Engineering a Cleaner Tomorrow through Design and Analysis of Two Stacks Medical Waste Disposal System for Health and Environmental Benefits

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Abstract. The rising volume of medical glass waste presents considerable challenges to both public health and environmental sustainability. This study aims to design an innovative Medical Glass Waste Shredder to improve waste management practices in healthcare facilities. Current glass shredding solutions face limitations in shredding capacity, safety, and compliance with recycling standards, hindering effective waste management. The primary objectives of this research include developing a shredder capable of processing up to 100 glass bottles per minute, achieving a bending safety factor of 5.45 for the pinion and 7.05 for the gear, and ensuring user safety with a designed surface safety factor of 1.22. The methodology encompasses a comprehensive literature review, design calculations, and CAD modeling of the shredder, emphasizing safety and environmental impact. Anticipated outcomes include a robust shredding solution that significantly reduces medical waste volume, improving disposal practices by up to 80%, increases recycling rates, and promotes environmental sustainability. Successful implementation of this innovative shredder is expected to enhance waste management, ensure regulatory compliance, and yield cost savings of up to 30% for healthcare organizations, ultimately contributing to a cleaner, healthier future for communities and ecosystems.

Keywords. Medical Glass Shredder, Waste Management, CAD modeling, Environmental Sustainability

1 Introduction

In today's rapidly growing world, the surge in population has led to a significant increase in the demand for medical facilities and equipment. A substantial portion of medications is stored in glass containers due to their effectiveness in preserving the integrity and safety of the contents from external environments. However, this growing reliance on glass containers has also contributed to escalating pollution levels, as improper disposal of these bottles can pose serious environmental hazards. Stray

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animals are particularly vulnerable as they often ingest waste from dumps, leading to severe harm [1]. Therefore, removing glass bottles from waste dumps and recycling them is crucial for mitigating this pollution and creating a safer environment. Several methods exist for disposing of glass waste, including grounding, shredding, melting, and reusing. Among these, shredding is generally considered the most economical and efficient approach for facilitating the reuse of glass materials. However, existing shredding technologies present notable limitations. Current shredders often fail to reduce glass to sufficiently small pieces, which limits their effectiveness and the recyclability of the glass fragments [2]. Furthermore, many shredders lack adequate safety features and are not optimized for the specific requirements of medical glass waste, which is typically more fragile and poses greater risks to users and the environment. A critical comparison of existing solutions reveals that while grounding and melting provide alternative methods for glass disposal, they are energy-intensive and less sustainable compared to shredding. Grounding often results in uneven particle sizes, making it less ideal for recycling purposes. Melting, on the other hand, requires significant energy input and emits harmful pollutants, further complicating its environmental impact [3]. Reusing glass containers, although an environmentally friendly option, is limited by contamination risks and the logistical challenges of collecting and sterilizing used medical glass [4].

While the primary focus of this study is the design and development of an innovative Medical Glass Waste Shredder, it is essential to consider broader aspects such as user interaction, safety, sustainability, and economic viability. Effective waste management solutions must not only be technically sound but also user-friendly, ensuring that healthcare workers can operate the shredder safely and efficiently. Additionally, the design must prioritize sustainability by minimizing environmental impact, such as reducing energy consumption and promoting recyclability of the shredded glass. Economic viability is also crucial, as the solution should be cost-effective for healthcare facilities to adopt widely. By addressing these key aspects, this study aims to develop a shredder that is not only technically advanced but also practical, safe, sustainable, and economically feasible for real-world application. This study aims to address these limitations by developing an innovative Medical Glass Waste Shredder that improves upon existing technologies. The proposed design focuses on enhancing shredding efficiency by incorporating a double-storey mechanism, which is specifically tailored to medical glass waste. This mechanism is intended to shred glass into a powder-like form, thereby increasing the material's reusability and reducing environmental hazards. By critically assessing current solutions and integrating key safety and environmental considerations, this research seeks to contribute to more effective and sustainable waste management practices in healthcare facilities.

2 Methodology

The initial phase of the design process involved selecting a mechanism that balanced efficiency with cost-effectiveness. After careful consideration, a configuration was chosen where a single pinion drives four gears attached to corresponding shafts. The input revolutions of the pinion and the number of teeth were determined based on the required operational parameters, specifically targeting a gear ratio of 1:2.5. The gear design was then developed based on these inputs, and iterative calculations were performed to achieve acceptable safety factors.

