Design and Development of a Compact Plastic Shredder for Recycling of ABS and PLA Thermoplastics

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Abstract. The accumulation of plastic waste is a significant environmental challenge, particularly in developing regions where recycling infrastructure is limited. This paper presents the development of a compact plastic shredder specifically designed to process ABS and PLA thermoplastics. The shredder offers a practical and efficient solution for small-scale recycling operations, bridging the gap between the need for recycling and the availability of suitable technology. The design process involved comprehensive modeling and analysis to ensure the shredder's efficiency and durability. Key components such as gears, couplings, and belt systems were designed and evaluated to meet performance criteria, focusing on reducing costs and maximizing effectiveness. Finite Element Analysis (FEA) was employed to assess the mechanical integrity of the shredder under various operational conditions, confirming its capability to withstand stresses and perform reliably. The shredding efficiency is 85%, and the throughput rate is 50 kg/h, which is competitive with other small-scale solutions. The results highlight the potential of this technology to improve recycling efforts in resource-constrained settings, contributing to a reduction in plastic pollution and supporting environmental sustainability.

Keywords: ABS and PLA thermoplastics, shedder, finite element analysis, sustainability

1 Introduction

Plastic waste is a major environmental threat, and recycling has become an urgent priority for its removal. This is especially important in developing economies like Nigeria, where the accumulation of non-biodegradable plastic waste has become a challenge. The current disposal methods mainly involve landfills, but they have raised serious environmental concerns that put human health and safety at risk [1]. Pollution caused by the buildup of plastic waste, especially in waterways and oceans, is a major concern. It has negative impacts on ecosystems and marine life. Additionally, despite the significant energy consumed in the production and manufacturing of plastics, very little of that energy is reclaimed at the end of the plastic product's life cycle. Instead, plastic waste is typically

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sent to landfills and takes up valuable space. However, it is worth noting that many plastic products do contain recycled energy [2].

A waste plastic shredder is a machine that breaks down used plastic bottles into smaller particles. A plastic shredder machine operates by feeding plastic waste into rotating blades that cut and shred the material into smaller pieces. These blades, which are mounted on a shaft or rotor, work together with stationary blades or a comb structure to break down the plastic into manageable particles. These particles can then undergo additional processing or recycling. This process improves the plastic's portability, making it easier to use in the creation of new products. Okunola et al. [3] designed a PET bottle recycling machine that also combines washing and shredding functions. Their machine's cutting blades are arranged in an auger screw configuration, achieving an efficiency rate of over 90%. Shiri et al. [4] created a machine that integrates washing and shredding within a single chamber. This machine's cutting unit features a combination of fixed and rotary blades and uses a belt drive system to power the rotary blade shaft. Ravi worked on enhancing the shredding machine's performance by optimizing the cutter blade design. The improved cutter blade, with its dual cutting edges, boosts performance and reduces operational time [5].

Despite the growing concern over plastic waste and the urgent need for effective recycling methods, there remains a significant gap in the development of efficient, compact, and cost-effective shredding technologies tailored for smallscale recycling operations. Current shredding solutions often lack optimization for specific materials, such as Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) thermoplastics, and do not adequately address the operational challenges faced in developing economies. This paper aims to fill this gap by presenting a comprehensive design and analysis of a mini plastic shredder, emphasizing its potential for enhancing recycling efficiency and sustainability.

2 Methodology

The methodology for this study involves the design of a mini plastic shredder tailored for recycling ABS and PLA thermoplastics. The design process included extensive Computer Aided Design (CAD) 2odelling and Finite Element Analysis (FEA) to ensure optimal performance and structural integrity. Key components such as spur gears, couplings, and V-belts were meticulously designed and selected based on theoretical calculations and practical requirements. The CAD model provided a detailed visualization of the shredder, facilitating design validation and optimization. The assembly of the shredder focused on achieving safety, cost efficiency, compactness, reliability, and minimal maintenance, thereby ensuring a robust and effective solution for plastic waste recycling.

2.1 Design of Spur Gear

Spur gears are popular in mechanical systems due to their simplicity, efficiency, and easy manufacture. The efficiency of spur gears is generally high, typically ranging from 95% to 99% when gears are well-designed and properly lubricated. Under average operating conditions, it can be estimated that the power loss at each mesh is approximately 1% of the potential power transmitted through the mesh [6]. These cylindrical gears have straight teeth that interlock smoothly, allowing for the transmission of rotational motion and torque between parallel shafts. Their simple design makes them accessible to manufacturers using standard tools and machinery [7].

The standard formula to find the interference between the gears is as follows [8]:

$$z_1 = sin2F_{20}\alpha \tag{1}$$

F_0 is 1 for standard gear tooth and standard pressure angle is 20.

The reduction ratio is the output shaft speed over the input shaft speed which can be calculated by:

$$\mathrm{i} = \mathrm{N}_2/\mathrm{N}_1 \tag{2}$$

The Lewis Form Factor denoted as Y, is a dimensionless parameter used in gear design to consider the strength of the gear tooth about its shape and size.

$$\mathrm{Y} = \pi \times \mathrm{y} \tag{3}$$

Y is the Lewis constant which is selected according to the pressure angle (α).

