contract.

Additionally, as shown in the data, this low energy size reduction process yields uniformly sized particles. Narrow size distribution aids biochemical and thermochemical conversion processes as the time or distance the center of each particle is more consistent, thus there are fewer over / under cooked particles, potentially yielding better quality conversion outputs. Preliminary work with cooperators suggests that there is increases in conversion output quality, however, more work needs to be done to determine exactly how great the benefit is.

Acknowledgements

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