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Wear and Damage Study of Straw Chopper Knives in Combine Harvesters

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Abstract: Most of the biomass of cereal straw is chopped and left on the field as organic fertilizer, but its conversion into fertilizer depends on the quality of chopping, which is influenced by the wear of the chopping blades. The aim of the study was to determine the influence of the contamination of the cereal straw on the wear of the combine chopper blades. The study was conducted during the harvest in 2022, when 30 ± 1% of the grain was lodged and contaminated with abrasive soil particles (poor conditions), and in 2023, when the straw was unlodged and clean (excellent conditions). Six sets of blades with different mechanical and geometric properties were selected. The results showed that the wear ranges were very different: 1.47–2.99 g/100 ha in 2022 and 0.72–2.14 g/100 ha in 2023. For micro-abrasive wear, the hardness of the blades (349–568 HV) and the cutting edge angle (20°–29°) were important factors of their wear resistance. When the clean straw was chopped, the influence of the blade hardness and cutting edge angle on wear was not significant, and the wear was less. The wear of the blades had a sinusoidal character, which was related to the position of the blades on the chopping drum. This character depends on the design of the chopper and not on the straw quality.

Keywords: straw; crushing; knives; hardness; edge angle; wear; wear modeling

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1. Introduction

As agricultural technology improves in conjunction with changing farming techniques and the rapid increase in no-till farming, more and more farms are choosing to conserve resources and move away from straw crushing. The reasons why farmers choose no-till farming are often related to cost reduction. Jokiniemi and co-authors have found that not using scrapers and leaving the straw unchopped reduces combine fuel consumption by about 17% [1]. However, this does not take into account the damage to the soil and future yields. And it is not just a question of not spreading the straw on the field at all, but also that the yield depends on whether the chopped straw is spread well enough. For example, research by Halko and others has shown that chopping and scattering poor quality straw leads to a yield loss of around 7.1% in the following season [2]. Other studies [3–5] show that the quality of the chopped straw is not only crucial for increasing the dry weight of the crops grown, but also for the quality of the soil's regeneration time in terms of soil nutrients or technological efficiency in the production of bioenergy or biomaterials. Cereal straw is a biomaterial with great potential: around 144 million tons of biomass are cultivated in Europe every year. There are a number of scientific studies worldwide that investigate the influence of straw chaff quality on the effective conversion of straw into fertilizer [2–5] and on the quality of raw materials for renewable energy [6–10] or biomaterials [11,12].

In addition, coarse straw on the soil surface hinders tillage and spring sowing as it clogs the working parts of the machines. The studies by Bilgili et al. show that the coarsely chopped straw spreads less well on the soil surface, has less contact with the soil surface, is less moistened, and is less easily decomposed into fertilizer if it is not treated with special fungicides to promote decomposition [13].

The quality of the chopped material is therefore a very important factor, but it is influenced by the wear of the chopping blades. It should be noted that combine harvester manufacturers do not specify a criterion for the wear limit of straw chopping blades, as the intensity of wear is determined by many factors, such as the physical–mechanical properties of the straw to be chopped and contamination. It is very rare for a manufacturer to specify a total number of hours for the wear of a knife. For example, it is claimed that a typical hardened steel blade can be operated for about 350 h before it is completely worn out, and reinforcement with hard metal coatings can extend the service life by a factor of up to 1.5 [14], but the conditions under which this applies are not specified.

The shape of the blades used in combine harvesters can generally be divided into two types: smooth and serrated blades. There are different research results on how the shape of the cutting edge affects chopping quality and wear. Some researchers find no significant differences in terms of wear volume or cutting quality between smooth and serrated blades. For example, a study conducted in Sweden by Lundin et al. comparing chopping blades with smooth and serrated cutting edges found that the blades with smooth edges wore down by 2.02 g (0.83% of the weight of 243 g) and that the blades with serrated edges wore down by 2.02 g (0.84% of the weight of 241 g). The chop quality remained similar at the different outputs, with an average chop length of ≈31 mm (Figure 1) [15]. The moisture content of the straw in the trial was 18–27%, and the area of the cut and chopped cereals (wheat and triticale) was 219 ha. Looking at the statistical mean length of the chopped straw, it can be seen that the length of the straw chopped with smooth knives is slightly higher.

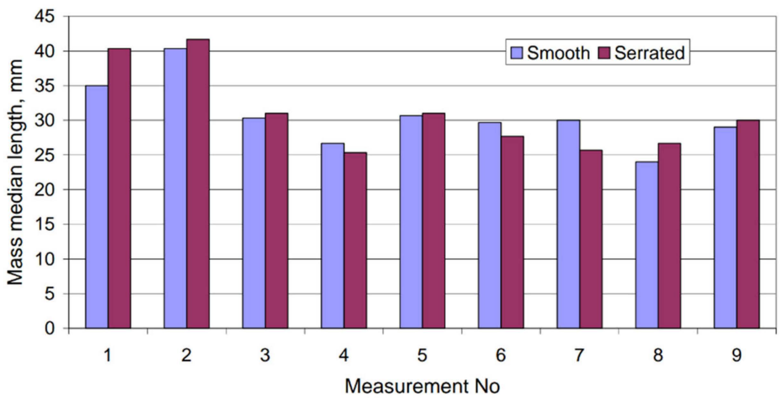


Figure 1. The average length of straw cuttings depending on the type of knife (left—smooth knives, right—serrated knives), after 9 measurements [15].

The different performances of smooth and serrated knives are confirmed by Gapparov and Karshiev [16]. In this paper, three different types of blades (fine-toothed, coarse-toothed, and smooth) are compared by analyzing the cutting quality and the damage/cracks on the surface of the chopped particles. It should be noted that the serrated blades are not double-edged, but also have cutting edges at the end of the blade. An overview of these blades can be seen in Figure 2.

With regard to the results of the study [16], the chopped straw was divided into three fraction sizes: >50 mm, 30–50 mm, and >30 mm (Table 1). Although the smooth double-edged knife had the longest cutting edge compared to the other knives tested, it was inferior to the toothed blades in terms of chopping quality. Various sources state that the cutting length should not exceed 30–40 mm. The type of cutting edge also resulted in a higher percentage of damaged clippings. The percentage of smooth blades was 78.9%, while the percentage of blades with fine and coarse serrations was 81.2% and 94.7%, respectively [16].

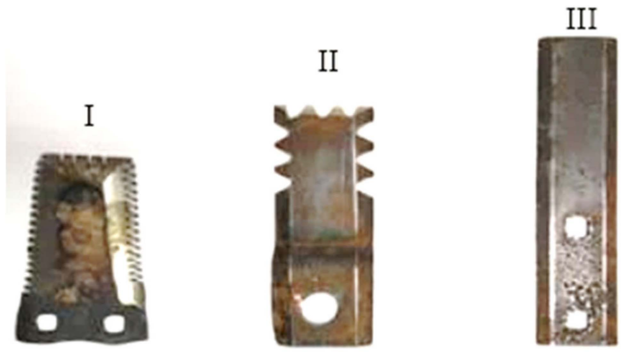


Figure 2. Images of different shaped knives: (**I**)—finely serrated edge; (**II**)—coarsely serrated edge; (**III**)—edge [16].