For the shaft design, the geometry of the cutter blades was selected first, which allowed for the determination of the corresponding shaft loads. The weight of the blades was converted into uniformly distributed loads along the shaft, which were then simplified into a concentrated load at the center. The load contribution from the waste material on the shaft was significantly lower than that of the blades, and thus it was neglected, as the safety factor provided sufficient coverage. The shaft diameters were calculated using singularity functions, leading to the design of a stepped shaft to minimize deformation. Additionally, the bearing life was calculated by selecting an appropriate bearing to handle the greater reaction load on the shaft, ensuring the durability and reliability of the assembly under operational conditions.

2.1 Batch Calculation

In order to design a shredder, it was needed to determine how much power is required to provide the necessary torque to the shaft.

$$Power = T \times \omega \tag{1}$$

$$Power = 4200\ lb.in \times 150\ rpm$$

$$Power = 1.588\ hp$$

So, selecting a 2hp motor for the shredder. Now calculating the volume or amount of the bottles to be shredded per unit time. The blades rotate 60 times in one minute and there are 29 blades on each shaft. The hopper has an area of 480 in^2 at the base. Considering the fragile nature of glass, the shredder will easily be able to shred it. Taking an average bottle diameter of 1.5 inch [5], a total of 320 bottles can be placed at the bottom of the hopper over the shaft blades. This is if we place the bottles straight and aligned with each other so that each bottle covers only 1.5 inch. By this, 100 bottles come in the cutting range of the blades. At 60 rpm the blades can easily shred 100 bottles per minute.

2.2 Gear Design

Gears play an important role in the working of shredders as they deliver power to the shafts from the motor. An efficient and cost-effective mechanism was selected for the gear train. Appropriate hardness of the material was selected to achieve acceptable safety factors. The following table 1 shows the parameters of the gear and pinion.

Table 1. Parameters Of Gear

Description	Value
Working speed (pinion)	150 rpm
Torque	4200 lb-in

Number of Gears	4
Gear Ratio	1:2.5
Number of teeth (Gear)	35
Number of teeth (Pinion)	14
Pressure angle	25°
Diametral Pitch	5 in

The bending stresses in the gear and pinion were calculated by the following equation [6, 7].

$$\sigma_b = \frac{W_t \times P_d}{F \times J} \times \frac{(K_a) \times (K_m)}{K_v} (K_s)(K_B)(K_I) \tag{2}$$

The surface stress in the gear mesh was calculated by the following equation [6].

$$\sigma_c = C_P \sqrt{\frac{W_t}{FId} \frac{C_a C_m}{C_v} C_s} \tag{3}$$

2.3 Shaft Design

Shafts are a crucial element in the function of shredders used to rotate the cutter blades. In order to achieve best performance appropriate material must be used [6]. This will help in achieving the optimal dimensions for the shaft application.

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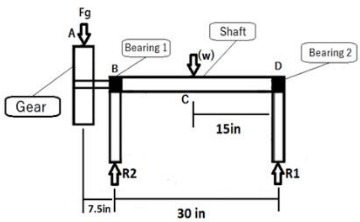

Fig. 1. Freebody Diagram of Shaft

Fig. 2. CAD design of Shaft

The reaction R_{2xy} shown in figure 1 was calculated by the following equation (3) [6]:

$$\Sigma M_D = W \times CD + R_{2y} \times BD + F_{gy} \times AD \tag{4}$$

The moment at each point was calculated by the following equation (4) [6]:

$$\Sigma M = R_1 < x - a >^1 + R_2 < x - a >^1 + F_{gy} < x - a >^1 + W < x - a >^1 \tag{5}$$

The shaft diameters at points A, B, C were calculated by the following equation (5) shown in figure 2 [6, 8]:

$$d = \left\{ \left(\frac{32 \times N_f}{\pi} \right) \left[\left(\frac{M_o}{S_e} \times k_f \right)^2 + \frac{3}{4} \left(k_{fsm} \times \frac{T}{S_{ut}} \right)^2 \right]^{\frac{1}{2}} \right\}^{\frac{1}{3}} \tag{6}$$

