Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-023-04805-6

ORIGINAL ARTICLE

Contact pressure analysis to allow improved design for the clearing plate in a biomass comminution system

Lianshan Lin[1] · Chris McKiernan[2] · David Lanning[2] · James R. Keiser[1] · Jun Qu[1]

Received: 30 May 2023 / Revised: 2 August 2023 / Accepted: 23 August 2023

Abstract
For biomass processing systems, feedstocks with small but equal sizes can improve flowability and thermochemical outputs. The Crumbler rotary shear system was designed to achieve such ideal feedstocks to reduce costs and energy throughout the biomass supply chain. Improving the wear resistance of major components in this system is important to decrease the cost. Accelerating the feedstock flow through the rotary shear machine plays an equivalent role of improving its efficiency. An analytical analysis and a finite-element analysis of the stationary clearing plate are presented in this work. These tools are used to investigate the effect of contact surface curvature on the impact pressure. The optimized new clearing plate design is expected to improve the component's lifetime and wood chips flowability. The field tests confirm that the trend of the new clearing plate design guided by FEA. The optimization method, model verification, and validation experience applied in this work can also be applied to other static components with similar simple contact wear problems.

Keywords Biomass comminution · Clearing plate · Finite element simulation · Tool wear · Wood chip · Contact pressure

1 Introduction

For bioconversion reactors, the fuel-grade wood chips are always a major hurdle to consistent feed rate. The wood chips' various sizes and shapes can cause flow plug and poor flow. Previous research has identified the major barriers for efficient supply of feedstock [1–5], including the biomass flowability. To guarantee flowability, ISO standard allows only a small portion of larger chips [6]. Even within that standard length, traditional hammer mills tend to generate superfine particles, particles approaching the standard size limit, or particles that are super long/short in one dimension [7]. These variations frequently block the biomass flow in the processing system. In general, hammer mills are more energy consuming than other feedstock processing designs and always have the flowability concern.

✉ Lianshan Lin
linl@ornl.gov

✉ Jun Qu
qujn@ornl.gov

1 Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

2 Forest Concepts, 3320 West Valley Highway N., D110, Auburn, WA 98001, USA

Rotary shear mills are designed to improve upon the traditional hammer or knife mills. They can increase the percentage of biomass particles in small but uniform size, thereby mitigating feeding difficulties. The Crumbler rotary shear system is a rotary shear design developed by Forest Concepts, LLC, that successfully converts wood chips into much more uniform particles with improved system energy efficiency [7].

Previous research showed that the rotary shear unit's cutters experienced significant abrasive wear [8, 9], especially when processing hard and dirty biomass such as dirty logging residue and recycled railroad ties. A new clearing plate design has been developed by Forest Concepts, but further analysis is needed to optimize the new design, not only to improve component's wear resistance but also, more importantly, to improve the wood chips' flowability. Finite element simulations and analytical solutions have been widely used along with optimization functions [10–12] to improve the rotary mechanical system's or static structure's performance. Multiple optimization objectives were involved in the work [11, 12], significantly complicating the methodology and increasing the difficulties of experimental validation.

The following sections present how we simplify the dynamic interaction between moving wood chips and stationary clearing plate into analytical and numerical analysis. The basic geometry of the studied component is introduced in the Section 2. Based on current new clearing plate design and analysis results at the contact surface, the Section 3 introduces three different contact profiles that are proposed to further optimize the shape of clearing plate. The Section 4 presents all the related simulation outcomes. In the Section 5, the new clearing plate profiles are eventually validated via field test by assembling corresponding plates in a real rotary shear machine. Followed by the Section 6, some findings of this work are briefly summarized in the Section 7.