Table 1. Results of chopping quality and proportion of damaged cuttings for different blades, in % [16].

Variants	The Content of Fractions by Size, mm			Split Stems
	Longer Than 50	30–50	Shorter Than 30	
I	18.2	74.4	7.4	81.2
II	3.3	82.0	14.7	94.7
III	26.3	68.6	5.1	78.9

So, the wear of smooth and serrated cutting edges can be very similar; this is the same result as that in previous studies [15], but serrated cutting edges have a slightly higher comminution quality. And it seems that this is the case at the beginning of the work, when the teeth of the cutting edge are not yet worn down. It is possible that the cutting quality then equalizes, but there are no data on the differences in comminution between the wear of the smooth and the wear of the serrated cutting edges, which could be the subject of future research.

Figure 3 shows the view of the blades from our 2022 season study [17]. Thirty to seventy percent of the blade teeth are completely worn, suggesting that the quality of straw chopping may be affected by blade wear as the straw slides for a longer time on the friction-rounded blade edge before cutting. In this case, the work is a compromise, i.e., it is acceptable as long as the cereal straw is dry. With wet straw, chopping only occurs due to the high blade speed—the straw is folded and broken or torn, but not cut or sliced through.

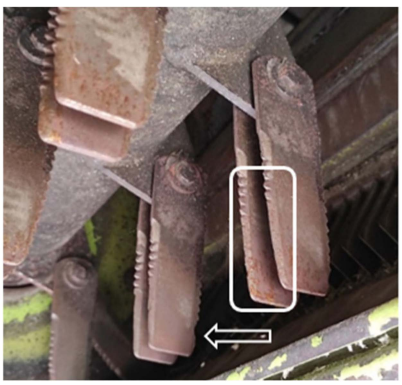


Figure 3. Chopper knives of the Claas Lexion 450 combine harvester. Complete wear of the knife teeth is shown by the white rectangle, and mechanical impact damage by the arrow [17].

There is work that states that cutting resistance can be effectively reduced by changing the cutting mode or changing the cutting edge profile according to the theory of slip cutting. One such study is presented by Hu J., Xu L. et al. [18], who simulate the influence of bionic cutting edges on the cutting quality of rice stalks. The images of the bionic and conventional blades are shown in Figure 4. In this study, discrete element modeling (DEM) of the cutting process was performed under the following conditions. According to the DEM results, the average and maximum cutting forces of the bionic blades were 44.9% lower compared to the smooth blades.

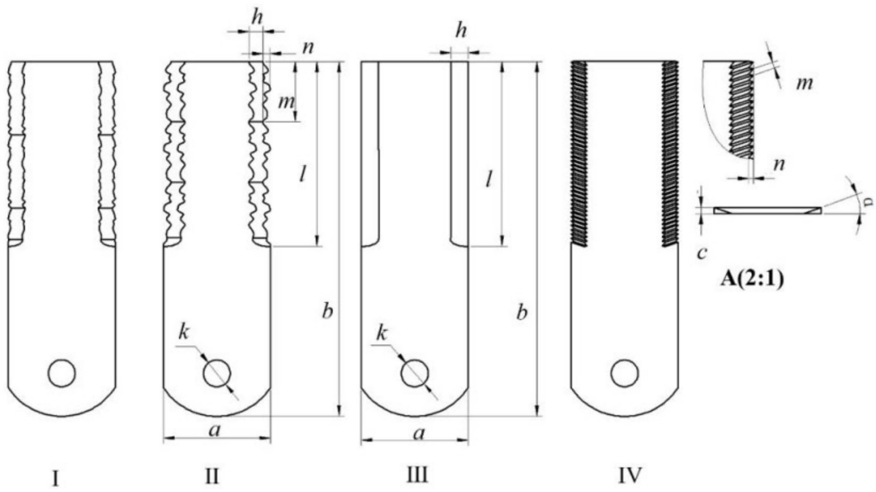


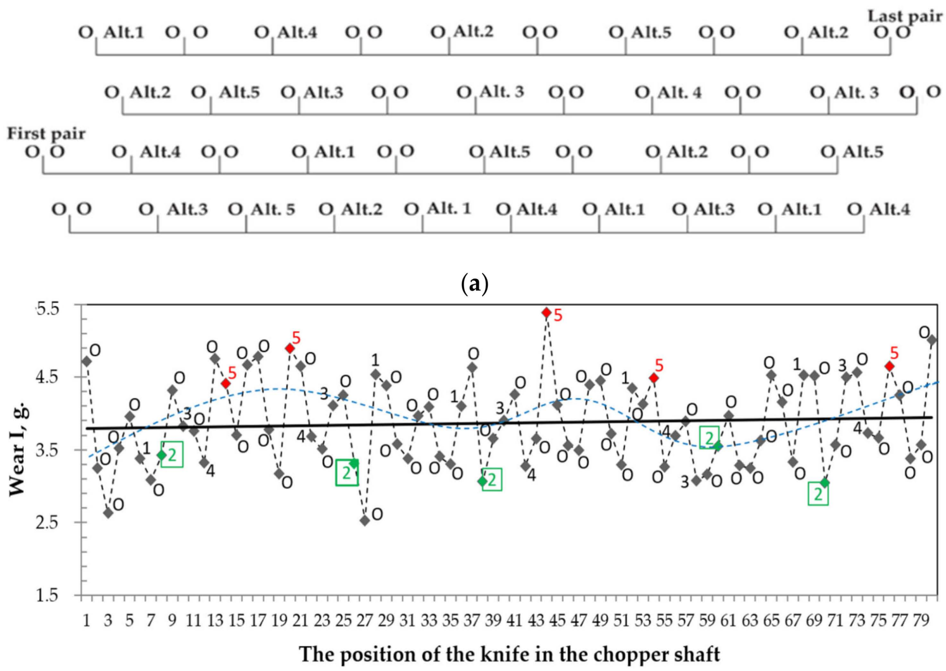
Figure 4. Bionic cutting blades (**I**,**II**) and general cutting blades (**III**,**IV**): (**I**), the edge of the left tooth of the locusta migration manilensis blade; (**II**), the edge of the right tooth of the locusta migration manilensis blade; (**III**), a smooth-edge blade; (**IV**), a serrated-edge blade; a is the blade width, mm; b is the blade length, mm; c is the blade thickness, mm; h is the blade width, mm; l is the blade length, mm; m is the tooth pitch, mm; n is the tooth height, mm; k is the diameter of the positioning hole, mm; α is the blade angle; A is an enlarged view of the serrated-edge blade [18].

