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Development of a Polymer Shredder Recycling Waste from 3D Printers

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ABSTRACT

The increasing use of 3D printers has heightened the need for sustainable solutions to manage the polymeric waste generated, such as PLA. This study presents the development of an innovative shredder capable of processing 3D printing waste and transforming it into reusable granules for the production process. The project involved the design of a knife mill, adapted for PLA, with blades offset by 30°, ensuring efficient distribution of cutting forces and reducing stress on the components. Critical components, such as blades, shafts, and motor, were dimensioned using precise calculations to determine cutting force, torque, and material resistance. The system was validated through finite element analysis (FEA), ensuring structural robustness and an adequate safety factor. The system allows for the adjustment of granule size using sieves with different calibers, making it adaptable to process requirements. It also includes safety devices that ensure reliable operation and protect the operators. The equipment proved versatile and capable of processing common polymers such as ABS, PETG, and PA. The results confirm that the shredder is a practical, efficient, and sustainable solution, contributing to the circular economy and reducing the environmental impact of 3D printing. In the future, improvements in design and automation could enhance its scalability and facilitate integration into industrial processes.

1. Introduction

New technologies have emerged rapidly in recent times, playing an increasingly crucial role in modernizing and optimizing business processes. Among these, 3D printing stands out as a constantly evolving technology with the potential to become an indispensable tool in Industry 4.0 [1], [2]. However, using polymers in 3D printing entails greater responsibility regarding the life cycle of these materials, as the process often generates significant amounts of waste, which are frequently unavoidable.

In this context, recycling plays a fundamental role in ensuring the sustainability of these resources and the efficient management of waste [3]. Many materials, such as PLA, ABS, PET, and other thermoplastics, possess characteristics that, although advantageous for 3D printing, can make their reintegration into sustainable production cycles more challenging [4]. Therefore, recycling waste generated by 3D printing emerges as an essential strategy to reduce environmental impact and promote a circular economy in this sector.

The present study focuses on developing an innovative solution for recycling waste from 3D printing. The main objective is to design and build equipment that enables the reuse of this waste within the printing process, contributing to a more sustainable and efficient approach. In this context, a conventional knife mill was selected for shredding various polymers, and it was adapted explicitly for PLA. This choice is justified by the equipment's versatility in processing different materials, its robustness, simplicity of construction, low production costs, and its ability to produce varied particle sizes, ensuring efficiency and adaptability to the proposed recycling process.

The document is structured into several sections, beginning with the Abstract, which provides an overview of the study, followed by the Introduction, which contextualizes the topic and highlights the importance of recycling within the circular economy. The Literature Review addresses 3D printing, the materials used, recycling methods, and polymer shredders. In the Materials and Methods section, the components of the shredder and the project requirements are described. In contrast, the Shredder Sizing section details the technical calculations for designing the blades, shafts, and motor. The Discussion and Conclusion explore the study's results and contributions. Finally, the References section supports the content presented.

2. Literature Review

2.1 3D Printers

3D printers are devices that transform digital ideas into physical objects through a process known as additive manufacturing [5]. Unlike traditional methods such as cutting or molding, these machines build objects layer by layer, using materials like plastics, resins, metals, ceramics, and even biomaterials. Although they first emerged in the 1980s, 3D printers have become more accessible and widely used over the past few decades due to technological advancements and cost reductions [6].

Currently, these printers have applications in various sectors. In industry, they play a key role in rapidly developing prototypes and producing customized parts. With the continuous advancement of technology, their innovation potential continues to grow, expanding opportunities for creativity and production across multiple fields [7].

2.2 Materials Used in 3D Printing

In FDM 3D printing, the most common materials are ABS, PLA, PET (including its variant PETG), and Nylon, each with distinct characteristics. ABS is a widely used thermoplastic polymer due to its low cost, well-established industrial support, and good mechanical performance. However, its high tendency to warp requires a heated bed to prevent print failures [8], [9].

