

Analysis and Modelling of the Nonwoven Waste Fabric Cutting Unit

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Abstract: In this study, the design and modeling of a shredding unit intended to fragment nonwoven waste fabrics and prepare them for recycling were carried out. Stress analyses were performed on the shaft attached to the blade, along with motor power and torque analyses required for smooth operation, and mass flow calculations. Mathematical models were developed based on these data. Additionally, structural analyses of the chassis, necessary for stable system operation, were conducted, resulting in a comprehensive mathematical model of the entire system.

KEYWORDS: NONWOVEN FABRIC, SHREDDING UNIT, BLADE DESIGN, SHAFT GEOMETRY, CUTTING EDGE ANGLE, FINITE ELEMENT ANALYSIS (FEA), STRESS ANALYSIS, TORQUE CALCULATION, MOTOR POWER ANALYSIS, MASS FLOW RATE, STRUCTURAL ANALYSIS, RECYCLING

1. Introduction

Nonwoven fabrics are widely used as raw materials in the production of various products such as wet wipes, cleaning cloths, and floor cloths. Within the scope of this study, the production processes of nonwoven fabrics were examined, focusing on the waste generated during these processes. Considering the environmental impact and costs associated with recycling this waste, there is a pressing need for a more efficient and eco-friendly solution.

The objective of this study is to design a machine capable of shredding production waste deemed unusable, enabling its reuse as raw material. This shredding process aims to reduce the size of waste materials to dimensions suitable for further recycling stages.

2. Method

A literature review on shredding systems revealed various design options [1,2]. After a comparative evaluation, the most suitable design for nonwoven fabric characteristics was determined to be a dual-shaft configuration with a series of blades rotating at an average speed of 70 RPM. This setup was chosen due to the low shear strength and elastic properties of nonwoven fabrics.

Shredding occurs through the opposite rotation of two shafts housed within a chassis. Cutting blades are mounted on these shafts, with spacers placed between them to direct the material toward the cutting edges of the blades.

Both shafts rotate at the same speed in opposite directions. In this study, it is intended to drive both shafts with a single motor to save on cost and power. The drive is transferred from one shaft to the other through a gear system.

The movement of the blades within the shredding region reduces the material to the desired particle size, allowing it to be discharged.

3. Analysis of Shredder Components

3.1. Analysis of Blade

The primary consideration in blade design is to ensure that the reaction force exerted on the cutting edges is symmetrically distributed across the shaft geometry. To achieve this, a polygonal model should be developed based on the number of cutting edges, and this configuration should be centered on the shaft.

The cutting edge angle is crucial for effective shredding and should be determined according to the size of the material to be shredded.

A literature review revealed various blade designs. When selecting the type of blade, the characteristics of the material to be shredded must be considered to choose an appropriate cutter model. Figure 1 shows various cutter models. [3,4,5,6]

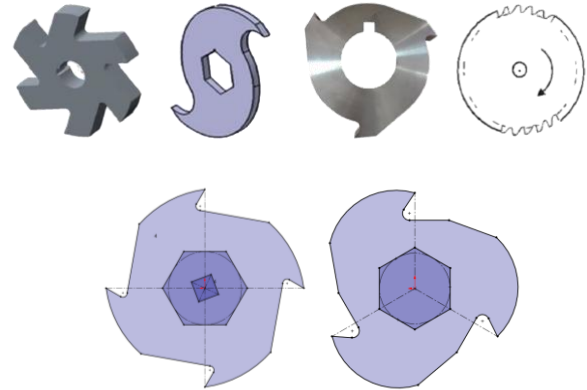


Figure 1. Various cutter models.

Finite element methods (FEM) can be applied to optimize the durability of the blades and the cutting edge geometry. Based on experimental studies on nonwoven fabric samples, the reaction force expected on the cutting edge can be predicted. [7,8]. Experimental results indicate that the tensile strength of the material is 4.57 MPa. Using this value, the drive force of the system can be calculated. The axial load acting on the blade geometry is calculated using the cutting edge area.

$$\sigma = 4,57 \text{ MPa} = F/A$$

$$\text{Area} = 120 \text{ mm}^2$$

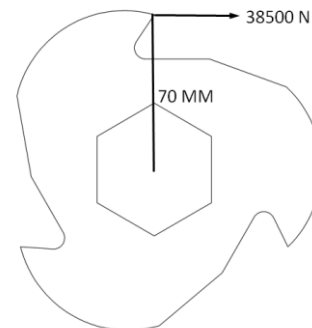
$$F = 548,4 \approx 550 \text{ N}$$

When calculating the required system power, all force components acting simultaneously must be considered.

Number of cutting blades → 70

Force on each cutting blade → 550 N

Total force → 38,500 N



$$T = 38500 \text{ N} \times 0,07 \text{ m} = 2695 \text{ Nm}$$

The torque required to withstand instantaneous stresses on the system has been calculated. Safety factors are not included in these results. The required power of the system depends on the RPM value, which is assumed to be 70 RPM. The shredding capacity has been taken as a determining factor in the design.