A laboratory test by the same authors shows a similar result, namely that the average cutting force with a bionic blade was 18.74–38.2% lower than that of a smooth blade and 1.63–25.2% lower than that of a serrated blade, and the field tests show that the power consumption of the straw cutter with a quarter of the bionic blades was 5.48% lower than that of a device with smooth blades [18]. As the authors stated, the cutting force is lower because the specific shape of the blade increases the contact area with the straw; the cutting ability of the bionic blade is better, and the degree of compression deformation is relatively low. Despite the good properties of the bionic blade, there are no such straw chopper blades on the market in practice. Therefore, without field tests, it is difficult to predict whether such blades would actually work longer than the conventional ones under real conditions. The numerical or laboratory studies on cutting force are often performed or simulated with a single new sharp blade without evaluating the changes due to wear. Field studies show that this circumstance rapidly changes the sharpness of the cutting edge. The rounding of the cutting edge during wear reduces the contact stresses, resulting in a higher power requirement for the cut. According to the studies, the maximum instantaneous cutting force can be up to 38.5 N at 2000 rpm and up to 60.1 N at 3000 rpm, which means that the power consumption increases accordingly [19].

Summarizing the results of the literature review and personal experience, it can be said that the most important factors influencing the cutting force are the cutting speed, the cutting angle (or shape) of the blade, and the distance (cutting gap) between the two counter blades.

The Claas combine harvester used for our study in the 2022 [17] and 2023 seasons has a cutting gap of 25 mm and a blade thickness of 4.0 mm. It is therefore clear that the possibility of straw shearing is not provided for in the design of the chopper. However, the cutting speeds in real choppers reach 92 ms^{-1}. The high peripheral speed of the blade means that part of the straw is cut "in the air" and another part is bent and broken or torn. The bending, especially when the blades are rounded due to wear, is caused by the fact that cellulose, the main component of straw, is an anisotropic (flexible) material [18]. The straw is best chopped when the distance between the blade and the counter blade is about 8–10 mm [19].

The idea for continuing the research was based on a study on combine blades in 2022, published in [17]. When the study was planned for 2022, it was not known that blade wear was related to the blade position on the combine drum. In this study, it was found that identical blades wear at different rates and that this is influenced by the different number of blades (one or two) passing through the same counter blade gap during operation. The wear of the blades had a sinusoidal character (see Figure 5b). When two blades operate in the same counter blade gap, the wear is less than when one blade operates in the same counter blade gap. However, the combined wear of two blades (working in the same back cutting gap) is greater than that of one blade working in the same back cutting gap.



(**a**)

(**b**)

Figure 5. Straw chopper blade wear study: (**a**) Diagram of the arrangement of the blades in the shaft of the straw chopper; (**b**) blade wear rates and average wear in the 2022 harvest ("O"—original, other manufacturers' blades: 1—Alt. 1, . . ., Alt. 5) [17]. The blue line (polynomial function) represents the average wear values of the blades according to the mounting position; black line in the graph shows wear average.

This study of the 2022 season was conducted under poor harvest conditions, when about 30 ± 1% of the harvested area was lying. The crop entering the combine's threshing, cleaning, and chopping systems was covered with soil (abrasive), and the wear of the chopping blades depended solely on the hardness of the blades—the harder the blade edge, the lower the wear [17]. It has been shown that micro-abrasive wear predominates at the high speeds of the movement of parts in an abrasive environment [20].

The aim of this study was therefore to investigate the dependence of the wear of the chopping blades on the position in the chopping drum and the mechanical properties in clean, non-lying grain (good working conditions) and to compare these results with the investigations of the 2022 season in order to determine the effects of the quality of the chopped straw on the wear of the blades under different conditions. An analysis of the mechanical damage caused by foreign bodies is also carried out. We hope that the results of these studies will help to predict the need for spare parts during the harvest season.

2. Materials and Methods

Sixty blades were used to determine the factors influencing wear ("Original" and four alternatives from different manufacturers, labeled "O" and Alt. 1, ..., Alt. 5). In the 2022 study, the random principle was used for the positioning of the blades in the chopper shaft, but after it was found that the position of the blades influenced wear [18], this principle was abandoned in the 2023 study.

The Claas Tucano 450, 220 kW combine harvester (CLAAS KGaA mbH, Harsewinkel, Germany), which is equipped with a 9 m^3 hopper, was chosen for the trials. A belt drive rotates the chopper shaft at a rotational frequency of 3550 rpm. This speed, the diameter of the chopper shaft, and the length of the knife resulted in a circular speed of the knife of 92 ms^{-1}.

The arrangement of the knives in the chopping drum for the 2023 study is shown in Figure 6. The images of the test objects were taken with a Sony A7 II 28–70 mm OSS digital camera (Japan).

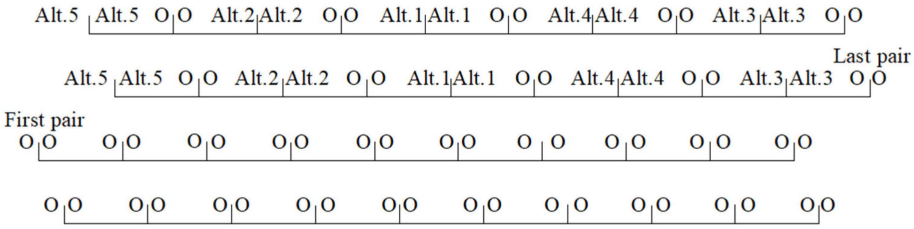


Figure 6. Position of the 80 blades on the loop's chopper shaft of a Claas Tucano 450 combine harvester.

Eighty blades are hinged in four rows (all 90°) to 40 loops on the chopping shaft. Two blades are attached to a loop axis with a distance of 25 mm between the blade planes. The chopping blade is usually hardened by induction heating. The blades are double-edged, with serrated blades with overall dimensions of 173 × 50 × 4 mm and a mass of 222–225 g [18]. The length of the cutting edge is 85–90 mm.

For the 2023 season study, a set of blades from the 2022 season study was used, with the second cutting edge not yet used (double-sided blade). In this way, we were able to maintain the characteristics of the blades for the 2023 study. The set of five blades from the different manufacturers was reduced to four blades, as one blade was used for each of the metallographic examinations in the 2022 season study. The remaining four blades from the different manufacturers were positioned on the shaft by evaluating the sinusoidal characteristic of the influence of position on wear. According to the information obtained in [17], the following blade positions were selected: minimum wear for two of the four blades (position of two blades working in the same counter blade gap) and maximum wear for the other two blades (position of one blade working in a counter blade gap). The remaining positions were filled with "original" blades ("O"—in the diagram) (Figure 6).

The properties of the blades used were different. The blade hardness, cutting edge angles, chemical composition, and average wear are given in Table 2. This was another reason why the blades had to be arranged in a certain order in the drum to ensure uniform wear conditions.

The work has continuity and is based on a comparison of results, which is why the data for the study conditions of 2022 are also presented. The harvest took place on a farm in Šakiai district, Lithuania, in August 2022. One hundred and thirty hectares of wheat (varieties Etana, Skagen) and 50 ha of rapeseed (Dominator) were harvested (180 ha in total). The proportion of laid crops in 2022 was 30 ± 1%. The average working speed of the combine harvester was low (4 km/h) due to the lying crop [17].

The 2023 harvest took place on the same farm in Šakiai district, in August. A 200 ha area was harvested with nothing lying on it (0%). The working speed of the combine harvester was 3–4.1 km/h. The low speed was influenced by the large amount of straw mass to be chopped, as the cereal base was the wheat variety Wendelin (175 ha), which is genetically highly contaminated [14], and the straw itself was not completely dry (25 ± 3%

moisture content) due to the wet weather conditions. Twenty-five hectares of oilseed rape was used (Dominator variety), i.e., a total of 200 ha.