2.2 Design of Coupling

Flexible jaw couplings are ideal for applications requiring moderate misalignment accommodation and vibration dampening, which helps reduce stress on gearbox and shredder components. Common materials include steel and aluminum, with the choice dependent on operating temperature, environmental conditions, component compatibility, and cost. Steel is preferred for its higher torque capacity and durability, particularly in corrosive environments. Ensuring proper alignment during installation is critical to minimizing misalignment and preventing premature wear, and the use of alignment tools is advisable to achieve precise alignment [9].

2.3 Design of Belt

Based on the maximum torque requirement of 500 Nm and an assumed operating speed of 60 rpm, the power requirement can be calculated using the following formula:

$$P = (2*pi*N*T)/60000 \qquad (4)$$

where P is the power (kW), N is the rotational speed (rpm) and T is the torque (Nm).

V-belts are the preferred choice for the belt drive system in mini plastic shredders because of their efficient power transmission capabilities. They excel in applications that require moderate to high torque, such as plastic shredders. V-belts have a proven track record of reliability and longevity in industrial settings, as they can withstand the rugged conditions commonly encountered in machinery like shredders. Moreover, V-belts are cost-effective and easily obtainable in different sizes and lengths, making them a practical option for a variety of applications. They are also relatively simple to install, making them well-suited for mini plastic shredder machines [10].

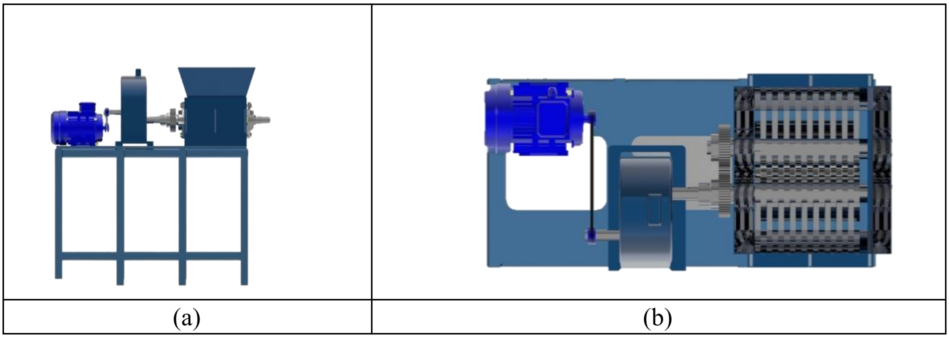
The length of the belt can be calculated by using this formula [8]:

$$L = 2C + (\pi(D_1 + D_2)) /2 \qquad (5)$$

where C is the center to center distance, D_1 is the smaller pulley diameter and D_2 is the larger pulley diameter.

2.4 CAD Modelling

A detailed CAD model of a plastic shredder machine has been designed and assembled using SolidWorks 2023, incorporating a gear drive-based reducer and an electronic motor to create a fully functional and efficient system. The plastic shredder machine, featuring precise geometrical representations in the Figure 1, effectively illustrates the mechanical components responsible for the shredding process. The gear drive-based reducer is depicted in Figure 1 with its gear train to ensure optimal power transmission, while the electronic motor functions as the prime mover to initiate and drive the shredding operation.



(a) (b)

Fig. 1. CAD model of mini plastic shredder (a) Front side view (b) Top side view

3 PERFORMANCE METRICS

The efficiency of the plastic shredder was evaluated by measuring the mass reduction and volume reduction ratios of processed ABS and PLA thermoplastics. The shredding efficiency is a crucial indicator of the machine's capability to effectively reduce the size of plastic waste, facilitating easier handling and subsequent recycling processes.

$$\text{Shredding Efficiency} = (\text{Output Mass}/\text{Input Mass})\ \text{X}\ 100\% \qquad (6)$$

Measure the throughput in terms of kilograms per hour (kg/h) or pieces per minute (ppm), which reflects the shredder's capacity to process plastic within a given timeframe.

4 Results and Discussion

4.1 Finite Element Analysis of Gears

A comprehensive static structural analysis of the spur gear used in the reduction gear mechanism of the shredder. The analysis evaluates the mechanical integrity and load-bearing capacity of the spur gears under varying operational conditions, which is critical for optimizing design, ensuring operational reliability, and enhancing the overall efficiency and longevity of the shredder's reduction gear mechanism.

