Design Optimization and Performance Evaluation of Corn Straw Crushing and Rubbing Filament Machine

Jianqiang Du,# He Su,# Shanzhu Qian, and Xuehong De *

China produces a large amount of corn straw after the harvest of staple grains every year. Fodder application of corn straw can reduce the waste of straw resources. Such usage also can guarantee the supply of high-quality coarse fodder for livestock and help the development of husbandry and the increase of production and income of farmers and herdsmen in China. Based on the requirements of livestock for straw feed consumption, the corn straw treatment process engineering was studied, and the overall structure, transmission scheme, and main working components of the corn straw crushing and rubbing filament machine were designed. The equipment was developed with three-dimensional modeling and solid design. Key components were verified through finite element analysis. Finally, a prototype was produced for testing. The experimental results showed that when the moisture content of corn straw was tested to be 20%, the percentage of filamentous straw of the equipment was 97.2%, and the calibrated unit power productivity could reach 82.8 kg/(kW · h). Through experiments, all indicators of the equipment met the relevant technical standards of the straw crushing and rubbing filament machine, providing theoretical basis and technical support for the design of the straw crushing and rubbing filament machine.

DOI: 10.15376/biores.19.2.2286-2298

Keywords: Corn straw; Crushing; Rubbing filament; Fodder

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INTRODUCTION

According to statistics in agricultural production, the annual total amount of straw production in China exceeds 700 million tons, while the input percentage of industrialization and reuse is only about 33%. This indicates a serious waste of straw resources and is not conducive to the effective creation of value of crop straw. At present, it is of practical significance for the agricultural sector to further process and re-treat crop straw through straw crushing and rubbing processes. The research results show that the performance of mechanical equipment is one of the main factors that affect the efficiency of straw processing. Therefore, the design and development of straw crushing and rubbing filament equipment is very important (Wang 2016; Yang *et al*. 2017; Li *et al*. 2018; Xiao *et al*. 2020).

Straw coarse fodder has some problems, such as hard chewing, poor palatability, large feeding waste, and low digestibility and absorption (Xie 2013). Straw crushing and rubbing filament is a key step in the comprehensive utilization of straw resources. After being crushed and kneaded, straw will become high-quality coarse fodder for ruminant livestock with high utilization value. The corn straw rubbing filament degree is evaluated by measuring its length and width after rubbing filament. According to the growth needs of livestock, straw feed is processed and prepared. In terms of straw feed processing length, it is generally recommended for cows to process 3 to 5 cm and sheep to process 2 to 3 cm lengths. Feeding is suitable for livestock to ruminate on straw feed; In terms of processing quality, kneading the straw into threads fully exposes the pulp inside the straw, which is advantageous for ruminant animals to absorb feed nutrients. Based on the above, an efficient straw crushing and rubbing filament machine is of great significance for making full use of agricultural straw resources, promoting agricultural mechanization and sustainable social development (Shang 2014). In terms of processing types, straw processing equipment can be divided into combined type, kneading type, hammer type, cutting type, *etc*. However, the processing effect of mechanical equipment is not ideal, such as high cost, difficult operation, low utilization rate, *etc*. The technical content still needs to be improved (Ren *et al*. 2017; Chen *et al*. 2018; Shi *et al*. 2020).

WORKING PRINCIPLE

Straw Feed Processing Requirements

As the main fodder for ruminant livestock, straw cannot be fed directly. It needs to be further processed according to the growth needs of livestock. In the process of resource utilization of crop straw, straw has been used as fodder in many areas. Straw becomes an important feed for cattle and sheep. Resource utilization reduces the waste of straw resources and increases fodder supply. The processing degree and quality of straw fodder will directly affect the palatability, nutrient composition, and storage time. It directly affects the feed intake rate and nutrient absorption rate of ruminant livestock, thereby affecting the economic benefits of farmers and herdsmen (Zhang 2016; Zhang *et al*. 2019).