Table 2. Cutting edge angle, average wear during testing (2023), hardness, and chemical composition of the chopper blades [17].

Sample	Edge Angle Θ, Degree	Hardness H, HV	Wear I, g	Chemical Composition by Mass (%)						
				Fe	C	Si	Mn	Ni	Cr	V
"O"	24.6	515 ± 14	2.35 ± 0.65	97.07	0.35	0.26	1.00	0.017	1.03	0.17
Alt. 1	24.0	394 ± 12	2.16 ± 0.37	97.46	0.23	0.22	0.89	0.030	1.00	0.12
Alt. 2	20.9	568 ± 11	2.64 ± 0.36	97.17	0.42	0.24	0.89	0.030	0.98	0.13
Alt. 3	27.1	469 ± 11	2.19 ± 0.27	96.80	0.30	0.22	0.97	0.122	1.03	0.17
Alt. 4	25.4	540 ± 12	2.07 ± 0.58	96.97	0.35	0.34	0.97	0.047	0.93	0.13
Alt. 5	29.2	349 ± 9	2.25 ± 0.19	97.95	0.16	0.24	0.90	0.030	0.49	0.04

The moisture content of the straw was determined using an MLW WSU 100 laboratory drying/heating oven (Memmert GmbH + Co. KG, Schwabach, Germany). Methodology—the sample was weighed before and after 24 h at 105 °C. The moisture content was calculated as the ratio of the difference between the masses of the samples and the initial mass of the sample.

Blade wear was measured to the nearest 0.001 g by changing the weight using a KERN 420-3NM balance (KERN & Sohn GmbH, Balingen, Germany).

The kinetic energy of the blade, which is calculated from the mass of the blade and the circular velocity of the center of mass, was 390 J. It is obvious that a breakage of the blade or a detachment of the blade from the suspension axis is extremely dangerous. The deformation of the chopping blades was examined to assess the risk of foreign bodies entering the threshing and cleaning mechanisms. Foreign bodies that damage the blades can cause the blades to come into contact with the counter blades and damage the balancing of the chopper shaft. The distance between the counter blades is 25 mm, and the blade thickness is 4 mm. According to these criteria, a deformation of the blade plane of up to 10 mm does not represent a significant risk. If the chipper is adjusted so that the blades do not reach the counter blade gap, a larger deformation is not dangerous. The deformation was determined using a Mitutoyo IP67 300 digital caliper gage (Mitutoyo Europe GmbH, Neuss, Germany).

The relationship between the blade hardness (HV), the cutting edge angle (Θ), and the blade wear was analyzed by MATLAB 2022a software using an Excel data file. The curve fitter tool was used, and a 95% confidence level was set. Only one of the several tested models was selected for further analysis. The selection criteria comprised the highest R^2 value and the lowest residual errors. The reliability of the results was assessed by performing a correlation analysis between the simulation and the experimental results in Excel based on the equation obtained.

3. Results

3.1. Wear Study

The visual change in the working surfaces of the blades used in 2022 is shown in Figure 7. The arrow shows the working surface, which is already worn, and the opposite surface, which is not worn (the cutting edge is perpendicular to the tip). The difference is easy to recognize.

Visual wear of the chopper blades in the 2023 harvest is shown in Figure 8.

The visual assessment (based on the rounding of the cutting teeth) shows a higher wear of the blades in the 2022 harvest (Figures 7 and 8). This is confirmed by the mass loss measurements: In 2022, the blade wear was between 2.64 and 5.39 g or 1.47 and 2.99 g per blade/100 ha, while in 2023 it was between 1.44 and 4.29 g or 0.72 and 2.14 g per blade/100 ha.

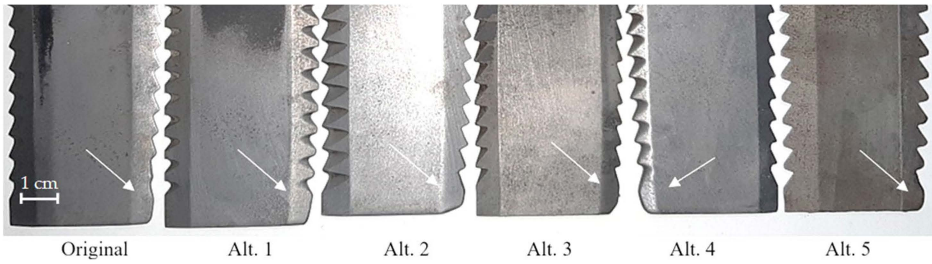


Figure 7. The visual typical difference between non-worn and worn chopping blade edges tested from "Original" to Alt. 5 after chopping the straw of cereal and oilseed rape from 180 ha area (white arrow indicates worn edge) [17].

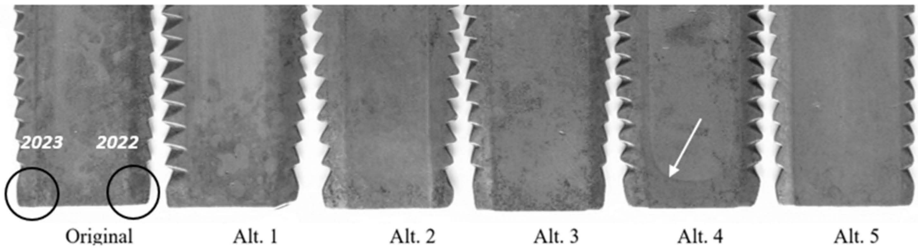


Figure 8. Visual wear of the blades in 2022 and 2023 harvests (right edge/angle used in 2022 harvest, left—in 2023 harvest). Worn chopping blade edges were tested from "Original" to Alt. 5 after chopping the straw of cereal and oilseed rape from a 200 ha area [17].

The sample Alt. 4 shows clear traces of heat treatment by induction heating, indicated by the arrow (Figure 8), but metallographic examinations of the microstructure of the blades from different manufacturers show that all the manufacturers used this hardening method [17]. This is the way to obtain the impact toughness of the blade steel, which is dictated by safety requirements.

The wear rates by mass for all the blades in 2022 and 2023 are shown in Figure 9.

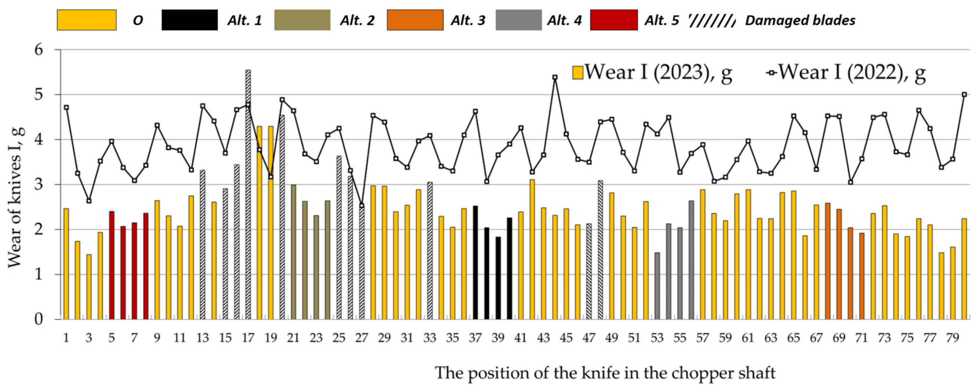


Figure 9. Individual and average blade wear in harvests of 2022 [17] and 2023. Color coding of chopper blade manufacturers.

