Finite Element Analysis and Experimental Research on the Crushing Blade of Corn Straw Returning and Land Preparation Machine

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Abstract: In response to the problems such as severe wear of the cutting tools, poor uniformity of the crushing process, and excessive energy consumption in the operation of corn straw returning in the northeastern black soil region, this paper designs a 7-shaped crushing blade. Based on the composite failure mechanism of straw shearing and bending, the key structural parameters of the tool were optimized and a three-dimensional model was established. The static finite element analysis of the tool was conducted using ANSYS Workbench. The stress, strain and deformation distribution patterns of the tool were systematically studied. The crushing performance and operational stability of the tool were evaluated through field experiments. The results showed that the maximum equivalent stress of the tool is 204.9 MPa, and the maximum equivalent strain is 9.96×10-4. Both are concentrated at the edge of the installation hole and the adjacent area of the bending transition section. The maximum total deformation is 0.936 mm, located at the free end of the cutting working section, meeting the structural strength and stiffness requirements of agricultural machinery. In the field experiments, the average qualified rate of straw crushing was 91.5%, demonstrating good stability and consistency. This research provides a theoretical basis and engineering reference for the optimization design of the tool structure of the corn straw returning equipment and the improvement of the overall performance of the machine.

Keywords: Corn Straw; Crushing Tool; Land Preparation Machine; Finite Element Analysis

1. Introduction

Corn is a major grain crop in China. By 2025, the national corn planting area had exceeded 650 million mu, and the straw production had exceed 300 million tons [1]. If a large amount of field straw is improperly handling, it not only leads to resource waste but also causes environmental pollution problems. With the promotion of conservation tillage technology, straw returning to the field has become an important technical path to increase soil organic matter content, improve soil aggregate structure, reduce agricultural non-point source pollution, and promote sustainable agricultural development [2,3]. However, the corn straw in the Northeast Black Region has the characteristics of high fiber content, strong toughness, and large fluctuations in moisture content. Moreover, the field operation environment is complex and harsh [4]. The current straw returning equipment generally has problems such as severe wear of cutting tools, concentrated impact load, high operation power consumption, and uneven straw crushing. These issues make it difficult to meet the operational requirements for precise land application [5-7].

At present, the commonly used crushing tools for straw returning to the field mainly include straight knives, L-shaped curved knives, hammer claw-type knives, and composite knives, etc. [8]. Among them, the straight knife has simple structure and single cutting path, which is prone to generating instantaneous high loads, has high energy consumption and the crushed straw is not uniform. The L-shaped curved knife achieves the synergy of cutting and tossing through a certain curvature, but it is prone to entanglement, which affects the continuity of the operation. The hammer claw-type knife utilizes the impact crushing mechanism to shred the straw, however, crushing length has a large dispersion, which is difficult to meet the requirements for precise land application. The composite knife combines multiple working modes, but it has complex structure and large quantity, and requires high power matching [9,10].

Based on this, this paper designs a 7-shaped crushing tool. Through the combination of theoretical analysis, finite element analysis and field experiments, a multi-angle systematic study on the tool structure, dynamic response and operation performance was conducted, with the aim of providing new ideas for the design of efficient and low-consumption straw returning tools.

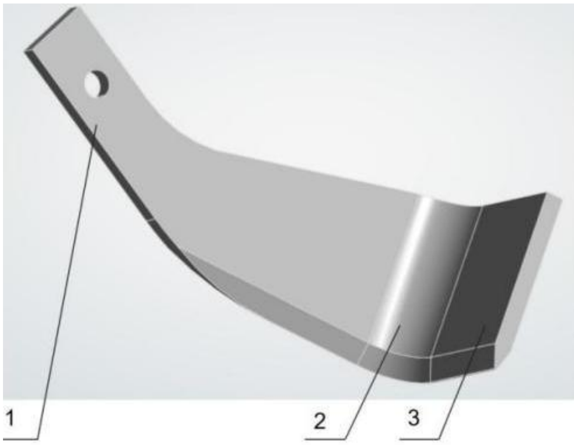
2. Design of the Tool Structure

2.1 Design of Tool Structure Parameters

Corn straws are a typical fiber-reinforced porous biological composite material. Their interior is composed of vascular bundles and parenchyma tissues, featuring significant anisotropy and hierarchical structure characteristics [11]. In the process of corn straw crushing and returning to the field, the structural parameters of the crushing tool directly determine the cutting performance, force state, and energy transfer path [12]. Based on agricultural machinery design theory, material mechanics analysis, and field operation characteristics, a 7-shaped crushing tool was designed. This tool consists of an installation end, a bending transition section, and a cutting working section, as shown in Figure 1. By introducing a spatial bending structure, the tool forms an asymmetric cutting trajectory during rotation, and generates shear force, bending force, and sliding cutting effect during the action of the straw. Compared with the traditional straight knife with a single shear mode, the setting of the bending transition section can effectively alleviate the load concentration, allowing the stress to gradually transmit along the knife body, reducing the load required per unit cutting area, and improving the efficiency of straw fracture and structural reliability.