Whole Machine Structure and Main Performance Parameters

The working process and structure of the equipment are shown in Figs. 1 and 2, respectively. The machine is mainly composed of transmission mechanism, feed flattening mechanism, cutting mechanism, breaking and rubbing transmission system, breaking and rubbing mechanism, outlet, body frame, motor, conveying feed cutting drive system, and other components. The motor transmits power through the transmission feed, cutting the transmission component and breaking it. Next comes the rubbing transmission component connected with the transmission mechanism, feed flattening mechanism, cutting mechanism, and breaking and rubbing mechanism. All mechanisms work together to ensure the realization of the functions of the whole machine.

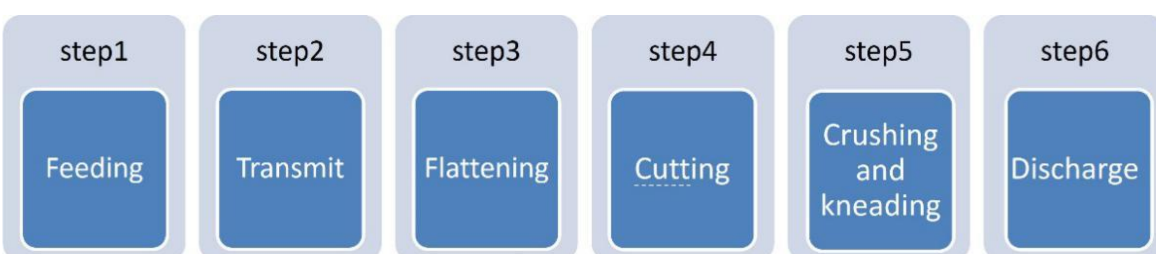

Fig. 1. Flow chart

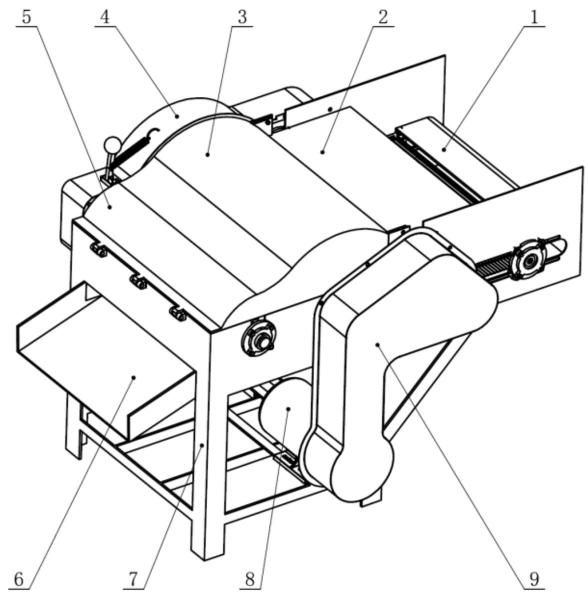

Fig. 2. Structural sketch of the whole machine. 1: Transmission mechanism; 2: Feed flattening mechanism; 3: Cutting mechanism; 4: Crushing and rubbing transmission system; 5: Breaking and rubbing mechanism; 6: Outlet; 7: Body frame; 8: Motor; 9: Conveying feed cutting drive system

Working Principle

During operation, the straw is placed on the conveying chain plate of the conveying mechanism. First, the chain plate transports the straw to the feeding flattening link. The upper and lower feeding flattening rollers of the feeding flattening mechanism grab the corn straw to break the section and flatten it. Second, the corn straw enters the cutting mechanism. The rotary cutter cut the straw into the feed length required by the livestock. The straw then enters the crushing and rubbing link. The corn straw in this section is subject to the combined effects of beating, shearing, collision, rubbing, and extrusion of the rubbing and cutting. The corn straw with thick and hard stem nodes is rubbed into soft silk with a length of no more than 5 cm. In the last step, the straw is thrown out through the outlet by the air flow of the high-speed rotation of the cutters to complete the crushing and rubbing operation of the corn straw.