Figure 9 shows the differences in the average wear values and the wear of the various blades in the years 2022 and 2023. The upper curve is the same as in Figure 5b. In all positions (1 to 80) where more blades were worn in 2022, more blades were worn in 2023, which means that the shape of the sine curve remains the same. The peaks of the upper curve of the year 2022 research coincide with the highest columns of the histogram of the year 2023 year research. But the values of the histogram are smaller than those of the curve. This means that the dependence of the wear on the position of the blade in the drum has not changed; the main difference is the amount of wear. This is a design feature of the shredder. Dashed columns mean that the blades have been damaged by foreign objects.

It should be noted that such damage as the chipping of the corner or teeth of the blade (will be discussed in Section 3.2) is probably due to contact with a small stone and does not change the wear results too much (dashed columns 13, 15, 25–27, 33, 47–49, Figure 9). However, larger bodies (especially metallic ones) can even seriously damage the geometry of the blade. In such a case, the wear of undamaged blades working together with damaged counter knives can reach higher values (columns 18, 20 and 17, 19 in Figure 9). All blades chop the straw by passing between the two counter blades, but half of the blades work in a (single) counter blade gap; the other half work through the counter blade gap by "passing" two blades. Two blades of the chopper passing through the counter blade gap are less worn than one blade performing the same function. However, the combined wear of two blades (working in the same counter blade gap) is higher than that of one blade working in the counter blade gap.

The average wear of the blades from the different manufacturers for the 2022 and 2023 seasons is shown in Figure 10.

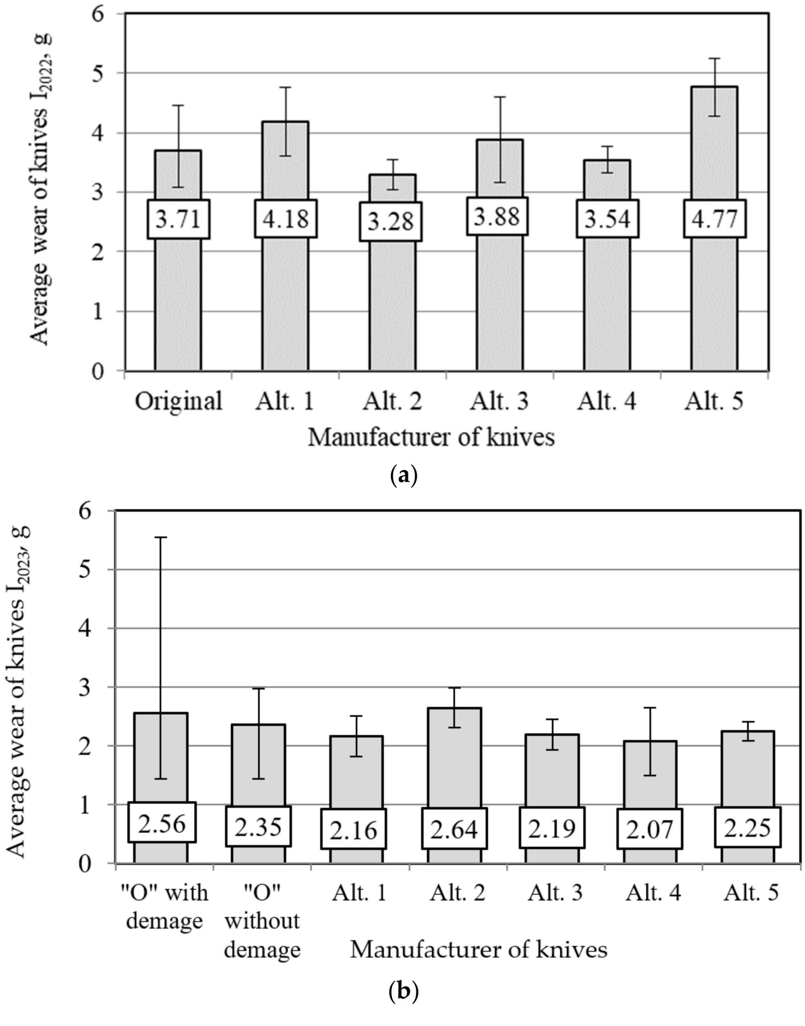


Figure 10. Average wear of blades from different manufacturers and their dispersion intervals: (**a**) 2022 [17], (**b**) 2023.

In 2022, the chopper blades used from different manufacturers had different (some of them statistically significant) differences in wear rates. In the 2023 season, as the average wear rates decreased, there were no statistically significant differences. The blades working in clean cereal mass "leveled off" in terms of wear resistance parameters, with not only a significant reduction but also no significant effect of blade hardness on the magnitude of wear. In the presence of abrasive aerosol in the cereal and air mass, the abrasion of chopper blades is influenced by micro-abrasive wear [17,20]. As a rule of thumb, harder steels with higher carbon content wear more slowly. Blades with a lower blade angle also tend to wear more slowly [17].

Figure 14 shows that the wear of the chopper blades during the 2023 harvest was significantly lower, even though 11.1% more cereal area was harvested. For the different blade manufacturers (for different blade hardnesses and blade angles), the reduction in wear in the 2023 season ranged from 25.3% (Alt. 2) to 64.6% (Alt. 5). The reduction in wear for the original blades was 40.7%.

There was only one potential influencing factor that reduced wear in the 2023 season—the absence of lodging (0%). The emergence of ≈30% of the acreage in the 2022 season resulted in the cereal stalks being covered with soil particles sprayed by raindrops. The contaminated stalks released abrasive particles due to the impact of the threshing drum; these were converted into an aerosol (a mixture of air, plant matter, and micro-abrasive dust) that moved towards the chopper. The aerosol of micro-abrasive particles and the residue of the abrasive particles on the chopped grain stalks created the conditions for the development of an erosive micro-abrasive wear process [17,20].

The average wear of the blades from different manufacturers in 2022 was calculated and showed that most of them had significant differences in average wear. The 2022 study showed that the micro-abrasive contamination of the stalk mass and the wear caused by the abrasive dust were the main factors; so, the blades with a higher hardness had a lower wear rate [17]. In the 2023 harvest, blade hardness had little effect on blade wear, but in contrast to 2022, the blade wear tended to be higher with increasing blade hardness (Figure 11). Considering that the chopped straw had a moisture content of 25 ± 3%, the wear results can be explained by the results of the study by [21]. They show that as the hardness of the steel increases, the corrosion resistance of the steel decreases as the amount of martensite and bainite in the steel increases. The microstructure of the straw chopper blades is discussed in [17].