Conversely, PLA stands out as a more environmentally friendly alternative, being produced from lactic acid derived from corn starch. This material is less sensitive to temperature variations and enables high-quality prints without needing a heated bed [4]. PET, known for its strength, has its modified variant, PETG, which combines greater transparency, durability, and ease of use, although at a higher cost than PLA.

Nylon, a polyamide with high rigidity, durability, and chemical stability, is recognized for its superior performance. However, the high cost of this material limits its large-scale application [8], [10].

2.3 Recycling of Polymeric Waste from 3D Printers

Polymers are essential and widely used materials worldwide due to their desirable properties, such as light weight, low maintenance requirements, weather resistance, low toxicity, transparency, and low cost, characteristics that drive their application across various sectors [11]. Currently, polymers are extensively used in industries such as agriculture, healthcare, electricity and electronics, packaging, transportation, and aerospace, among others [12].

Polymers are often designed for single-use applications due to their excellent performance, which includes light weight, low cost, ease of processing, and outstanding mechanical properties [13]. However, the degradation of most polymers in the environment is extremely slow due to their stable chemical structure. As a result, it is estimated that large amounts of polymeric waste are generated annually [14]. The proper management of polymeric waste is undoubtedly a major global challenge, and controlling such waste has become a global consensus.

There are three main types of polymer recycling: chemical, energy recovery/incineration, and mechanical. Chemical recycling involves depolymerizing polymers to obtain chemical substances or raw materials [15]. Energy recovery and incineration are used when selective recycling is not feasible or has already been exhausted [16].

Mechanical recycling of polymers is a sustainable method that aims to reuse discarded plastics by transforming them into new products without altering their original chemical structure [17].

This process is structured into five main stages, ensuring plastic's efficient and sustainable transformation.
The first stage, pre-separation, can be performed manually or automatically using equipment such as optical readers and ballistic separators. This stage aims to ensure the homogeneity of the final product, facilitating the subsequent steps [18]. The second stage, fragmentation or grinding, involves shredding the plastic in specific mills adjusted to the type of material, reducing it to sizes suitable for further processing. The third stage, washing and separation, place the materials in water tanks to separate them based on density: less dense plastics float, while denser ones sink, enabling effective separation [19]. The fourth stage, drying, exposes the plastic granules to hot air, ensuring they achieve the appropriate moisture content for the next stages, avoiding issues during extrusion. Finally, the fifth stage, extrusion, melt the dried granules in extruder machines, transforming them into continuous filaments [3], which are then cooled in water tanks and cut into small granules ready for reuse.

This sequence of stages ensures the efficient recycling of plastics, promoting sustainability and the circular economy.

2.4 Polymer Shredders

There are several types of mechanical shredders whose selection depends on factors such as the type of material to be processed, operating speed, desired granule size, and other criteria [20].

Currently, several projects involve the design of polymer shredders. For example, [21] address the development of a polymeric scrap shredder to provide a solution for managing nylon waste generated in industrial processes, particularly in machining contexts. This project aims to develop a machine capable of shredding nylon scraps to reduce waste volume and prepare the material for reuse, promoting industrial recycling practices.

There is also the project by [3], in which the shredder used was designed to process polymer waste, such as PLA and ABS, reducing it into small pieces with dimensions suitable for the extrusion process. The shredder has stainless steel blades, precisely spaced to produce particles smaller than 5 mm. The system, powered by an electric motor, ensures high durability and efficiency in shredding, facilitating recycling and the production of uniform and consistent filaments for 3D printers.

In turn, the project by [22] focuses on a shredder designed to reduce the size of polymeric waste into small particles, with applications in recycling and reuse. This shredder uses an electric motor that generates torque to drive a shaft with cutting blades. These rotating blades work together with static blades positioned in the shredding chamber to fragment the materials. A mesh at the bottom of the chamber ensures that only particles of the desired size are released into the collection container.

2.5 Knife Mill

The operation of a knife mill is based on reducing the material volume through mechanical grinding, which occurs via direct contact between the cutting blades and the material, operating at a relatively low rotational speed [23].