Motive Power Scheme Design

The transmission diagram of the straw rubbing filament machine is shown in Fig. 3. The motor transmits power to the straw cutting shaft through belt transmission, enabling the straw cutting mechanism to operate. The straw cutting shaft transmits power to the rubbing and cutting shaft and the lower feed flattening roller shaft through gear transmission. The rubbing and cutting shaft drive the crushing and rubbing rotor to rotate, thereby achieving the operation of the crushing and rubbing filament mechanism. The lower feed flattening roller shaft transmits power to the upper feed flattening roller shaft through gear transmission, and at the same time, the power is transmitted to the driving shaft of the conveyor chain plate through chain transmission. In this way, the feeding and flattening mechanism operation function is achieved. Then, the drive shaft of the conveyor chain plate and the active shaft of the conveyor belt are connected by the conveyor chain plate to jointly complete the feeding operation.

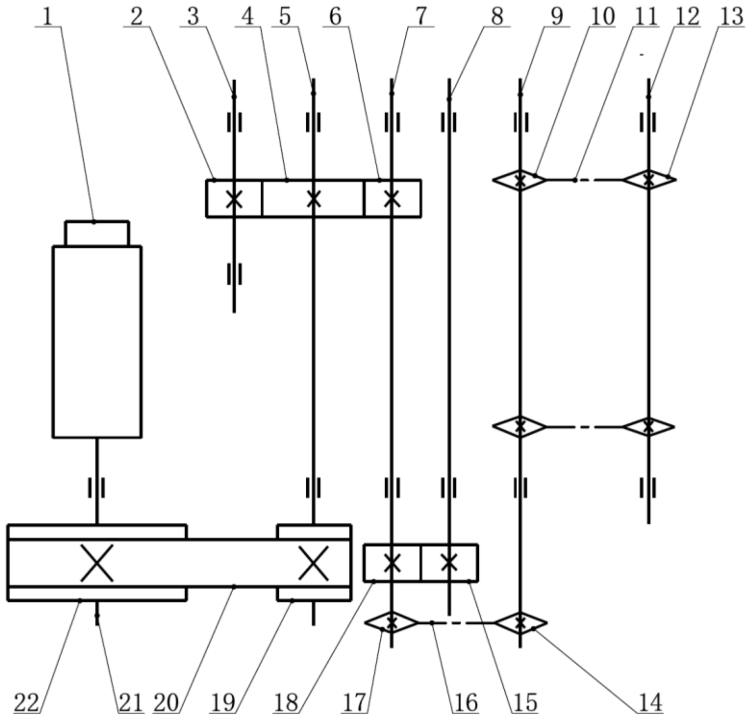

Fig. 3. Transmission diagram of straw crushing and rubbing filament machine. 1: The motor; 2. Rubbing and cutting shaft gear; 3: Rubbing and cutting shaft; 4: Straw cutting shaft gear; 5: Straw cutting shaft: 6: Lower feed flattening roller drive input gear; 7: Lower feed flattening roller shaft; 8: Upper feed flattening roller shaft; 9: Drive shaft of conveyor chain plate; 10: Transmission chain plate drive shaft power output sprocket; 11: Conveyor chain plate; 12: Conveyor chain plate movable shaft; 13: Conveyor chain plate movable shaft sprocket; 14: Transmission chain plate driving shaft power input sprocket; 15: Upper feed flattening roller drive gear; 16: Drive Chain; 17: Lower feed flattening roller shaft sprocket; 18: Lower feed flattening roller transmission output gear; 19: Straw cutting shaft pulley; 20: Drive belt; 21: Motor output shaft; and 22: Motor output pulley

DESIGN OF MAIN WORKING COMPONENTS

Conveying and Feed-Flattening Mechanism

The structure of the conveying and feed-flattening mechanism is shown in Fig. 4. This device is composed of a frame, a conveyor chain plate, a lower feed flattening roller, an upper feed flattening roller, an upper feed flattening roller transmission gear, a lower feed flattening roller transmission output gear, a transmission chain, a fixed shaft for the conveyor chain plate, and a movable shaft for the conveyor chain plate. Each working component is installed on the frame through a bearing seat. The movable shaft of the conveyor chain plate and the upper feed flattening roller are installed in a sliding groove that can be moved and adjusted. The gap between the two feed flattening rollers can be adjusted according to the material properties. The key task of the feed flattening roller is to grasp and flatten the straw. When installing the movable shaft of the conveyor chain plate, it can also be adjusted in the sliding groove to ensure that the tension of the conveyor chain plate is moderate during operation.