2 Current design of rotatory cutters and clearing plate

The current Crumbler rotary shear system consists of two rows of cutters that rotate against each other. The protruding blade teeth on the cutters drag and shear the feeding wood chips into smaller particles. Figure 1 illustrates the working mechanism of this rotary shear system, showing one pair of rotating cutters, one clearing plate, one spacer, and one feeding wood chip. The spacer blocks the wood chips from entering the shaft. The clearing plate has a Mickey Mouse-shaped design, as shown in Fig. 1 (green) that fits with the revisions in cutter blade and other components. The big wood chip enters the gap between cutters, and then the cutter's teeth and edges break it into smaller pieces. The resultant smaller wood particles hit the clearing plate's contact edge after moving along with the rotating cutters and then slip away from the rotary cutter system to the downstream. Forest Concepts have observed erosive and abrasive wear at the clearing plate contact edge, particularly at the A–C section in Fig. 1(b) and (c) where the wood particles and clearing plate have major contact interaction. Forest Concepts have also observed a wood particle flow problem at the clearing plate contact edge. The rotating cutters move the broken wood particles around to reach the clearing plate, bringing friction from the cutters' side surfaces to stuck wood particles in the gap. The broken wood particle flow capability significantly relies on the contact edge shape. As a new design, this Mickey Mouse-shaped clearing plate has little data on its flow capability. Therefore, a dynamic contact analysis between wood particle and clearing plate and optimization of the clearing plate contact edge are needed to improve the design.

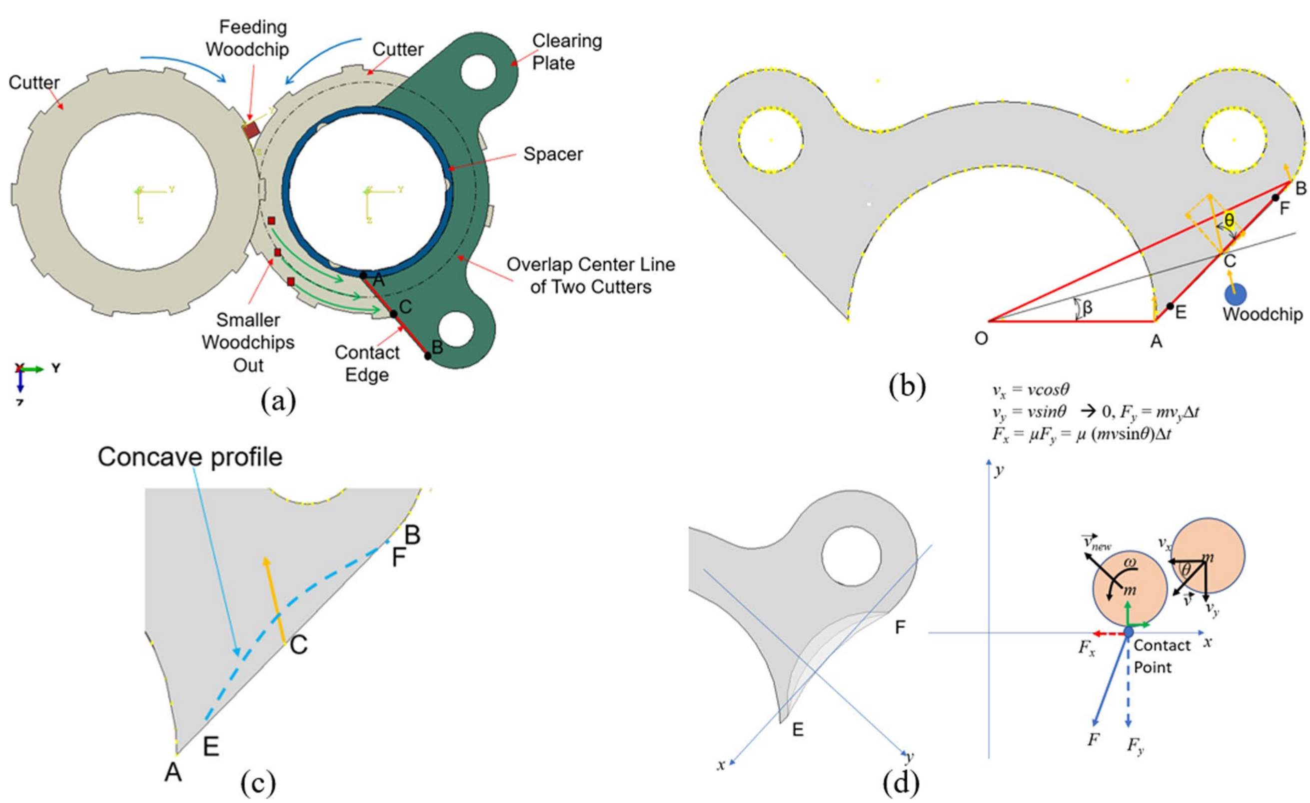

Fig. 1 Rotary machine biomass processing illustration and initial optimization idea of concave profile on contact edge. **a** System illustration showing cutters, clearing plate, spacer, and wood chip. **b** Current straight-edge design. **c** Illustration of concave profile between points E and F. **d** Wood particle impact analysis at local contact point and three concave profiles as new design candidates