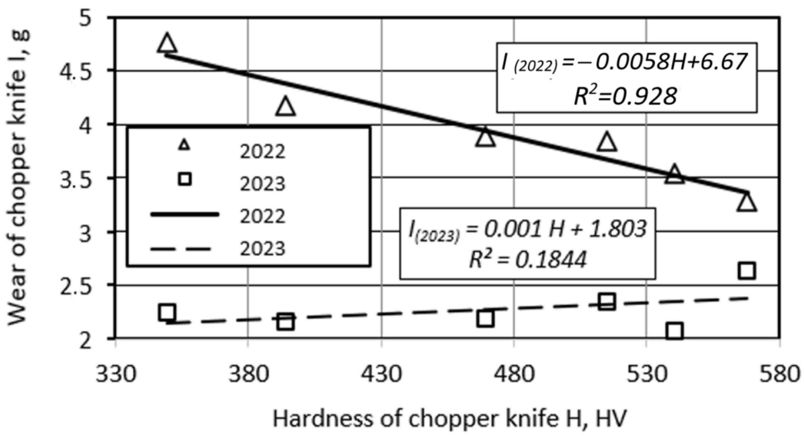


Figure 11. The effect of blade hardness on wear in 2022 [17] and 2023.

The results of the 2022 study show that the higher the cutting edge angle, the higher the wear [17], because the higher the contact angle with the abrasive particles, the higher the contact forces that cause microchipping of the blade steel. The effect of the cutting edge angle on blade wear in 2023 is shown in Figure 12. This is a significantly different result. If the crop is cut without storage and without contamination by abrasive microparticles, an increase in the blade angle (regardless of the other blade properties) leads to a slight reduction in wear.

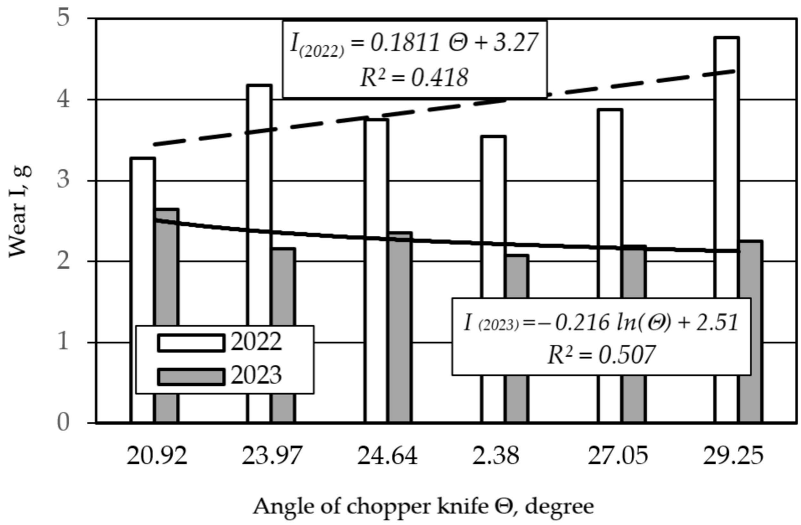


Figure 12. The effect of blade angle on wear in 2022 [17] and 2023.

As shown in Figure 13a, the wear intensity varies depending on the main influencing factors (hardness H and angle θ of the blade edge), according to a quadratic function described by the following equation (95% confidence level):

$$I = f\,(H, \theta) = -7.37 + 6.55 \times 10^{-3}\, H + 8.21 \times 10^{-2}\, \theta - 5.83 \times H2\ \theta 2 + 1.08 \times 10^{-3}\, H\, \theta \qquad (1)$$

where H is the Vickers hardness of the cutting edge, HV; Θ is the angle of the cutting edge, in degrees. The correlation plot between the experimental and simulation data (sum of squares of residual errors, SSE = 0.001243098) is shown in Figure 13b.

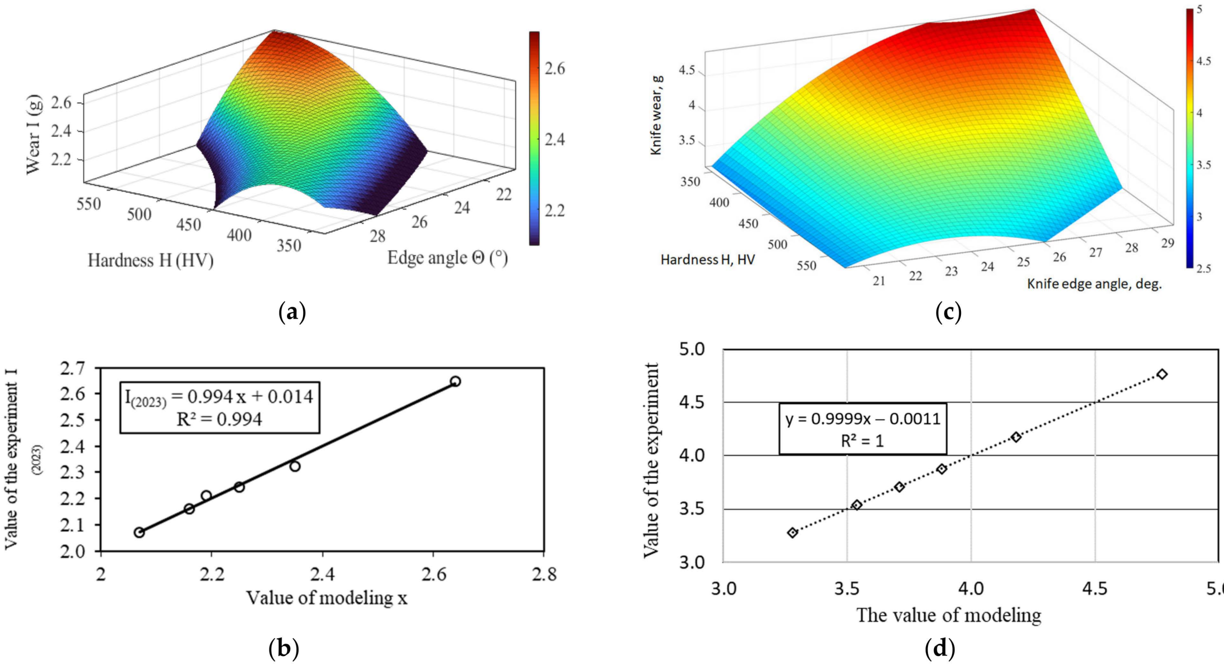


Figure 13. Simulation results: (**a**) Plot of the dependence of wear I_{2023} on the main influencing factors (H, Θ); (**b**) plot of the correlation between the experimental (2023 season) and the simulation data (sum of the squares of the residual errors, SSE = 0.001243098); (**c**) plot of the dependence of wear I_{2022} on the main influencing factors (H, Θ) [18]; (**d**) plot of the correlation between the experimental and the simulation data (sum of the squares of the residual errors, SSE = 1.664×10^{-27}) [18].

Figure 13 clearly shows the difference between the wear results when the clean and abrasive-contaminated straw were crushed. In the case of clean straw, the total wear was lower. But, if the angle Θ of the cutting edge was higher, the wear would not be so intensive if the hardness increased. And when Θ was smaller, then the higher the hardness and the higher the wear (Figure 13a). Everything was different when shredding the abrasive-contaminated straw. At a small angle, the wear intensity did not depend much on the hardness. But at larger cutting edge angles, the wear values increased dramatically (Figure 13b).