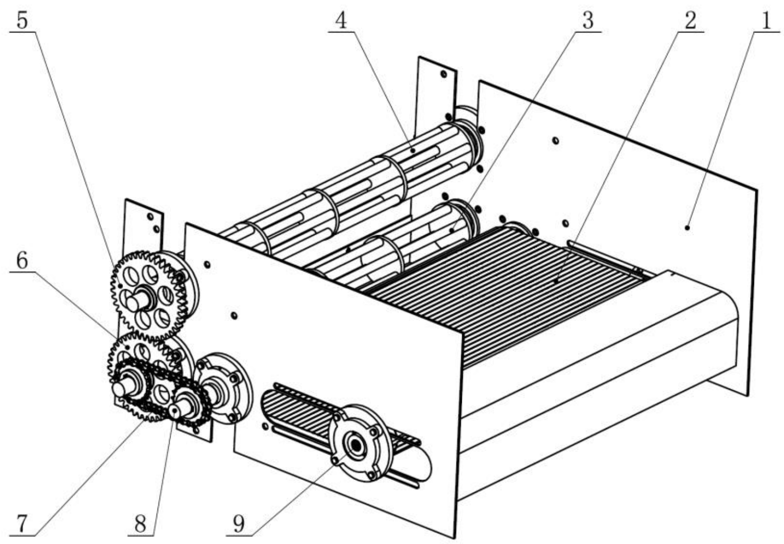

Fig. 4. Structure diagram of conveying and feeding flattening mechanism. 1: Body frame; 2: Conveyor chain plate; 3: Lower feed flattening roller; 4: upper feed flattening roller; 5: upper feed flattening roller transmission gear; 6: lower feed flattening roller transmission output gear; 7: Transmission chain; 8: Transmission chain plate driving shaft; and 9: Conveyor chain plate movable shaft

The parameters of the transmission mechanism are designed as follows. The special double side plate with hole sleeve roller chain is adopted for transmission chain plate of the transmission chain, and the linear speed of the transmission chain plate υ_L (Dey *et al*. 2013). The liner velocity is calculated following Eq. 1,

$$\upsilon_L = (0.7 \sim 0.8)\ \upsilon_W \tag{1}$$

where υ_L is linear velocity of the conveyor chain (m/s), υ_W is the linear speed of the lower feed flattening roller (m/s), and the range of linear speed values is (0.8 to 1.0) m/s.

To improve efficiency, υ_W was taken as 1.0 m/s. According to the design requirements and technical parameters of the mechanism, the transmission ratio of the lower feed flattening roller and the conveyor chain active shaft chain is 1:1, with the same rotational speed. According to Eq. 1, it can be inferred that,

$$D_L = (0.7 \sim 0.8)\ D_W \tag{2}$$

where D_L is diameter of the conveyor chain roller (mm), and D_W is the diameter of the lower feed flattening roller (mm).

Experimental verification was made. When the coefficient was 0.8, the feed blockage rate was the lowest and the productivity was the highest in conveying corn straw. According to the design requirements, it is most reasonable to take D_W as 130 mm. From Eqs. 1 and 2, it was obtained that υ_L was 0.8 m/s, and D_L was 104 mm.

The working performance of the feed flattening roller is determined by its shape, diameter, and rotational speed. According to the data, the diameter of the flattening roller can be determined by Eq. 3,

$$D_W = \frac{t(1-\mu)}{2(1-cos\,\phi)} \tag{3}$$

where t is thickness (mm) of straw on the conveyor chain, μ is the compression coefficient of straw, generally taken as 0.7, and ϕ is friction angle between straw and flattening roller, generally taken as 30°.

According to the design requirements of this machine and the agricultural machinery design manual, the diameter of the lower feed flattening roller is selected to be 130 mm.

When the flattening roller is working, the straw is subjected to positive pressure F and frictional force f. F is perpendicular to f, snd the angle between the axis line of the feeding roller and F is α. The stress analysis of straw is shown in Fig. 5. The two flattening rollers adopt the same structural size and material (Tao *et al.* 2013).