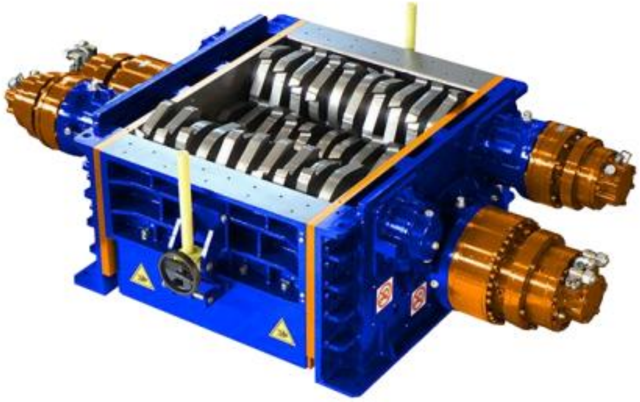

Figure 1. Knife crusher mill [23].

The blades have different geometries, varying in the number of cutting edges, outer diameter, attack angle, and thickness, depending on the type of material to be processed, its shape, and the operating speed and capacity [23].

In the case of grain size or granulometry, it is regulated by sieves with openings of specific diameters. Changing the sieve's caliber makes it possible to obtain grains of different sizes [24], as illustrated in Figure 2.

Figure 2. Sieves of different calibers [24].

The safety of this equipment is crucial due to the high risk of severe injuries to the operator. Certified safety devices were integrated into its design.

A macro analysis of the system allows the identification of critical elements for the equipment's operation, reliability, and safety, which will be studied in greater detail. The remaining components, such as structural parts and connecting elements, will be selected by comparison with similar systems, ensuring operator safety and equipment integrity.

3. Materials and Methods

In the design of polymer shredders, it is essential to consider their main components and the technical-operational requirements that ensure proper functioning and structural resistance. This section addresses the constituent parts of the shredder system and describes the technical characteristics necessary to meet the project’s defined objectives. The analysis includes mechanical, operational, and maintenance specifications, determining the system’s effectiveness and adaptability to specific process conditions.

Thus, the elements to be studied are:

- Blades;
- Motion transmission shafts for the blades;
- Motor/reducer.

The calculation and selection of components are based on the following project requirements:

- Capability to shred PLA plastic parts up to 350x350x400 mm;
- Production capacity of 1 kg/h of granules;
- Adjustable grain diameter;
- Easy disassembly for cleaning and maintenance;
- 220V AC power supply.

4. Sizing of the Crusher

To proceed with the sizing of the shredder, it was essential to understand the characteristics of PLA, as this was the only way to determine the necessary specifications for the equipment to shred PLA waste according to the desired requirements.

For this purpose, the following data were obtained from the existing literature:

Table 1. PLA physical characteristics.

Modulus of elasticity	4258	Mpa
Maximum tensile stress	40	MPa
Shear strength limit	35	MPa

Hardness	84	Shore D

For the sizing of the shredder, it was essential to identify the materials and components required for its construction, define the optimal design of both the equipment and its constituent elements, and select a suitable motor to ensure the efficient operation of the two shafts by the established requirements. All necessary calculations were carried out to support these decisions, and they are detailed in this section.

4.1 Knives

The first parameter to determine is the cutting force per blade, essential to ensure the equipment's ability to efficiently shred a PLA part. For this calculation, a blade with a thickness of 5 mm and a cutting edge height of 4 mm were considered, dimensions that allow the evaluation of the equipment's performance under the expected operating conditions. This value will serve as the basis for sizing the shredding system, ensuring that the applied forces are appropriate for the material being processed without compromising the integrity of the blades or the other components of the equipment.

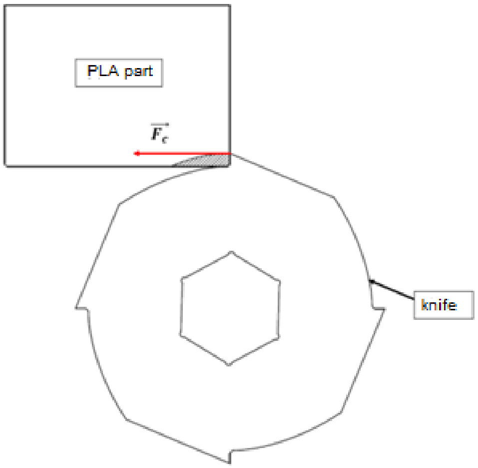

Figure 3. Knife/PLA part interaction.