Based on the mechanical characteristics of the rotating tool and the straw covering condition, in order to ensure that the tool has sufficient linear speed and cutting envelope, while controlling the bending moment of the tool body, the design of the main structure of the tool that the unfolded length is 275 mm and the effective length after bending is 220 mm. This is used to balance the working radius and structural strength of the tool.

Considering the working resistance and the crushing efficiency, the maximum width of the cutting edge is set at 80 mm to enhance the contact coverage of the straw, improve the cutting continuity and the spreading effect. To achieve the effect of composite cutting, the tool is equipped with a 90° bent structure, enabling it to form a distinct spatial introduction effect during the circular rotation process, reducing entanglement, and simultaneously generating cutting and sliding cutting effects, thereby reducing the demand for pure shear load. The width of installation end is 30 mm, which is sufficient to meet the minimum clearance distance and strength requirements for the assembly of the tool holder.



1.Installation End; 2. Bending Transition Section; 3. Cutting Working Section

Figure 1. 3D Model of 7-Blade Crushing Tool

To meet the requirements of bending strength and impact resistance, the thickness of the tool should be 5 to 10 mm. Research shows [13] that as the thickness increases, the quality and rotational inertia of the tool also increase, while the deformation decreases. However, thicker tools are not conducive to the crushing of straw. Considering the bending strength, impact resistance, rotational inertia and crushing effect, the thickness of the tool is designed to be 8 mm. The cutting edge angle of the tool is set at 30°, which can maintain the shearing ability while reducing the wear on the tool.

The tool material is selected as 60Si2Mn spring steel, which possesses a high elastic limit and impact resistance. Local quenching treatment is carried out on the cutting edge to enhance wear resistance and service life. The key structural parameters of the 7-shaped crushing tool are shown in Table 1.

Table 1. Design of Key Structural Parameters for 7-Blade Shredding Tool

Parameter	Symbol	Unit	Value
Unfolded Length of Tool	L_0	mm	275
Effective Length After Bending	L_e	mm	220
Installation End Width	b_0	mm	30
Maximum Width of The Cutting Edge	b_c	mm	80
Thickness of the Tool	h	mm	8
Cutting Edge Angle of the Tool	α	°	30
Bending Angle	θ	°	90

2.2 Analysis of Force Application on Tools and Structural Rationality

The 7-shaped crushing tool structure can change the load transmission path, and the destruction process of corn straw under the action of the tool can be expressed as the combined effect of shear force Fs, bending force Fb and friction force Ff. The breaking condition of the stalk can be expressed as:

$$\sigma_{eq}=\sqrt{\sigma_b{}^2+3\tau_s{}^2}\geq\sigma_{crit} \quad (1)$$

where σ_b is bending stress， τ_s is shear stress, σ_{crit} is limiting strength of straw.

From Equation (1), it can be seen that compared with the traditional straight knife which only relies on a single shear effect, the 7-shaped crushing tool significantly increases the σ_b component through its bent structure, thereby reducing the load required for pure shear and making the straw more prone to fracture. If the shear failure approximation is used for calculation, the theoretical breaking force of the straw can be expressed as:

$$F_s=\tau\cdot A \quad (2)$$

where τ is corn straw shear strength, A is the cross-sectional area of the corn straw after being cut.

The cross-sectional area of the corn straw after being cut can be expressed as

$$A=\frac{\pi}{4}D^2 \quad (3)$$

Based on the generally measured range of corn straws in the field at the mature stage in the Northeastern region, taking the outer diameter of the straw D is 20 mm, the calculated yield A is 3.14×10-4 m2. Corn straws are not ideal brittle materials. Their cutting process is greatly affected by moisture content, cutting speed, and the direction of fiber arrangement, etc. Generally, the shear strength of corn straws is 0.6×106 to 1.2×106 Pa [14]. Considering the characteristics of the mature straw outer skin fibers being relatively strong and internode tissues having high toughness, this paper takes the shear strength τ of corn straws as 0.8×106 Pa. Then, the theoretical cutting force of the straw Fs is 251.2 N.

Considering that the 7-shaped crushing tool not only undergoes pure shearing in actual operations, but also involves bending, cracking and sliding cutting effects, the theoretical shear value cannot fully represent the instantaneous peak load. To reflect the additional influences brought by the tearing of straw fibers, fluctuations of cutting speed and the irregularity of straw posture, a dynamic load correction coefficient kd is introduced. Then, the actual cutting load of the straw can be expressed as

$$F = k_d \cdot F_s \quad (4)$$

Usually, k_d is taken as1.20 to1.50 [15]. In this paper, k_d is set to 1.30, then F is 326.56 N, which means the actual equivalent load exerted by the straw on the tool is approximately 327 N. This calculation result can be used for setting the boundary loads in the subsequent finite element analysis.