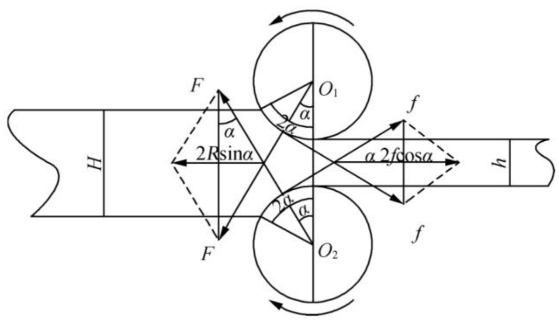

Fig. 5. Force analysis diagram of corn straw

When working, the following condition (Eq. 4) should be met,

$$f \cos\alpha \geqslant F \sin\alpha \quad (4)$$

where F is positive pressure of the flattening roller on the straw (N), f is friction force of the flattening roller on the straw (N), and α is the angle between the axis line of the flattening roller and F (°).

The radius of the two flattening rollers should meet the following equation.

$$r_w \geqslant \frac{H-h}{2(1-\cos 2\alpha)} \quad (5)$$

where r_w is radius of the flattening roller (mm), H is thickness of straw before compression, generally 40 to 60 mm, and h is the thickness of straw after compression, usually 10 to 30 mm.

To fully flatten the straw and ensure smooth material transportation, the two flattening rollers should have different rotational speeds. The upper roller speed should be slightly higher than the lower roller with a certain speed ratio. The straw will be close to the lower roller. The speed difference between the upper and lower rollers causes the corn straw to flatten and crack. Under the pushing action of the upper and lower flattening rollers, the straw is sent to the rotating cutting range of the cutting knife to ensure the cutting condition. The differential speed between the two rollers is determined by the teeth number of meshing gears at the installation shaft end.

The transmission ratio $i1_2 = n_1/n_2 = 0.8$, and the linear speed of the lower flattening roller is 1.0 m/s (Li 2003). The value of n_1 is given by,

$$n_1 = \frac{60 v_1}{\pi D_W} \quad (6)$$

where n_1 is rotational speed of the lower flattening roller (r/min), D_W is the diameter of the feeding roller (mm), and v_1 is the linear velocity of the lower flattening roller (m/s).

According to Eqs. 4 and 5, it can be calculated that the radii of the two feeding rollers must meet the following equation, $r_w \geq 60$ mm. Therefore, the selected radius of the feeding roller is 65 mm, which meets the design requirements. From Eq. 6, $n_1 = 150$ r/min can be obtained by substituting $i1_2 = 0.8$, $n_2 = 187$ r/min.

Cutting Mechanism

The cutting mechanism is composed of straw cutting shaft belt pulley, straw cutting shaft, bearing seat, body frame, fixed knife bracket, fixed knife blade, moving knife blade, moving knife bracket, cutting shaft gear, and other parts. The structure is shown in Fig. 6. Power is transmitted to the straw cutting shaft through belt transmission. The straw cutting shaft is rigidly connected to the moving knife bracket, which is equipped with a moving knife. With the action of the straw cutting shaft, a shear effect is formed between the moving and fixed blades to cut the flattened straw. At the same time, power is transmitted to the flattening mechanism and the crushing and rubbing filament mechanism through gear transmission.

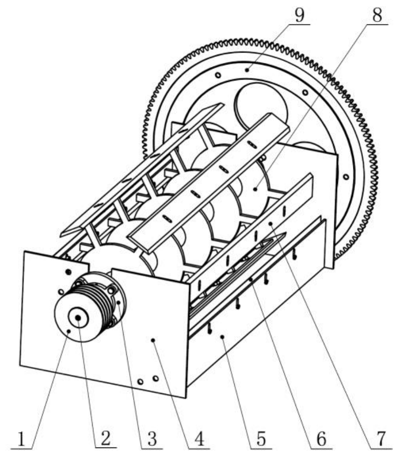

Fig. 6. Structural sketch of cutting mechanism. 1: Straw cutting shaft belt pulley; 2: Straw cutting shaft; 3: Bearing block; 4: Body frame; 5: Fixed knife bracket; 6: Fixed knife blade; 7: Moving knife blade; 8: Moving knife bracket; 9: Cutting shaft gear