For a system with 70 blades, each with three cutting edges, operating at 70 RPM, the shredding rate is as follows:

- Per revolution → 210 cut
- Per minute → 14700 cut/min
- Per hour → 882000 cut/h
- Volume per cut → $7500 \text{ mm}^3 = 7,5 \times 10^{-6} \text{ m}^3$
- Hourly shredded volume → 6.615 m^3
- Product density → $118,3 \text{ kg/m}^3$
- Mass Flow → $6615 \text{ m}^3/\text{h} \times 118,3 \text{ kg/m}^3$
→ 782.55 kg/h

System efficiency has not been accounted for.

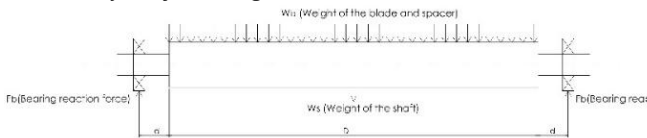
3.2. Analysis of Shaft

The shaft is a rotating machine element used to transmit power from one part to another. For better power transmission, the section of the shaft where the blades are mounted has a hexagonal shape. The blades are mounted onto the shaft along with spacers.

The shaft material selected for the project is 304 stainless steel (1.4301). This stainless steel has perfect mechanical properties for the project. It has high machinability and excellent corrosion resistance.

Due to the weight of the blades and spacers, a bending stress occurs on the shaft.

3.2.1. Analysis of Bending



- $W_b \approx 250 \text{ N}$
- $F_b = (W_b + W_s) / 2 = 175 \text{ N}$
- $W_s \approx 100 \text{ N}$
- $D \approx 0,5 \text{ m}$
- $d \approx 0,1 \text{ m}$
- $M_{b,max} \approx 61,25 \text{ N}\cdot\text{m}$
- $\sigma_{max} = (M_{b,max} \times d) / I$
- σ_{max} : max. bending stress (N/mm²)
- $M_{b,max}$: max. bending moment (N-mm)
- d: diameter of shaft (mm)
- I: moment of inertia of the cross-section about the neutral axis (mm⁴)
- $\sigma_{max} \approx 4,2 \text{ MPa}$

In Figures 2 and 3, the deformation and bending distribution under the influence of bending moment are shown.

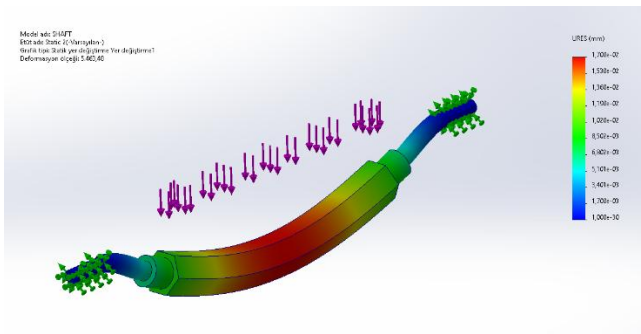


Figure 2. Deformation at Bending Moment(mm)

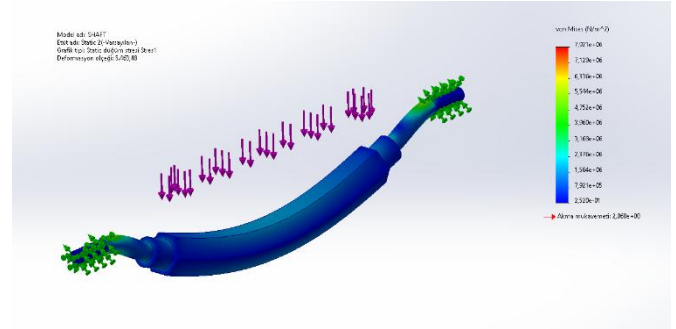


Figure 3. Bending Stress (N/m²)

3.2.2. Analysis of Torsion:

The shaft is not only subjected to bending stress but also experiences torsional stress caused by the drive from the motor.

$$\tau = (T \times d) / J$$

τ : shear stress (N/mm²)

T: applied moment (N-mm)

d: diameter of shaft (mm)

J: polar moment of inertia of the cross-section about the axis of rotation (mm⁴).

$$\tau \approx 92,4 \text{ MPa}$$

Von Mises Criterion:

$$\sigma_{eq} = \sqrt{(\sigma^2 + 3\tau^2)} = 160,1 \text{ MPa}$$

Since $\sigma_y \gg \sigma_{eq}$ the shaft is safe in terms of strength.

In Figures 4 and 5, the deformation and torsion stresses of the shaft are shown.