3. Finite Element Analysis

3.1 Application of Constraints and Loads

Creating a 7-shaped crushing tool model in Pro/E, saved the entity in igs or stp format, and imported into ANSYS Workbench. The model was meshed using the free grid method, resulting in 15,622 nodes and 8,311 grid cells. During the process of straw crushing, it is required that the crushing tool to operate continuously. To enhance the service life and mechanical performance of the tools, the material selected is 60Si2Mn. The material properties are shown in Table 2.

Table 2. Material Characteristics

Material	Elasticity Modulus /E MPa	Poisson Ratio /v	Density /ρ kg/m^3	Yield Strength /σ_s MPa
60Si2Mn	2.06×10^5	0.3	7.85×10^3	1176

In the actual operating environment, the 7-shaped crushing tool is rigidly connected to the cutter shaft through a U-shaped cutter holder, and it rotates simultaneously with the cutter shaft. Therefore, a fixed constraint is applied at the installation hole of crushing tool, and at the same time, an equivalent load of 327 N perpendicular to the cutting edge direction is applied respectively in the cutting working section and the bending transition section. The finite element model of the crushing tool is set up.

3.2 Result

When the load value reaches or exceeds the yield limit of the material, the crushing tool will undergo irreversible failure behaviors such as bending deformation and fracture. Therefore, the total deformation, stress and strain analysis are added for solution and optimization.

Figure 2 is cloud diagram of stress distribution. It can be seen that the maximum equivalent stress is 204.9 MPa, which mainly occurs at the edge of the installation hole and the adjacent area of the bending transition section. This is because the local interface of the cutting working section and the bending transition section can release some stress through overall flexure. When the load is transmitted to the installation end, due to the change in structural geometric and the increased boundary constraints, significant stress concentration will form inside the material. Compared with the yield strength of material is 1176 MPa, the maximum stress is only 17.4% of this value, indicating that the tool has a high safety margin under the designed load conditions and a high anti-failure capability in actual operating conditions.

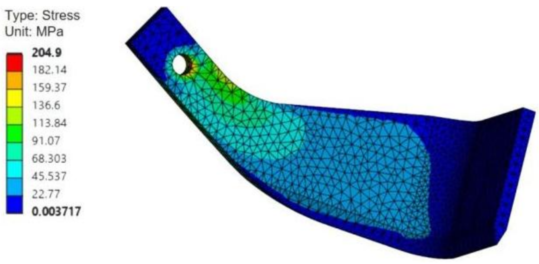


Figure 2. Cloud Diagram of Stress Distribution

Figure 3 is the cloud diagram of strain distribution. It can be seen that the maximum strain is 9.96×10-4, and its distribution location is basically consistent with the stress distribution area. It mainly occurs at the edge of the installation hole and the adjacent area of the bending transition section. This is because when the external load is transmitted from the working end along the tool body to the installation end, due to the rigid constraint at the installation end, the local material needs to withstand greater strain coordination. This area is more prone to forming higher strain concentration. However, the strain level is relatively low, there is no risk of plastic deformation, and the structural stability is good.

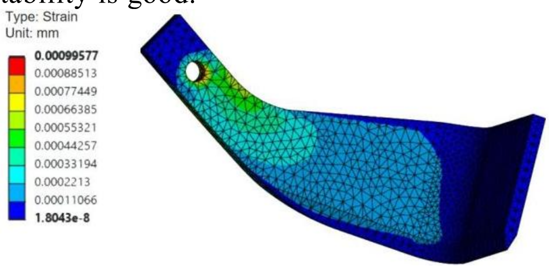


Figure 3. Cloud Diagram of Strain Distribution

Figure 4 is the cloud diagram of total deformation. It can be seen that the maximum deformation value is 0.936 mm, which mainly occurs at the free end position of the cutting working section. While the deformation near the installation end is close to zero. This is because the tool is rigidly connected to the cutter holder through the installation hole. The displacement at the installation end is completely constrained. The cutting load of the straw is mainly applied to the bending transition section and the cutting working section. When the external load is transmitted from the tool body to the installation end, significant bending deformation will occur in the cutting working section. From the quantitative analysis, the effective working length of the tool is 220 mm, and the maximum deformation is 0.936 mm, which accounts for only 0.43% of the effective working length. This falls within the small deformation range (≤ 1%). This indicates that the tool will not undergo significant deformation during the cutting process, ensuring the stability of the cutting trajectory.