Compared to the 2022 factors of blade hardness and angle on wear, the 2023 response is more complex. Higher hardness and lower blade angle led to higher wear. At low hardness (350–400 HV), the effect of angle variation on wear is lower. At higher edge angles (which do not change), but only with increasing hardness, the wear initially increases and then tends to decrease. However, if the edge angle remains unchanged and only the hardness increases, the wear increases. The lowest wear is observed under different conditions. With a larger blade edge angle, the lower wear is due to the higher hardness, but with a smaller blade edge angle, the lower wear is observed with a lower blade edge hardness.

3.2. Evaluation of Mechanical Damage

Figure 14 shows images of one used and two new Alt. 1 blades, which show via comparison that the tips of teeth 1–4 and the blade edge angle (black rectangle) are the most worn. The wear on teeth 6–7 (black square) was insignificant.

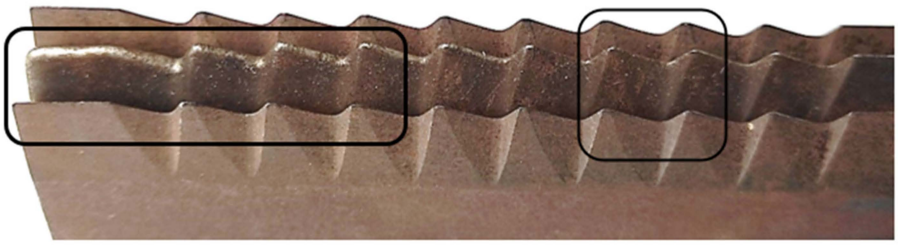


Figure 14. Comparison of the cutting edge conditions of the Alt. 1 blades: the external blades are new, and the middle one was used in the 2023 season. Magnification 2×.

Although the wear is only 2–3 g, the changes and differences in the rounding of the blade corners and tooth tips are obvious. This inevitably leads to a change in the deformation and separation conditions of grain stalks [18].

It is logical that foreign bodies with a greater mass cause more damage (or total loss) to machine elements. The type of foreign bodies (in shape and material) that damage the chopping blades of the combine harvester remains undetermined, apart from the special case where the chopper is stopped by a metal body of a suitable size. This is a special feature of the design work. There is no doubt that the introduction of foreign bodies into the combine harvester is the result of agrotechnical culture (contamination of fields with stones and other debris).

In the 2022 season, 4 blades were damaged under poor working conditions (lodged cereals), while in the 2023 season with no lodged cereals, 11 blades (15%) were damaged. This is an unexpected result, and there is reason to believe that accidental causes predominate. Those damages can be divided into two groups: cutting off and cutting off in combination with deformation. The mechanical damage to the chipper blades caused by foreign bodies is shown in Figures 15 and 16. The average weight change (2.56 g) of the blades with cut-off damage was 8.2% higher than the average wear (2.35 g) of the mechanically undamaged blades. The blades with combined damage had a mass loss of 5.54 g. Some of the mechanically damaged blades are shown in Figure 15. The blades are damaged the least when the point of impact is at the corner of the cutting edge (Figure 15a,b). The greatest damage is caused when the impact occurs near the center of the blade (Figure 15e). However, due to the high rotational speed of the chipper shaft, these cases are rare.

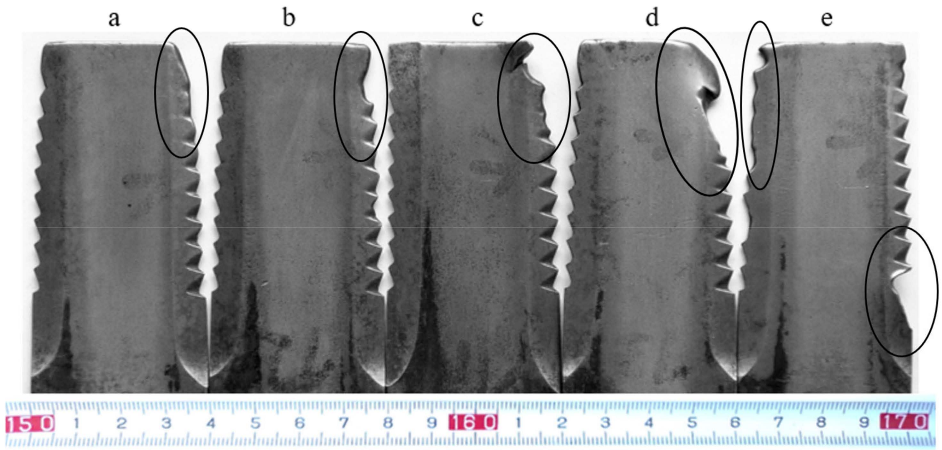
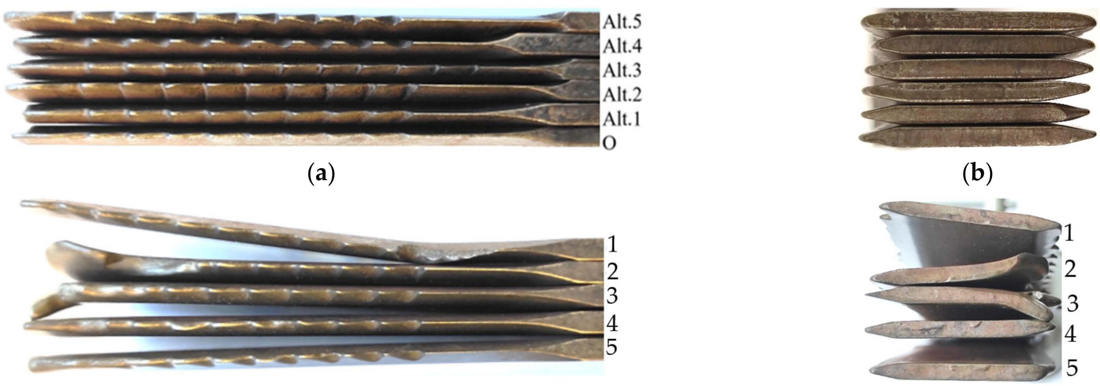


Figure 15. Mechanical damage to the right cutting edge of the chopper blades caused by foreign bodies (view of the blade plane).



(**a**) (**b**)

(**c**) (**d**)

Figure 16. Damage to the cutting edges of the chopper blades used in the 2023 season: (**a**) normally worn cutting edges and the end views of them (**b**), (**c**) the cutting edges of the blades that have been deformed by impacts and the end views of them (**d**).

The material (metal, stones, etc.) and characteristics (mass and shape) of these objects entering the threshing and cleaning device are not known. However, the observations can be summarized as a whole. From the blades damaged in the 2023 season, five were selected that were characteristic in terms of the degree of damage, but with different degrees of deformation. The mechanical damage to the blades was divided into three groups: (I) fracture of teeth 1–2 or corner displacement (Figure 15a,b,e), (II) bending of the blade corner with/without cracking of the blade steel and damage to up to three or four teeth (Figure 15c,d), and (III) deformation of the blade plane and fracture of the blade plane (Figure 16c,d).