Figure 3 represents the interaction between the blades and the PLA parts during the shredding process. In this context, the cutting force acts tangentially to the rotational movement of the blades, a behavior analogous to a conventional material removal process. Based on this analogy, the cutting force can be determined by calculating the cutting power, as indicated in Equation 1. This approach enables an accurate analysis of the forces involved, contributing to the proper sizing of the system.

$$Pc = \frac{a_p.a_e.v_f.k_c}{60*10^6} \qquad \text{Equation 1}$$

Where:

- ap is the depth of cut, which in this case corresponds to the cutting edge height;
- ae is the width of cut or blade thickness;
- vf is the cutting feed; and
- kc is the specific cutting resistance.

To determine the cutting feed (vf), it was considered that, with each blade rotation, each cutting edge is responsible for removing the maximum possible thickness of material. Given that the cutting edge height is

4 mm, the feed per cutting edge (fz) is also 4 mm. This assumption allows for calculating the required linear feed, ensuring that material removal is efficient and meets the project specifications.

The linear feed speed can be determined using the following equation:

$$v_f = f_z.z.n \qquad \text{Equation 2}$$

Where:
z is the number of cutting edges per blade, and
n is the rotational speed in rpm.

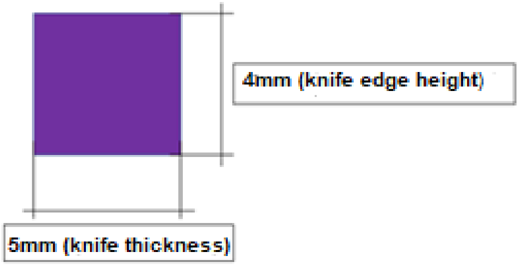

Figure 4. PLA knife/piece cutting area.

Since the specific cutting resistance (kc) for PLA was not identified, the general specific cutting resistance for thermoplastics, which is 150 MPa, was considered.
By assuming a cutting speed (vc) of 70 m/min and a blade diameter (d) of 90 mm, the rotational speed (n) is calculated to be 260 rpm.

Thus, the values for the linear feed speed and the cutting power are obtained as follows:

$$v_f = 4 * 4 * 260 \iff v_f = 4160\, mm/min \qquad \text{Equation 3}$$

$$p_c = \frac{4*5*4160*150}{60*10^6} \iff p_c = 0{,}208\, kw \qquad \text{Equation 4}$$

$n = 260\, rpm$

$z = 4$

$f_z = 4\, mm$

$a_p = 4\, mm$ → Cutting edge height

$a_e = 5\, mm$ → Blade thickness

Once the cutting power is obtained, it is possible to determine the torque per blade and the corresponding cutting force:

$$p_c = M_{knife} * n \qquad \text{Equation 5}$$

If we have:

$$n = 260\, rpm \rightarrow 27{,}23 \frac{rad}{s} \qquad \text{Equation 6}$$

Therefore:

$$M_{knife} = \frac{p_c}{n} \rightarrow M_{knife} = \frac{208}{27{,}23} \Leftrightarrow M_{knife} = 7{,}64\ N.m \qquad \text{Equation 7}$$

$$F_c = \frac{M_{knive}}{r_{knive}} \rightarrow F_c = \frac{7{,}64}{0{,}045} \Leftrightarrow F_c = 169{,}75\ N \qquad \text{Equation 8}$$

The cutting force, applied tangentially to the blade's cutting edge during rotation, was used in a finite element analysis to validate the blade geometry. For this purpose, the software Autodesk Inventor 2020 for Windows [25] and its stress analysis tool were utilized.