3 Analytical analysis and numerical simulation

Assuming the wood rotates with the cutter to touch clearing plate edge AB, its rotating vector is centered at point O, which is also the center of the rotary cutter. In the current design, angle OAB is about 135°. Point C is about the center of edge AB and coincides with the cutter's outer rim. The initial idea is to revise the straight edge AB, particularly from section EF (point E and F are determined from field experience, AE: 3.175 mm, EF: 38.1 mm, little contact appears at AE section), into a concave curve. The concave profile between points E and F is expected to decrease the normal impact from wood particles, reduce the tangential resistance, and facilitate wood particle movement.

A simple analytical method is introduced in Fig. 1(d) to decompose the impact of wood particle on local concave edge EF. The wood particle (mass m) moves with initial speed $\vec{v}$ to reach the contact point and then bounces back with new speed $\overrightarrow{v_{new}}$ and angular velocity ω owing to the tangential contact force F_x from friction. When the particle touches the edge, the vertical speed component v_y decreases to 0 at time interval Δt, converting the momentum into vertical force F_y. Because of the frictional coefficient μ, the frictional force F_x on the tangential direction is proportional to F_y, which results in the bouncing particle's angular velocity ω. This analysis reveals that the small angle θ will simultaneously decrease vertical force F_y and tangential force F_x.

To further verify the effect of concave profile design, we perform a series of dynamic finite element simulations to understand the effect of the concave edge on the contact pressure. Between contact edge points E and F, three different concave profiles—shallow, medium, and deep—are planned in the finite element simulation. The wood particle has dimensions of 3.175-mm diameter and 3.175-mm length. These dimensions are based on the average particle size in the downstream. The finite element simulation focuses on the contact pressure, so we simplify the orthotropic wood chip material into an isotropic one: 12% moisture yellow birch was chosen as a representative so that Young's modulus $E = 13.9$ GPa, Poisson's ratio $\nu = 0.3$, and density $\rho = 762$ kg/m^3. The clearing plate is A2 tool steel, which has density of 7870 kg/m^3, Young's modulus 214 GPa, and Poisson's ratio 0.29 according to Granta's Cambridge Engineering Selector database [13]. The frictional coefficient μ between wood particle and clearing plate is 0.3, and general surface-to-surface contact interaction is used in the finite element contact solution. By overlapping the three concave profiles, Fig. 2(a) shows the geometry of the concave designs and the initial location of the wood particle. Denoting the center of the wood particle as point W, the radius R_wood that the wood particle rotates around the clearing plate center O has two values, 50.9 mm and 46.8 mm, and the particle has the same initial rotational speed of 100 rad/s. The radius of concave profiles R has three values: 58.7, 31.8, and 23.8 mm. The static clearing plate is fixed at the two inner circles of the Mickey ears, as shown in Fig. 2(b). Instead of using the algorithm to find the optimized contact edge shape on the clearing plate, we performed dynamic finite element simulations of the same wood particle hitting different concave edges. These results were compared with the result of original straight-edge design. This procedure avoided the iterations of contact edge design and reduced the optimization complexity.

The hard contact pressure–overclosure relationship in ABAQUS implies that [14] (1) the surfaces transmit no contact pressure unless the nodes of the secondary surface contact the primary surface; (2) no penetration is allowed at each constraint location (depending on the constraint enforcement method used, this condition will either be strictly satisfied or approximated); and (3) the magnitude of contact pressure that can be transmitted when the surfaces are in contact is unlimited. This hard contact mode agrees with the assumed behavior on the normal interface between wood chip and cutters; therefore, we adopt it for all the dynamic simulations in this project.