The high speed of the chopper (3550 min^{-1}) is most likely to cause damage (deformation) at the corners of the blades and the first and second teeth. The proportion of such damage was the highest at 11.25%. In the presence of a large/massive foreign body, the blade angle can be deformed; furthermore, the body of the blade can be torn off or ripped, damage can reach the fifth tooth, and blade body deformation and splitting can occur (Figure 16c,d). The proportion of such blades was 2.5%. If the impact point is in the middle of the blade (20–35 mm from the corner), planar deformation begins (bending of the blade, Figure 16c, 1). The impact is also transmitted to the axes of the blade attachment, significant damage is created at the point of contact (possibly on both sides), and the shape of the blades resembles that of an aircraft propeller. In this case, the rotation of the blade around the attachment point/axis requires a large change in the moment of inertia/impact energy, which leads to high damage. This is best illustrated by the two projections of the blades—the cutting edges and the rear view. The share of such blades was 1.25%. The quantitative and qualitative characteristics of the damage to the chopper blades are presented in Table 3.

Table 3. Quantitative and qualitative characteristics of blade damage.

Damage Group	Attribute	Blade	Damage Characteristics
I	Breaking of teeth 1–2 or chipping of a corner	Figure 15a	7 mm blade plane deformation
		Figure 15b	Local 1 mm corner deformation
II	Bending of the blade corner with/without tearing of the blade steel, damage up to teeth 3–4	Figure 15c	Local 6 mm corner deformation
		Figure 15d	Local deformation of the point of damage (4 mm) and plane (7 mm)
III	Deformation of blade plane, fracture	Figure 15e	12 mm blade deformation. Impact location—center of blade (helical deformation)

Figure 16a shows that blade length can be different by up to 10 mm. According to Figure 14, the significant wear can be seen on teeth 1–4; in total, there may be nine teeth.

4. Discussion

There are several reasons for the decline in wear in 2023, and the analysis of these reasons is important. An increase in the harvested area (in 2023) should logically increase the wear of the blades, as should an increase in the vegetative mass of the crop (wheat variety Wendelin) [22]. Cereal stalks that are not dry at harvest (or wetter because a large part is dry, as in 2022) also make it more difficult to chop the straw and thus have an impact on the increase in wear. The unlodged cereals are drier and are crushed by breaking with impact; so, the friction between the blade and the straw is minimal (2023).

In addition, the moisture content of the grain stalks (the grassy nature of the grain) tends to increase the corrosion processes of the steels in general [23]. The average moisture content of the straw mass in our case was 25 $\pm$ 3%. Oxygen dissolved in water is one of the most important corrosion factors. The corrosion rate of iron and steel increases with the increasing concentration of dissolved oxygen in the moisture [24]. Cereal straw contains a variety of ingredients. Some of them (flavonoids, alkaloids, and phytofenols) can act as corrosion inhibitors [25]; others (acids and fertilizer residues) can promote corrosion [26,27]. During the operation of the crusher, the temperature increases due to friction; this is a factor that also influences corrosion. However, it should be noted that the effects of corrosion on the wear and durability of combine blades have not yet been sufficiently researched.

We saw classical phenomena of wear when analyzing the 2022 season, such as direct dependence—if the hardness of the blade is lower, the wear in the presence of an abrasive is greater. The same occurred with the angle (sharpness) of the blade—a sharper blade snaps faster. But, why the dependence between abrasion, hardness, and angle is different in the case of clean straw, should be additionally investigated, and the corrosion factor should be evaluated as well.

Virtually all simulations and experimental studies are performed with new blades, especially when serrated blades are used. The cutting edges of the blades wear quickly, and the contact geometry changes after the start of operation. The cutting forces (loads) to which the blades of the choppers in use are subjected change rapidly. Therefore, studies that evaluate both the parameters of the new product and the change in parameters during the life of the machine are of greater importance.

The results obtained in 2022 and 2023 allow us to say that the average efficiency of a blade can be 5 ha. One set of knives is enough to chop the plant mass of grain and rapeseed from an area of 400 ha if there are 80 blades in the drum, the grain is not lying down, and there are no foreign objects in the field. For the emergency replacement of blades deformed by mechanical foreign bodies, it is sufficient to have about 2% of the number of blades installed in the combine harvester.

When chopping plant mass in good condition (clean and the crops are not lying down), all the blades available on the market can be used, as the influence of blade hardness and blade angle on wear is not significant. However, when chopping plant matter that is contaminated with abrasive microparticles, harder blades with a smaller blade angle should be selected.

Despite the poor harvesting conditions in 2022, only 4 of the 80 blades of the chopper were mechanically damaged by foreign objects; in contrast, 11 blades were mechanically damaged by foreign objects in 2023 under good working conditions. The maximum weight changes in the blades damaged in the different seasons were practically identical at 5.55 and 5.39 g (Figure 9).

All blades chop the straw by passing between the two counter blades, but half of the blades work in a (single) counter blade gap, the other half work through the counter blade gap by "passing" two blades. Two blades of the chopper passing through the counter blade gap are less worn than one blade performing the same function. However, the combined wear of two blades (working in the same counter blade gap) is greater than that of one blade working in the counter blade gap, especially if some blades are damaged or deformed by foreign objects.

5. Conclusions

During grain harvesting, when the stalks are lying down and often contaminated with abrasive soil particles, the intensive micro-abrasive wear of the straw chopper blades is characteristic. In this case, the hardness of the blade and the angle of the cutting edge are factors that influence the wear resistance (the higher the hardness and the smaller the angle of the cutting edge, the lower the wear).

In the case of abrasive clean straw, the influence of hardness and angle on the abrasion resistance of the blade is not significant—no significant difference in abrasion was found between the blades of different hardnesses. Based on the research analysis, it can be predicted that one set of blades is enough to chop the plant mass of grain and rapeseed from an area of 400 ha if the grain is clean and not lying down and there are no foreign objects in the field. The entry of foreign objects into the shredder is unpredictable. The stock for emergency replacement of 2% of the blade number installed in the combine harvester is sufficient.

The wear of the blades had a sinusoidal character, related to blade position on the chopper drum. That character depends on harvester chopper construction and does not depend on straw quality. When two blades operate in the same counter blade gap, the wear is less than when one blade operates in the same counter blade gap.

Laboratory tests of the cutting force of straws are meaningful if the cutting speeds correspond to realistic conditions and the cutting geometry changes as the blades wear.

Numerical studies of blade wear are most meaningful in a long-term context due to the increase in cutting edge radius during wear and the fundamental change in cutting conditions.

The wear of blades by mass is described by a mathematical equation under good conditions:

$$I = f(H, \theta) = -7.37 + 6.55 \times 10^{-3}\, H + 8.21 \times 10^{-2}\, \theta - 5.83 \times H2\, \theta2 + 1.08 \times 10^{-3}\, H\, \theta \quad (2)$$

where H is the Vickers hardness of the cutting edge, HV; Θ is the blade angle of the blades, in degrees.

The conclusions are reasonable when it comes to a combine with a chopper drum with 80 blades. Analogous studies, analyzing shredders with different structural characteristics, would be useful and would help predict the need for spare parts for the harvest season.

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