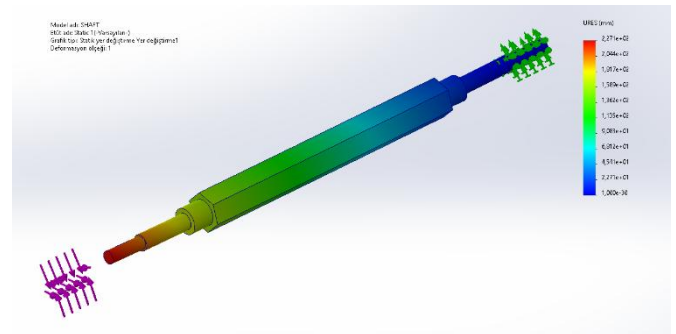


Figure 4. Deformation at torsion moment (mm)

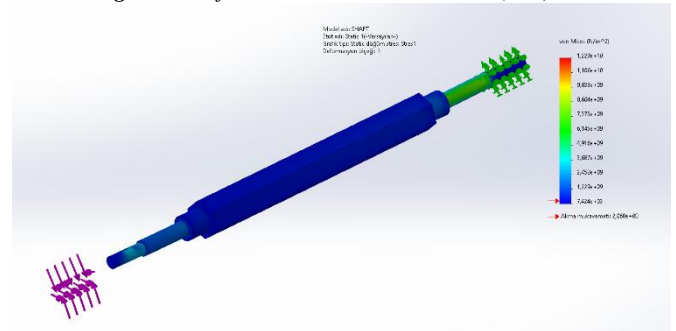


Figure 5. Torsion Stress (N/m²)

3.3. Design of Shredding Chamber

The shredding chamber protects the shredder machine from external influences. It also ensures the bearing of the shafts. The parts forming the chamber are welded together. The fastening components are bolted together for ease of assembly and disassembly.

Isometric and top views of the designed shredding chamber are given in Figure 6a and 6b.

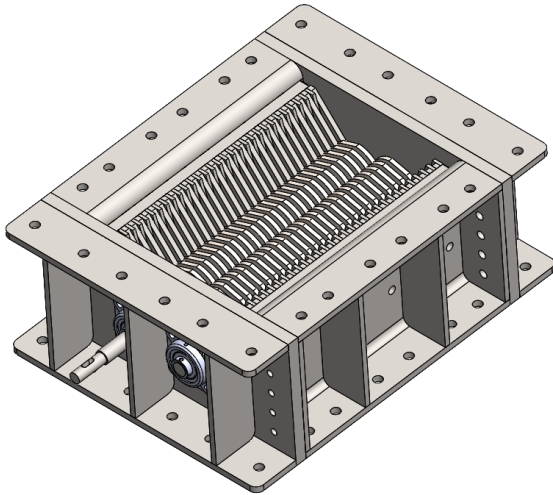


Figure 6.a.

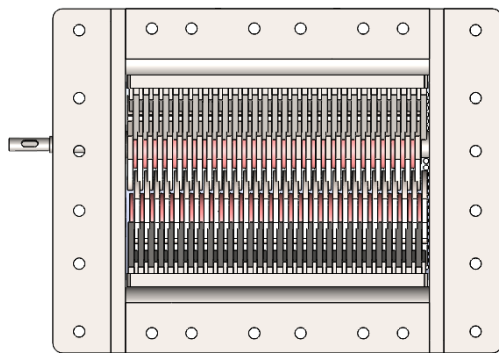


Figure 6.b.

Figure 6.a. Isometric and 6.b. top views of the designed shredding chamber

4. Results

The design and mathematical model of the shredder unit, aimed at efficiently fragmenting nonwoven waste fabrics to make them suitable for recycling, have been successfully developed. The performance of the designed shredder unit aligns with the mathematical model concerning motor power, torque requirements, cutting efficiency, and system stability. Subsequent torque and power analyses demonstrated that the system operates stably at 70 RPM with a dual-shaft configuration and 70 cutting blades under moderate load conditions [4, 9]. The cutting angle and placement were optimized based on the low shear strength and elastic properties of nonwoven fabrics. Test results confirmed that the blades effectively reduced the material to the desired particle size, proving the system's efficiency. The mass flow rate of 782.55 kg/h, defined in the model, was validated by the experimental results [6, 10].

Stress analyses and vibration modeling within the mathematical model were used to assess load distribution on the shaft and the system's long-term durability. Structural analyses performed with finite element methods indicated that the symmetrical configuration of the blade and shaft geometry effectively distributed the loads, ensuring stable operation. These results confirm that the system could function effectively even if shredding capacity were increased.

Experimental testing of the system showed that the motor power matched the values projected in the design, and the drive mechanism could efficiently operate both shafts with a single motor. This design offers a low-cost and energy-efficient solution.

Based on the findings of this study, it is recommended to test different blade angles and motor speeds to further enhance the efficiency of the shredder unit. Additionally, using high-durability alloys or coatings for the blade and shaft materials could improve the system's long-term durability.

These results demonstrate that the improved shredder unit could serve as an effective system contributing to the recycling process of nonwoven waste fabrics.

5. Conclusion

The shredder unit for efficiently processing nonwoven waste fabrics into recyclable forms was successfully designed and validated. Experimental results confirmed its stable operation at 70 RPM with a dual-shaft configuration and 70 cutting blades, aligning with the mathematical model in terms of motor power, torque requirements, and cutting efficiency. The system achieved a mass flow rate of 782.55 kg/h, with effective load distribution ensuring long-term durability.

This cost-effective and energy-efficient design demonstrates significant potential for recycling nonwoven fabrics. Future studies should explore optimizing blade angles and motor speeds while enhancing material durability for improved performance under higher loads.

6. Acknowledgments

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