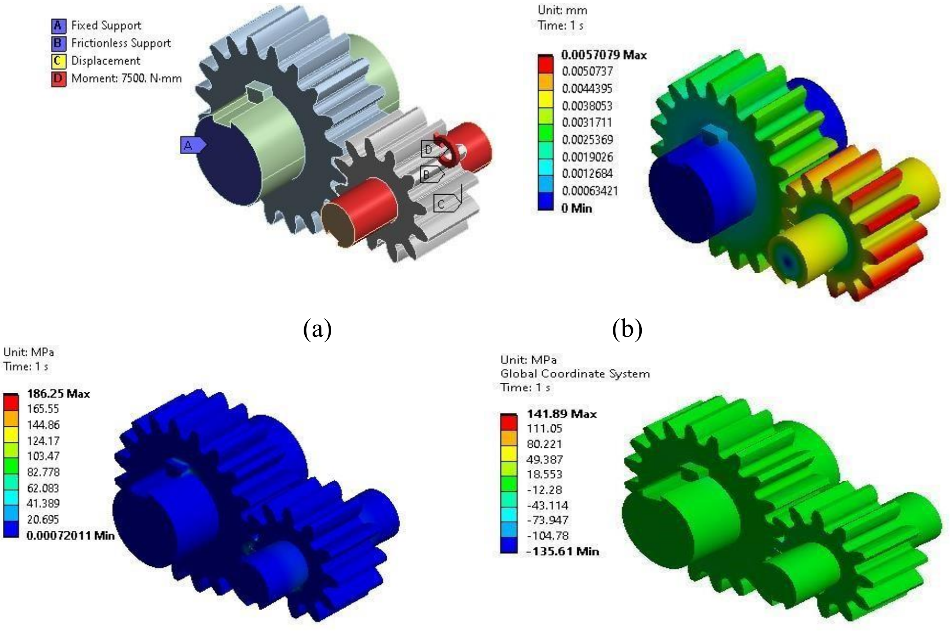
A detailed Finite Element Analysis (FEA) was conducted using an extensive mesh composed of 360,186 nodes and 98,190 elements. This fine mesh enabled precise modeling of the spur gear's geometry and its complex interactions under load, providing high-resolution insight into stress distributions and deformation patterns. The spur gear's geometry was carefully defined to reflect its actual design, with an emphasis on capturing complex features essential for accurate stress and deformation analysis. The mesh density was optimized to balance computational efficiency with the need for detail, especially in regions of high-stress concentration such as gear teeth.

Boundary conditions were applied to simulate real-world operational scenarios shown in Figure 2 (a). The gear was subjected to static loads, including torque and radial forces, representative of the conditions experienced during normal shredder operation. The constraints were applied to reflect the gear's attachment to the shaft and interaction with other components in the system, ensuring that the simulation mimics actual physical conditions. The primary loads considered were those resulting from torque transmission and radial forces, which are critical in assessing the gear's performance.

The FEA results provide a detailed understanding of the spur gear's performance under load, highlighting key areas such as stress concentration and potential failure points. The analysis revealed that the maximum deformation occurred at the tips of the gear teeth, which is consistent with expectations given the torque application and the inherent design of spur gears. The total deformation shown in Figure 2(b) is 0.00571 mm, indicating that the gear can maintain its structural integrity when subjected to operational loads.

The equivalent stress distribution showed that the maximum stress occurred at the root of the gear teeth, a typical stress concentration point (Figure 2 (c)). The peak von Mises stress was 186.25 MPa which was evaluated against the material's yield strength to ensure that the gear would not undergo plastic deformation under the applied loads. The normal stress analysis provided insight into the gear's ability to withstand perpendicular forces acting on the teeth. The results shown in Figure 2 (d) indicated that the normal stresses were 141.89 MPa which was well within the safe limits for the selected material, confirming the adequacy of the design for the intended application.

The static structural analysis confirms that the spur gear design is robust enough to handle the operational demands of the shredder. The stress and deformation patterns align with theoretical predictions, affirming the validity of the design choices. The identification of high-stress areas, primarily at the gear tooth root, provides valuable information for further optimization, such as material selection or geometric refinement.



(a) (b)

(c) (d)

Fig. 2. (a) Boundary conditions on spur gears (b) Total deformation on spur gears (c) Equivalent stress on spur gears (d)Normal stress on spur gears

The spur gear exhibited a Lewis form factor of 0.44, ensuring adequate strength to withstand operational stresses. The safety factor for the gear design was determined to be 1.5, adhering to industry standards for mechanical reliability. The shredder achieved a shredding efficiency of 85%, demonstrating its capability to effectively process ABS and PLA thermoplastics. The throughput rate was measured at 50 kg/h, which is competitive with existing smallscale recycling solutions.

4 Conclusion

This study presents the successful design and development of a compact plastic shredder tailored for recycling ABS and PLA thermoplastics. The shredder demonstrated a shredding efficiency of 85% and a throughput rate of 50 kg/h, proving to be a competitive solution for small-scale recycling operations. By employing spur gears, couplings, and V-belts, alongside detailed CAD modeling and finite element analysis, the machine achieved high reliability and structural integrity, with a safety factor of 1.5. These findings indicate the shredder's potential to significantly enhance recycling efforts, particularly in developing regions where existing infrastructure is inadequate. The design not only addresses the urgent need for more effective recycling technologies but also supports environmental sustainability by reducing plastic waste. This machine provides a practical and affordable option for small businesses and communities seeking to implement local recycling initiatives.

The implications of this work extend beyond the current scope, offering a foundation for future research focused on optimizing the shredder for additional plastic types and enhancing its overall performance. Further exploration of blade design and material selection, as well as the integration of smart technologies, could improve efficiency and broaden the shredder's applicability. By continuing to innovate in these areas, this research can contribute to more sustainable waste management practices and help mitigate the global issue of plastic pollution.

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