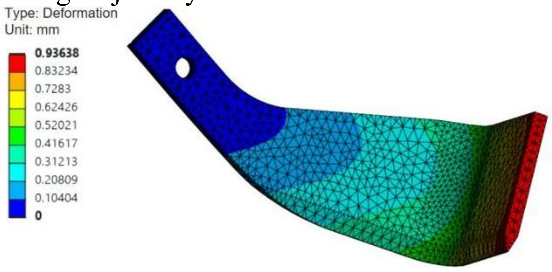


Figure 4. Cloud Diagram of Total Deformation Distribution

4. Field Experiment

To verify the operational performance of the 7-shaped crushing tool designed under actual working conditions, the field in the Jianshe village of Ning'an City, Mudanjiang (after the harvest of corn in late October 2025) was selected as the experiment site. Five sampling points were selected in the experimental site, each sampling point was an equal area of 1 m × 1 m. The tillage depth was 25 mm. Samples of crushed corn straws within the area were collected to avoid errors caused by uneven distribution of straws in a single area. The test equipment was the 1SZLYQH-202 combined tillage machine for complete straw return and tillage (Mudanjiang Zhongling Machinery Co., Ltd.), with a 7-shaped crushing tool installed on the front axle. The working width was 2020 mm. The power of the accompanying tractor ranged from 73.5 to 110.3 kW, as shown in Figure 5.

Figure 5. 1SZLYQH-202 Combined Tillage Machine for Complete Straw Return and Tillage

According to "GB/T 24675.6-2021 Protected Tillage Machinery", a straight ruler with an accuracy of ± 1 mm was used to measure the length of the crushed straw. The standard for qualification was that the length of the straw should be no more than 100 mm. The weighed of the straw with unqualified length was measured, and the qualified rate of the straw crushing length was calculated. The results are shown in Table 3.

Table 3. The Qualified Rate of Corn Stalks Crushing Length

Measured Points	Total Mass of Straw / (g)	Unqualified Quality of Straw / (g)	Qualified Rate of Straw Crushing / (%)
1	1282.5	132.1	89.7
2	1356.4	104.6	92.3
3	1497.3	107.8	92.8
4	1224.9	144.5	88.2
5	1173.8	63.4	94.6

As can be seen from Table 3, the differences among the data of each group are small, and with no abnormal fluctuations. This indicates that the cutting tool can maintain stable crushing performance under different operation strokes, and the operation consistency is good, meeting the quality requirements for fine tillage of straw. At the same time, the finite element analysis shows that the deformation of the cutting tool is relatively small, the stress distribution is reasonable, which is consistent with the experimental results, and verifies the rationality of the cutting tool structure design. In order to further analyze the stability of the performance of the 7-shaped crushing tool in field operations, the qualified rate of straw crushing was statistically analyzed. According to the data in Table 3, the average value of the qualified rate of straw crushing at each measurement point was calculated, which can be expressed as

$$\bar{x}=\frac{1}{n}\sum_{i=1}^{n} x_i \quad (5)$$

Where $\bar{x}$ is universal mean, $\bar{x_i}$ is the qualified rate of straw crushing at each measurement point, n is the total number of samples.

After substituting the data into the calculation, it can be obtained that $\bar{x} \approx$ 91.5%. To calculate the standard deviation S of the qualified rate of straw crushing at each measurement point, it can be expressed as

$$S=\sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}} \quad (6)$$

The coefficient of variation (CV) can be expressed as

$$CV=\frac{S}{\bar{x}} \quad (7)$$

After substituting the data for calculation, we obtain S = 2.55% and CV = 2.79%. The coefficient of variation is relatively small, indicating that the dispersion of the experiment results is relatively low, and the performance of the cutting tool is stable. According to the relevant requirements of 《GB/T 24675.6-2021》, the qualified rate of straw crushing reaches over 85%, the operation requirements will be met. The results of this study are significantly superior to the standard requirements, indicating that the designed cutting tool has excellent adaptability and reliability under actual operation conditions.

5. Conclusion

(1) Based on the composite failure mechanism of straw shearing and bending, a 7-shaped crushing tool was designed, and the key structural parameter combinations were determined to achieve low load and high uniformity of crushing.
(2) The finite element analysis showed that the maximum equivalent stress of the cutting tool was 204.9 MPa, the maximum strain was 9.96×10-4, and the maximum deformation was 0.936 mm. All of these meet the strength and stiffness requirements for agricultural machinery.
(3) The results of field experiments showed that the average qualification rate of straw crushing was 91.5%, the coefficient of variation was 2.79%. The operation stability and consistency were good, meeting the requirements of conservation tillage technology.
The 7-shaped structure optimizes the load transmission path, achieving combined effect of shearing, sliding cutting and bending, effectively reducing stress concentration and improving the crushing quality. It provides new path and universal method for the lightweight and efficient design of tools for straw returning, and has significant engineering value for promoting the upgrading of protective tillage equipment for black soil.

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