The installation structure of the moving knife is shown in Fig. 7. Based on the sliding cutting effect of the moving and fixed blades on straw (Yan 2008; Zheng *et al*. 2016; Ma *et al*. 2019; Zhang *et al*. 2019; Wang *et al*. 2021), considering the convenience of balancing sliding in cutting of straw, the angle between the straight line of the moving blade and the plane passing through the main shaft is 5 °, and 6 blades are evenly and radially arranged. During work, the moving blade moves in a circular motion to rotate and cut the corn straw output by the flattening mechanism. The linear speed at the blade of the moving blade is 32 m/s, and the circumference diameter of the moving knife is 430 mm, then the speed of the straw cutting shaft can be calculated by the following Eq. 7:

$$n_Z = \frac{60 v_Z}{\pi D_Z} \tag{7}$$

The cutting cycle of the moving knife can be expressed as Eq. 8,

$$T_Z = \frac{\pi D_Z}{1000 N v_Z} \tag{8}$$

where N is number of uniformly distributed blades in the circumferential direction, usually taken as 6, D_Z is the rotating circumference diameter of the moving knife (mm), generally taken as 430 mm, and v_Z is the linear speed of the moving knife (m/s), generally taken as 32 m/s.

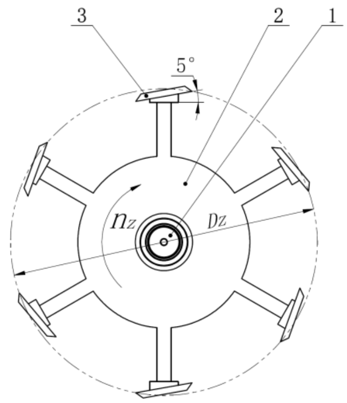

Fig. 7. Installation structure diagram of moving knife. 1: Straw cutting shaft; 2: Moving knife bracket; and 3: Moving knife blade

Crushing and Rubbing Filament Mechanism

The function of the crushing and rubbing filament mechanism is to knead the chopped straw, so that the hard knots, straw cores, and grains in the straw feed are evenly broken and formed into strips and silk under the rubbing effect. This mechanism consists of a rubbing and cutting shaft, a rubbing and cutting cutter disc, a rubbing and cutting cutter, *etc*. The rubbing and cutting knife discs are evenly spaced and welded onto the rubbing and cutting shaft. The rubbing and cutting knives are all moving and installed on a high-speed rotating rubbing and cutting cutter disc. Six evenly distributed rubbing and cutting knives are installed on both sides of each disc in a staggered manner. There are a total of 10 rubbing and cutting discs on the mechanism. This design is convenient for the installation and disassembly of the mechanism and the replacement of the crushing and rubbing cutter. The structure of the crushing and rubbing rotor is shown in Fig. 8.

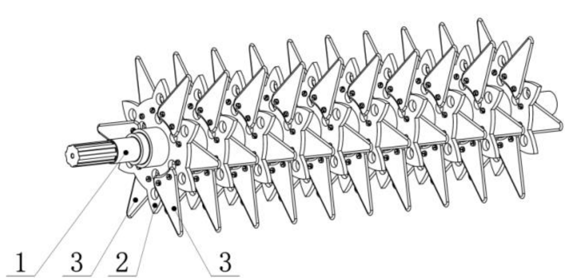

Fig. 8. Structural diagram of crushing and thread rubbing rotor. 1: Rubbing and cutting shaft; 2: Rubbing and cutting cutter disc; and 3: Rubbing and cutting cutter

To improve the efficiency of rubbing and cutting, the speed of the rubbing and cutting shaft is designed to be 2900 r/min. Due to the large number of rubbing and cutting discs on the rubbing and cutting shaft, their mass is large, and their rotational speed is high, so the diameter of the rubbing and cutting shaft is the main design parameter. The feeding method designed for this machine is tangential feeding. Based on the design requirements for the diameter of the rubbing and cutting shaft and the priority of using series standards, a rotor diameter of 390 mm is selected (Wang *et al*. 1992). The diameter of the rubbing and cutting shaft is expressed as follows (Pu 2013; Li *et al*. 2014). The value of the minimum diameter of the rubbing and cutting shaft (mm), d_r, is given by,

$$d_r = A\sqrt[3]{\frac{P}{n_r}} \tag{9}$$

where P is power transmitted by the rubbing and cutting shaft (kw) and n_r is rubbing and cutting shaft speed (r/min).