2.4 Bearing Life

Bearings play a crucial role in the rotation of components within a mechanism. They provide easy rotation of parts with reduced friction and minimal wear and tear of the rotating components. Bearing life is the estimate of number of cycles a bearing can provide before failing due to fatigue. As there is already a number of rotation cycles of the designed gears, therefore bearing cycles must be greater than the gear cycles in order to keep the shredder working. The bearing life was calculated by the following equation (6) [6, 9,10]:

$$L_{10} = \left(\frac{C}{P} \right)^{\frac{1}{3}} \tag{7}$$

Where C is the dynamic load rating of the selected bearing: $C = 19300\ lb$ and $P = 1665.43\ lb$ is the load applied on the bearing. This load P is the reaction force applied of the shaft at point B. The load at point B was simply used for bearing life estimate because it was greater than the rest of the loads. So, a bearing designed at the maximum load will be able to withstand the smaller loads too shown in figure 3.

Fig.3. Bearing CAD Model

2.5 Hopper Design

The hopper of the glass shredder is designed with a trapezoidal geometry, providing a calculated volume capacity of 21,695 cubic inches. This capacity is adequate to accommodate a large number of glass bottles, ensuring efficient operation. The hopper features a straight, non-curved profile and is securely mounted at the top of the shredder, facilitating the direct feed of material into the shredding mechanism. Additionally, at the base of the shredder, where the processed glass particles exit the cutting blades, a detachable storage box is affixed. This storage box is engineered to collect all the shredded material efficiently. Its detachable design offers the practical advantage of easy removal and disposal of the accumulated waste, enhancing the overall usability and maintenance of the shredder system shown in figure 4.

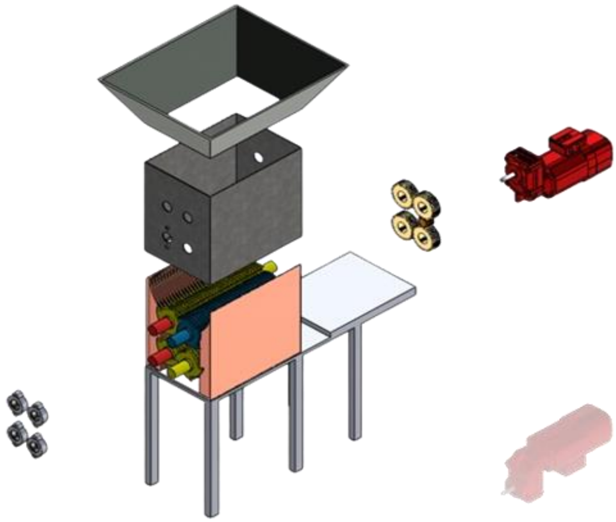

Fig. 4. Shows the double stage mechanism of the shredder. This design will effectively shred glass and make it easy to be recycled and reused. The gear and pinion arrangement can also be observed from the figure. This configuration was used so that only one pinion is used to derive the gear set, minimizing the cost of the shredder.

3 RESULTS AND DISCUSSION

The Table 2 shows the results obtained by the design process. In the design process, achieving bending and surface safety factors greater than one was a critical objective to ensure the structural integrity and durability of the gear system. After two iterations, the desired safety factors were successfully met, demonstrating the robustness of the design approach. Additionally, the shaft diameters at points A, B, and D were initially calculated to be 1.37 inches based on the load requirements. However, to prevent a significant and potentially problematic step in the shaft diameters, the final diameter at these points was increased to 3.0 inches. This adjustment not only enhanced the structural consistency of the shaft but also contributed to its overall strength. Furthermore, the bearing life was meticulously calculated to exceed the number of cycles expected for the gear, ensuring long-term reliability. As a result, an appropriate bearing was selected to meet the operational demands, thereby reinforcing the design's focus on longevity and performance.

Table 2. Design Results

Description	Value
Bending Safety Factor (Pinion)	5.45
Bending Safety Factor (Gear)	7.05
Surface Safety Factor (Gear Mesh)	1.22
Shaft Diameter (Point C)	3.45 in
Shaft Diameter (Point B, D)	3.0 in
Shaft Diameter (Point A)	3.0 in
Bearing Life	1557.5 million revs.