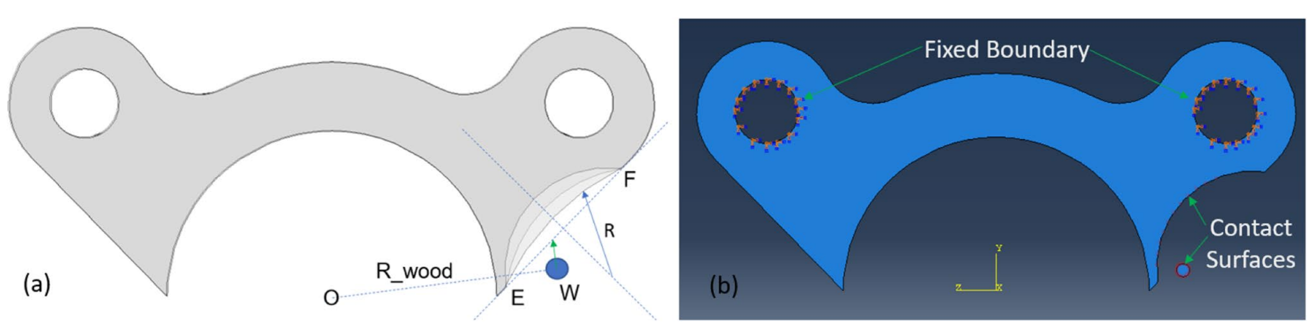

Fig. 2 Concave profiles and finite element model setup. **a** Three concave profiles and location of wood particle. **b** Boundary condition and contact surfaces

4 Simulation results

All the simulations were performed using the 2019 Golden (base) version of the finite element analysis software Abaqus/Explicit (Dassault Systèmes, 2018) [15]. With this finite element model setup, Figs. 3 and 4 show the contact pressures when the moving wood particle impacts the clearing plate edges, including the straight edge named "Original" and the other three concave profiles with radii 58.7, 31.8, and 23.8 mm, respectively. Figure 3 presents the results of the case in which *R_wood* is 50.9, and Fig. 4 presents the case in which *R_wood* is 46.8 mm. In each plot, the first row shows the contact pressure normal to the edge surface, and the second row shows the contact pressure tangential to the edge surface at the contact point. The contact pressures of these two cases are compared in Fig. 5. The contact pressure analysis among different edge profiles, along with the analytical solution, support using concave edges to reduce the normal contact pressure and shear friction. New clearing plates with three different concave profiles were manufactured and tested in a working machine to further validate our optimization design.

In finite element simulation, the contact pressure is sensitive to the mesh density. The mesh sensitivity in this clearing plate model is investigated by using the original straight-edge design in the *R_wood* = 46.8-mm case. The original straight contact edge surface is divided into 3 (thickness) × 20 (length) elements, which returns a maximum normal contact pressure of 5.38 MPa. Two finer meshes, 6 × 40 and 12 × 80, were tested on the same model, yielding maximum normal contact pressure of 19.29 and 41.85 MPa, respectively. The increasing maximum normal contact pressure indicates the stress localization when the mesh is refined, which is outside the scope of this work. All the finite element models in this work had the same mesh density, particularly on the contact edge, to enable comparable results.

5 Benchmark test results

Clearing plates with three different concave radii were manufactured and assembled in a real rotary shear machine for field tests. In the same test machine, different clearing plates—the original design and the shallow (*R* = 58.7 mm), medium (*R* = 31.8 mm), and deep (*R* = 23.8 mm) concave designs—were assembled in different sections for a better comparison. Owing to the difficulty of measuring the contact pressure in situ, a thin layer of white primer was painted on the concave surfaces to help expose the wear regions at these surfaces. Figure 6(a) shows these clearing plates in initial state before wood particles were fed into the machine.