The material used for rubbing and cutting the shaft is carbon steel, and the value range of A obtained through quenching and tempering treatment is 103 to 126, so the maximum value of A is 126. According to Eq. 9, d is 18 mm. In order to ensure safe load and improve service life, the minimum cross-sectional diameter of the rubbing and cutting shaft is designed to be 30 mm. The elastic modulus and Poisson's ratio of 45 can be determined through the mechanical design manual. The detailed parameters are shown in Table 1. The data are brought into SolidWorks software (Dassault Systemes, 2021, Paris, France), the Simulation plug-in is used for finite element analysis, and the results are compared with the allowable stress of 45 after modulation in the mechanical design manual, so as to achieve the purpose of checking the shaft strength.

Table 1. Elastic Modulus and Poisson's Ratio of Carbon Steel

Item	Value
Elastic modulus *E* (GPa)	196 to 206
Shear modulus *E* (GPa)	79
Poisson's ratio	0.3

In the simulation finite element analysis, a torque of 300 N.m was applied to verify the dangerous section stress of each shaft. The maximum allowable surface compressive stress of 45 steel after modulation treatment is 158 MPa. The maximum allowable contact stress is 470 MPa. Design requirements are met. The results of the rubbing and cutting shaft verification are shown in Fig. 9.

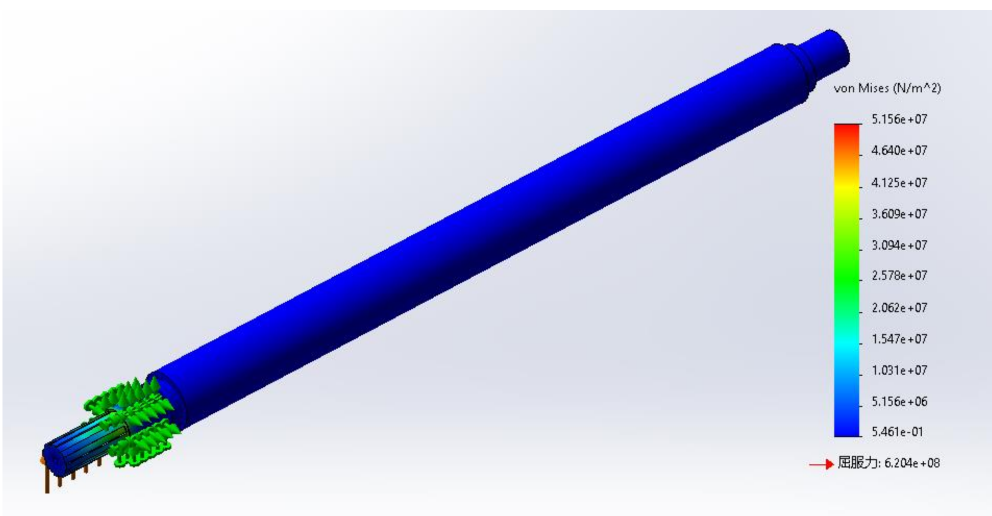

Fig. 9. Figures of finite element analysis results of rubbing and cutting shaft

PERFORMANCE TEST

Test Requirements and Methods

The experiment was conducted at the experimental station of Inner Mongolia Huayu Agriculture and Animal Husbandry Machinery Co., Ltd. The tested straw variety was Xianyu 335, which was harvested and dried in the suburbs of Baotou City, Inner Mongolia in 2022, and then compressed by a Huade traction picking and bundling machine (Inner Mongolia Huade Grass Machinery Co., Ltd.). The straw bundles were 500 mm in length, 360 mm in width, and 460 mm in height, with a density of 260 kg/m^3 and a length range of 80 to 150 mm. Random sampling measurement of straw moisture content within a range of 12.61% to 21.12%. Straw with a moisture content range of 15% to 21% was selected as the experimental material.