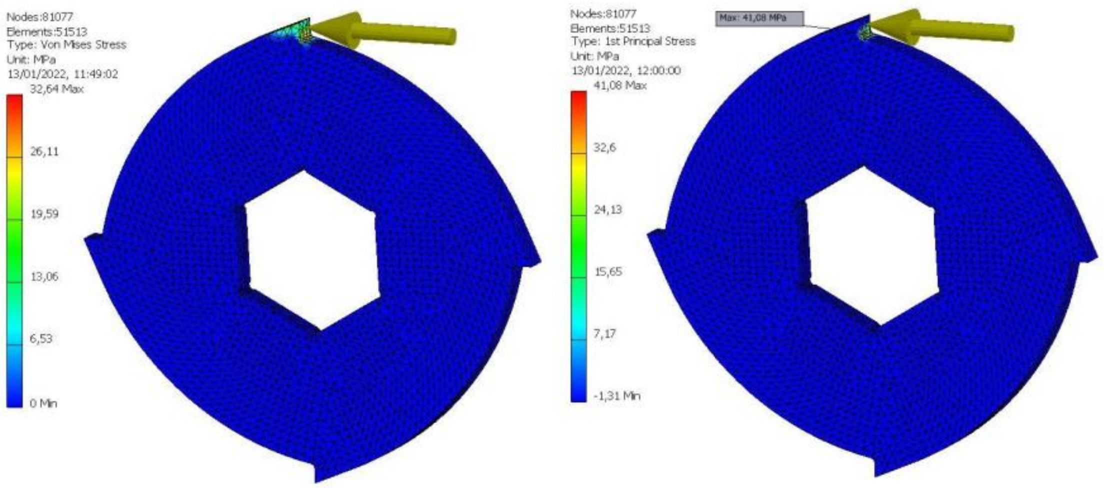

Figure 5. a) Finite element analysis applying 170N of force to the knife – Von Mises stress; b) Finite element analysis applying 170N of force to the knife – Maximum main stress.

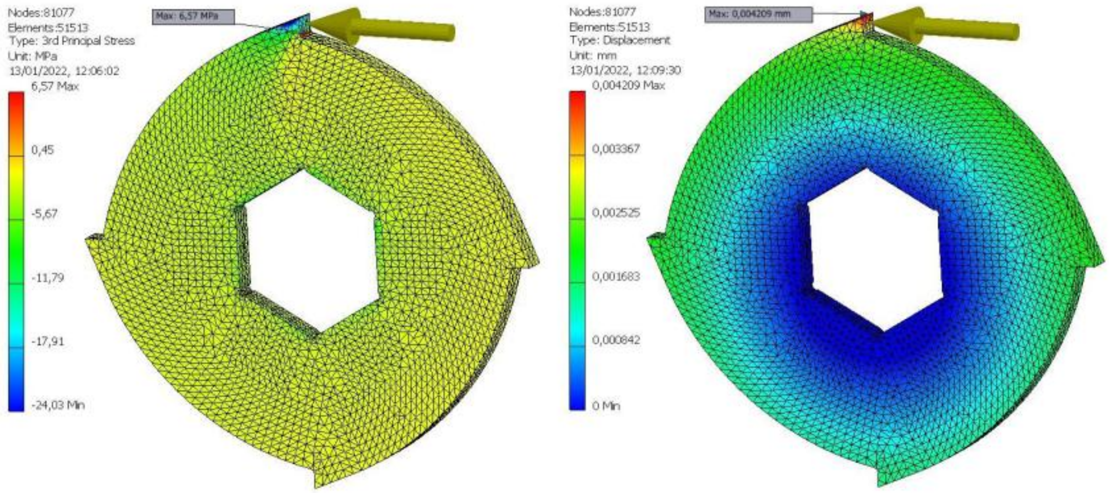

Figure 6. a) Finite element analysis applying 170N of force to the knife – Minimum main stress; b) Finite element analysis applying 170N of force to the knife – Deformation.