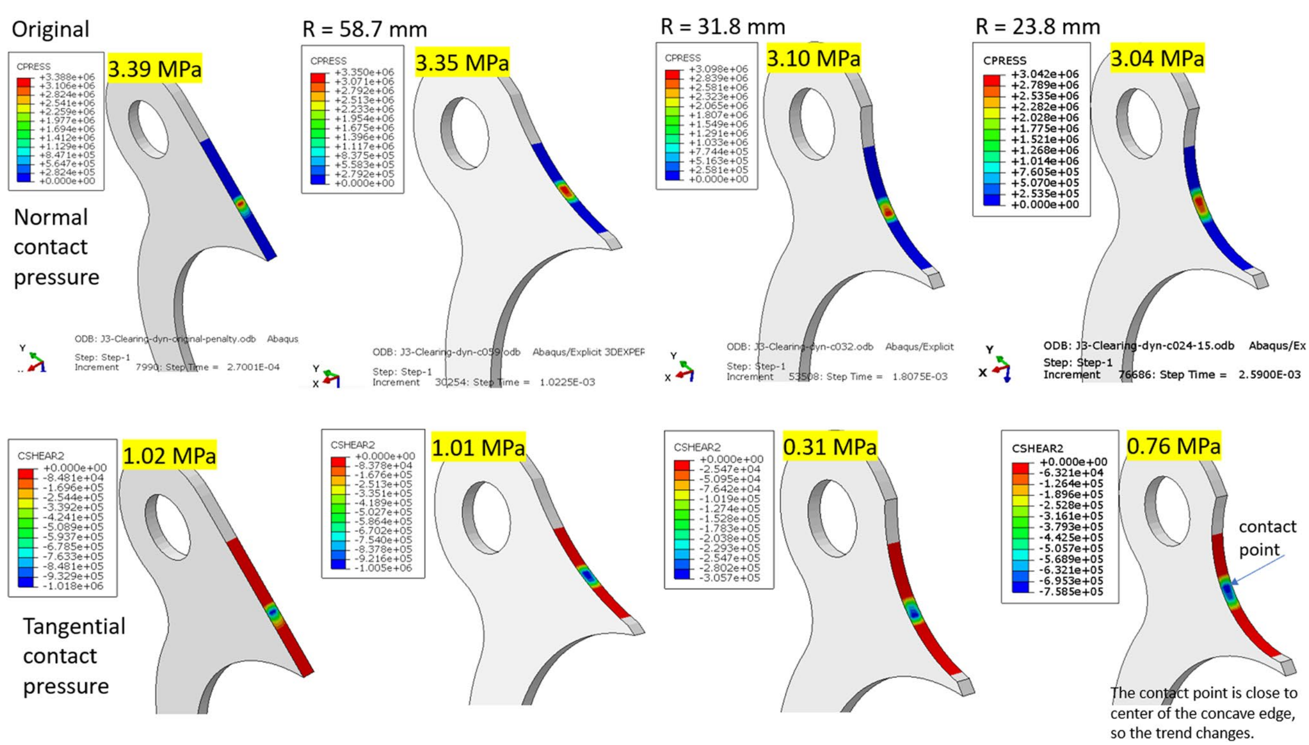

Fig. 3 Contact pressure of *R_wood* = 50.9-mm case, the first row for normal contact pressure and the second row for tangential contact pressure