A detailed numerical analysis of the gear was conducted using the static structural module of the commercial software ANSYS to evaluate its performance under load conditions. The finite element analysis (FEA) results are presented in the following section. Figure 6 illustrates the total deformation within the gear mesh, revealing that the highest deformation occurs at the gear teeth, specifically in the regions where contact with the pinion takes place. This observation is critical, as it identifies the teeth as the primary zones of mechanical stress and deformation during operation. Additionally, Figure 7 depicts the distribution of equivalent (von Mises) stress within the gear mesh. The analysis indicates that the maximum equivalent stress is concentrated in the contact region between the meshing teeth of the two gears. This stress concentration is a key factor in assessing the gear's load-bearing capacity and potential failure points, providing essential insights for optimizing gear design and ensuring reliable operation under varying load conditions.

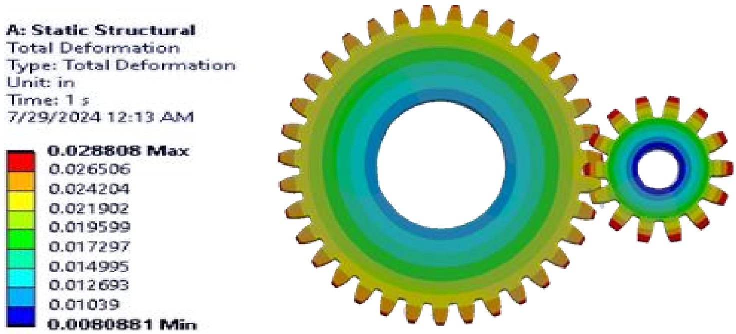

Fig. 6. Total Deformation on Gear

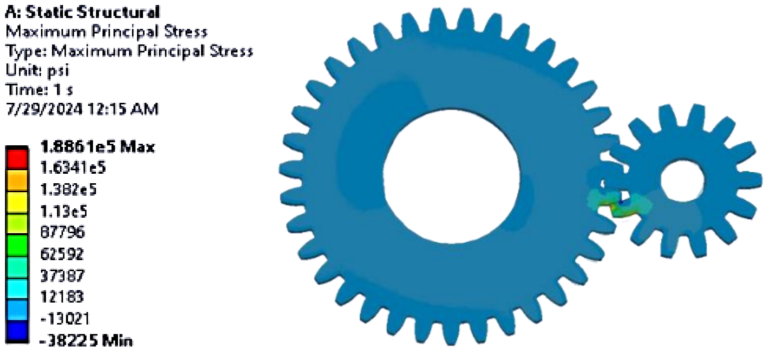

Fig.7. Equivalent Stress on Gear

4 CONCLUSION

The design of an innovative Medical Glass Waste Shredder represents a significant advancement in waste management practices within healthcare facilities. The shredder's double-stage configuration effectively reduces the size of shredded glass waste, making it easier to recycle and reuse. The design achieved a bending safety factor of 5.45 for the pinion and 7.05 for the gear, along with a surface safety factor of 1.22 for the gear mesh. These safety factors underscore the robustness and reliability of the shredder under operational conditions. Additionally, the final shaft diameters were optimized to 3.0 inches, enhancing structural integrity, and the bearing life was calculated to exceed 1557.5 million revolutions, ensuring long-term durability. The driving mechanism, which uses a single pinion to drive all four gears, further contributes to the economic efficiency of the design. The successful implementation of this shredder is anticipated to significantly improve medical waste management by processing up to 100 glass bottles per minute, reducing waste volume by up to 80%, and promoting recycling, thereby contributing to environmental sustainability and cost savings of up to 30% for healthcare facilities. However, the study has some limitations. The design and calculations are based on theoretical models and simulations, which may not fully capture the complexities of real-world operations. The impact of variables such as glass composition, bottle shape, and varying loads on the shredder's performance needs to be evaluated through practical testing. Additionally, the study did not explore the potential effects of long-term wear and tear on the shredder's components, which could affect its efficiency over time. For future research, field tests should be conducted in various healthcare settings to validate the shredder's performance, efficiency, and user satisfaction. Furthermore, exploring the integration of smart technologies, such as IoT sensors for real-time monitoring, could enhance operational control and maintenance scheduling. Investigating the environmental impact of the shredded glass particles and their recyclability in different industries would also provide valuable insights into the broader applicability and sustainability of the designed shredder. These areas of future work will help solidify the shredder's role in advancing medical waste management and fostering a more sustainable healthcare system.

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