The experimental equipment includes YP2001N electronic balance and digital DHS16-A moisture rapid tester (Shanghai Precision Science Instrument Co., Ltd.), DZSF520 vibrating screen (Henan Dahan Machinery Equipment Co., Ltd.), stopwatch, floor scale, *etc*.

Before each load test, a prototype was tested for 1.0 to 5 min before feeding the weighed test straw. At the same time, started accumulating power consumption and test time. When all the test straw entered the prototype, accumulation stopped and the power consumption and test time were recorded.

After all the straw in the prototype was emptied, the operation of the prototype was stopped, all the processed finished products were collected, and weighed (including finished product samples). The formula used for calculating the calibrated unit power productivity was as follows,

$$E = \frac{G}{T \cdot P} \times \frac{1-S}{1-S_b} \times 60 \quad (10)$$

where G is mass of straw used in the experiment (kg), T is test time (min), P is total rated power of supporting power, which in this test was 7.5 kW, S is moisture content of experimental straw (%), and S_b is standard moisture content of straw, which in this experiment was 20%.

After the stable discharge of the load test, the finished product sample should be taken at the finished product outlet once every 5 min, a total of 3 times, and each time no less than 200 g of sample should be taken.

Three samples were mixed and weighed. The filamentous straw that met the requirements were selected and their mass was taken. The percentage of filamentous straw was calculated as follows,

$$S = \frac{m_1}{m} \times 100 \quad (11)$$

where S is the percentage of filamentous straw (%), m_1 is the mass of filamentous straw in the sample (g), and m is mass of straw sample (g).

Test Results and Analysis

The performance test results of the straw crushing and rubbing filament machine obtained by using the above measurement method are shown in Table 2.

Table 2. Comparison of Straw Crushing and Rubbing Filament Machine Performance

Items	Test Mean	Quality Index
The percentage of filamentous straw (%)	97.2	≥ 90
Rated unit power productivity (kg/(kW·h))	82.76	≥ 70

The experimental results show that during the operation of this machine, the percentage of filamentous straw was 97.2%, and the unit power productivity could reach 82.8 kg/(kW·h). The test results met the requirements of the standards DG/T 053 (2017) "Forage crusher" and NY/T 509 (2015) "Technical specification for quality evaluation of straw crusher" (Zhang *et al*. 2016; DG/T 053 2017; NY/T 509 2015). Compared to the existing models, the percentage of filamentous straw and production efficiency were improved because the main working mode of this machine being a combination of cutting and rubbing. The straw rubbing effect is obvious through the comprehensive effects of flattening, cutting, crushing, and rubbing, and there is no blockage in the conveying feed.

CONCLUSIONS

1. The main working components of the straw crushing and rubbing filament machine were designed. The structure and working parameters of the conveying and feed-flattening mechanism, cutting mechanism, crushing, and rubbing mechanism were determined. The designed straw crushing and rubbing filament machine were observed to run smoothly, with good rubbing quality and high production efficiency.
2. The experimental results showed that the designed cutting and rubbing filament machine achieved a rubbing production rate of 97.2% and a rated unit power production of 82.8 kg/(kW·h), respectively. The test results were able to meet the requirements of the straw crushing and rubbing filament machine, and the on-site performance test indicators met the requirements of national and industry standards. It can be applied to feed processing in fields, feed processing plants, and animal husbandry plants to process and prepare high-quality straw feed that meets the requirements of livestock feeding.

ACKNOWLEDGMENTS

The authors are grateful for the funding support of the Major Science and Technology Special Projects of Inner Mongolia Autonomous Region (Grant No. 2022YFDZ0022 and 2022YFDZ0032), the Inner Mongolia Natural Science Foundation (Grant No. 2021MS05044 and 2019MS05003), and the Scientific Research Projects in Higher Education Institutions in Inner Mongolia (Grant No. NJZZ21017) for carrying out this research work.

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Article submitted: December 20, 2023; Peer review completed: January 27, 2024; Revised version received and accepted: February 13, 2024; Published: February 21, 2024.
DOI: 10.15376/biores.19.2.2286-2298