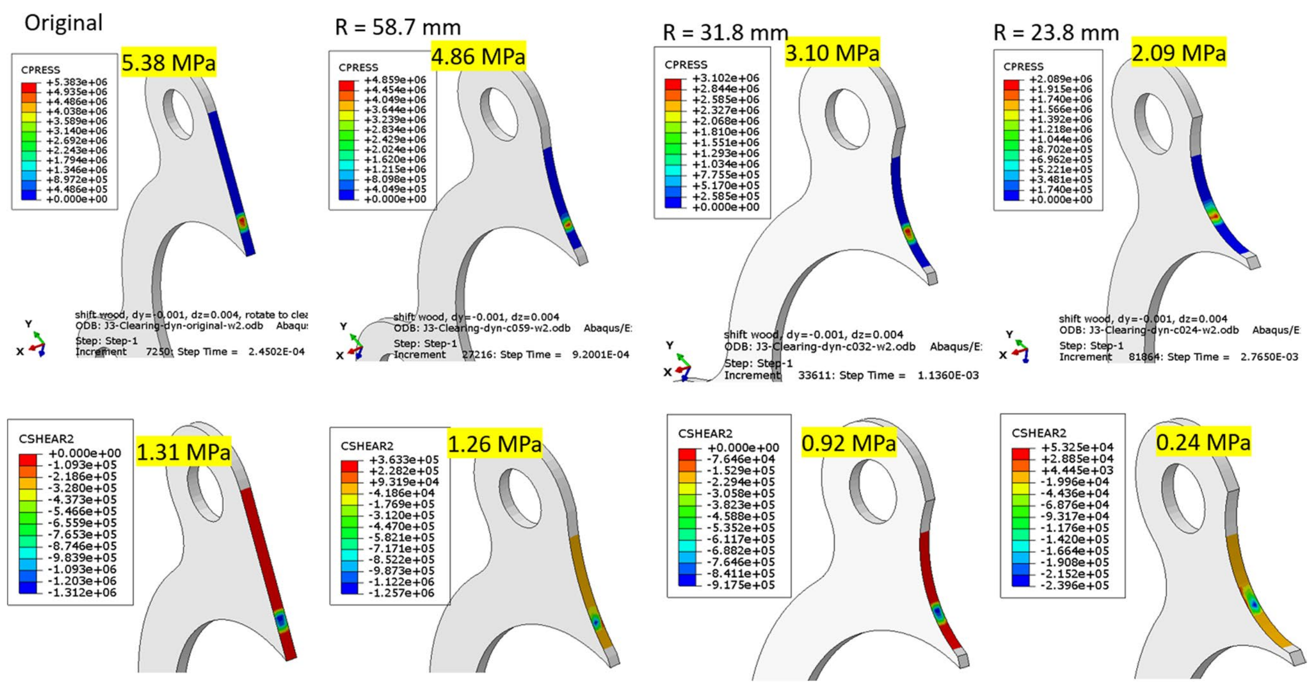

Fig. 4 Contact pressure of *R_wood* = 46.8-mm case, the first row for normal contact pressure and the second row for tangential contact pressure

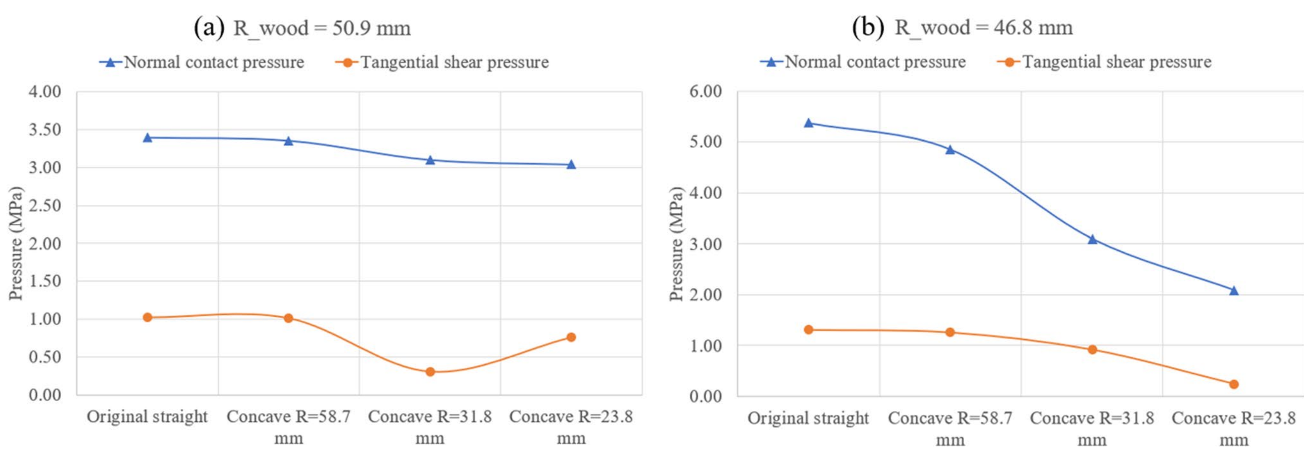

Fig. 5 Contact pressure for different edge profiles. **a** *R_wood* = 50.9-mm case. **b** *R_wood* = 46.8-mm case

Three batches (passes) of forest residuals were fed into the rotary shear machine. After completing the three batches, the machine was stopped to examine the difference in abrasion across the clearing plates. Figure 6(b) shows the side-by-side comparison of the representative clearing plates after the wear test. The baseline straight edge clearing plates clearly exhibits concentrated rubbing (paint off) against the woodchips at the first half of the arc (near the cutter center). The prototype clearing plates with a shallow curvature ($R = 58.7$ mm) had somewhat less concentrated rubbing. The clearing plates with a medium curvature ($R = 31.8$ mm) show more dispersed paint removal. The deep curvature ($R = 23.8$ mm) exhibited uniform paint removal on the receiving edge of the clearing plates but caused wedging problems during the test (shown in Fig. 6(c)).

The curved contact edge reduces the maximum contact pressure at the first half of the arc (near the cutter center), as predicted by finite element analysis in previous section. However, a higher chance of wedging occurred at the second half of the arc (at cutter perimeter as particle exits the machine). These hypotheses were confirmed in the experiments and the medium curvature was identified as the optimal design.

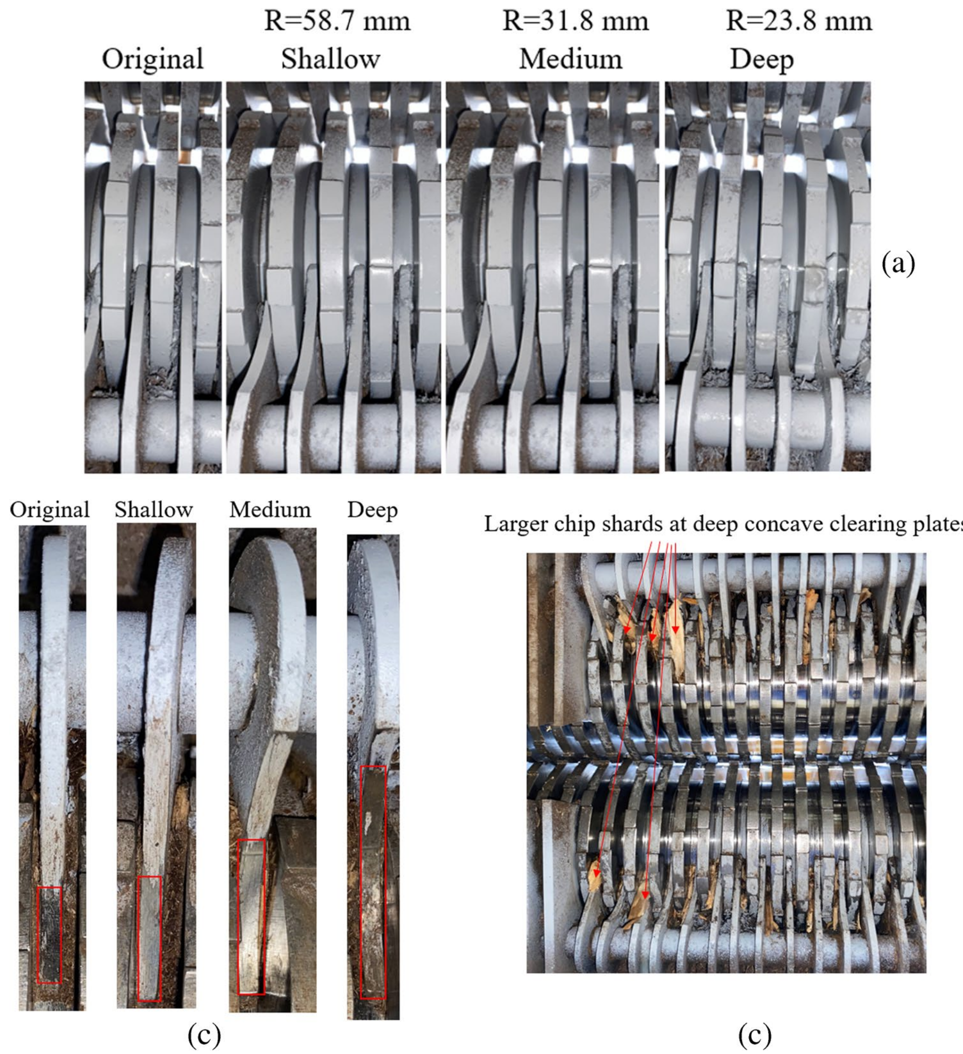

Fig. 6 Benchmark test of clearing plates in different concave radii. **a** Clearing plates were painted with white primer to enable visualizing wear location. **b** Clearing plates wear results with worn area highlighted in boxes. **c** Larger chip shards at deep concave clearing plates

6 Discussion

By comparing the pressure value of the original straight-edge design with concave designs, the finite element analysis suggests that the concave profile reduces the normal contact pressure when the wood particle impacts the first half of the concave profile (between point E and C). As the radius of the concave profile decreases, the concavity goes deeper into the clearing plate, yielding a smaller normal pressure. The tangential pressure also generally becomes smaller as the radius gets smaller, with only one exception in Fig. 3: the $R = 23.8$-mm case has a higher tangential value. A closer look at the contact point suggests that it almost reaches the point C, the midpoint of the concave profile. At this deepest location of the concave profile, the local edge is equivalent to its original straight edge, so the benefit of the concave shape no longer exists. This exception does not appear in the $R\_wood = 46.8$-mm case.

Of the new designs in the wear experiment, the shallow concavity design appears to experience the paint removal. The finite element analysis suggests that the near-tip section of the clearing plate is supposed to have higher contact pressure that potentially leads to wear and jam. A curvature is introduced to reduce the maximum contact pressure at the first half of the arc (near the cutters), but this curvature increases the chance for wedging at the second half of the arc (away from the cutters). For all the concave clearing plates, the wear test caused mild paint removal in the contact region and less material removal at the edge tip than the original design. The results validated the lower contact pressure with a deeper curvature result predicted by finite element analysis. However, larger chips wedged into the deep concave design in the analytical analysis and in the numerical simulation because of a larger angle θ, which led to a longer worn area (more than 75% of the curvature length) on the concave surface. This exception suggested that deep concavity might be excessive, and the shallow or medium curvatures appeared to be more appropriate.

7 Conclusions

In summary, the concave profiles will reduce the normal impact on the clearing plate edge and decrease the tangential contact pressure, which improves the wood particles' flow along the contact edge. Prototypes of new clearing plates with these different concave profiles were manufactured and assembled in a rotary shear machine. Field tests with wood chips revealed that the shallow and medium concave clearing plates could reduce the contact pressure on the contact surface compared with the original straight design, thereby increasing the feedstock flow after shearing and decreasing the abrasive wear. The deep concavity design was not suggested because of the unacceptable wedging of larger chips observed in field test.

Acknowledgements This research was sponsored by the Feedstock Conversion Interface Consortium of the US Department of Energy Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office. This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

Author contribution L. L.: conceptualization, methodology, investigation, formal analysis, writing: original draft.
C. M.: investigation, writing: review and editing.
D. L.: validation, investigation, writing: review and editing.
J. K.: conceptualization, writing: review and editing.
J. Q.: conceptualization, methodology, resources, investigation, project administration, supervision, funding acquisition, writing: review and editing.

Funding This research was sponsored by the Feedstock Conversion Interface Consortium of the US Department of Energy Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office.

Data availability Not applicable.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

References

1. Miao Z, Grift TE, Hansen AC, Ting KC (2011) Energy requirement for comminution of biomass in relation to particle physical properties. Ind Crops Prod 33:504–513
2. Mani S, Tabil LG, Sokhansanj S (2006) Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenerg 30(7):648–654
3. Shaw M (2008) Feedstock and process variables influencing biomass densification. Master thesis of University of Saskatchewan, Saskatoon, Saskatchewan, Canada
4. Felix E, Tilley DR (2009) Integrated energy, environmental and financial analysis of ethanol production from cellulosic switchgrass. Energy 34(4):410–436
5. Rezaei H, Lim CJ, Lau A, Sokhansanj S (2016) Size, shape and flow characterization of ground wood chip and ground wood pellet particles. Powder Technol 1(301):737–746
6. International Organization for Standardization (2020) Solid biofuels—Fuel specifications and classes—Part 9: graded hog fuel and wood chips for industrial use (ISO Standard No. ISO/TS 17225–9:2020). https://www.iso.org/standard/75158.html. Accessed 12/8/2022
7. Oyedeji O, Gitman P, Qu J, Webb E (2020) Understanding the impact of lignocellulosic biomass variability on size reduction process: a review. ACS Sustain Chem Eng 8:2327–2343
8. Lee K, Lanning D, Lin L, Cakmak E, Keiser JR, Jun Qu (2021) Wear mechanism analysis of a new rotary shear biomass comminution system. ACS Sustain Chem Eng 9(35):11652–11660
9. Lin L, Lanning D, Keiser J, Qu J (2022) Investigation of cutter–woodchip contact pressure in a new biomass comminution system. Front Energy Res 10:754811
10. Thai LM, Luat DT, Van Ke T, Phung VM (2023) Finite-element modeling for static bending analysis of rotating two-layer FGM beams with shear connectors resting on imperfect elastic foundations. J Aerosp Eng 36(3):04023013
11. Dang HM, Bui VP, Phung VB, Thom DV, Van Minh P, Gavriushin SS, Duc NV (2021) Development of a generalized mathematical model for slider-crank mechanism based on multiobjective concurrent engineering with application. Arab J Sci Eng 46:8037–8053
12. Ta DT, Tran VK (2020) Static bending analysis of symmetrical three-layer FGM beam with shear connectors under static load. J Sci Tech 15(3):68–78
13. (2014) GRANTA DESIGN software, CES Selector. Granta Design Limited, Cambridge, UK
14. (2019) ABAQUS Interactions, SIMULIA User Assistance Version R 2017x. Dassault Systemes Simulia Corp
15. (2020) ABAQUS Explicit dynamics analysis, SIMULIA User Assistance Version 2019. Dassault Systemes Simulia Corp