4.2 Shafts

The sizing of the shafts responsible for transmitting the motor's motion to the blades is a crucial step in the design of the shredding system. These shafts must be designed to withstand the forces generated during operation, ensuring efficiency and durability. The shredding system consists of two parallel shafts interconnected through gears, whose primary function is to transfer the motor's rotational motion to the blades. This mechanism must ensure a uniform and reliable power transmission, minimizing energy losses and optimizing the equipment's performance. Additionally, it is necessary to calculate the power required by the motor to meet the system's operational demands, considering factors such as cutting resistance, the generated torque, and the rotational speed needed for the efficient operation of the blades.

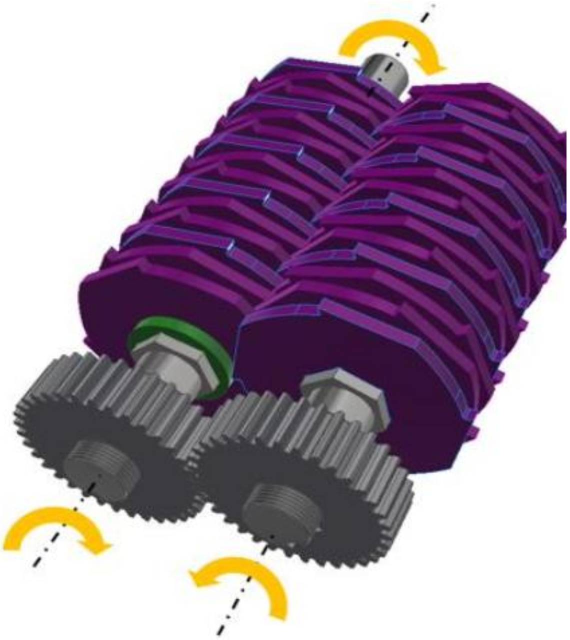

Figure 7. Arrangement of knives and transmission shafts.

In Figure 7, it can be observed that the blades are not aligned but offset by 30° relative to each other. This configuration was designed to ensure that only 10 blades are simultaneously in operation during the cutting process, thereby reducing the load applied to the system. As a result, each shaft is responsible for transmitting the torque required to operate five blades per cutting cycle, optimizing the distribution of forces and minimizing component wear. This arrangement contributes to greater energy efficiency and enhances the durability of the shredding system

$M_{\text{knife}} = 7{,}64\ N.m$

$N_{\text{knives}} = 5$ knives Equation 9

$M_{\text{shaft}} = M_{\text{knife}}.N_{\text{knives}} \rightarrow M_{\text{shaft}} = 7{,}64 * 5 \Leftrightarrow M_{\text{shaft}} = 38{,}2\ N.m$

The primary shaft, directly connected to the motor, is subjected to a 76.4 N·m torque during each cutting cycle due to the force transmission to the blade system. Through a detailed analysis of the stresses applied to the shaft, a maximum shear stress of 25.20 MPa was determined, located in the section connected to the motor. To ensure structural integrity and operational reliability, a diameter of 24.9 mm was specified for this section, ensuring that the shaft can withstand the applied loads with an appropriate safety factor.

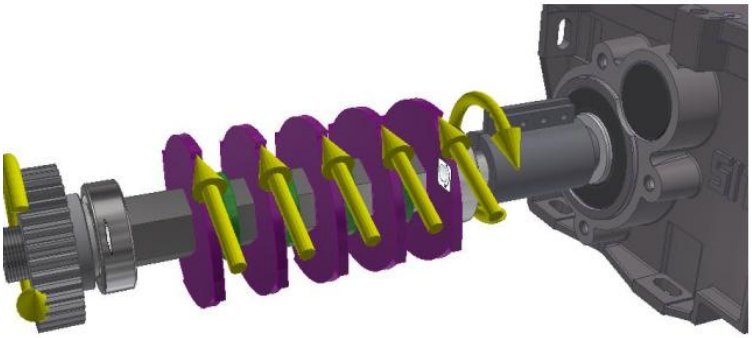

Figure 8. Representation of forces applied to the blade assembly on the shaft.

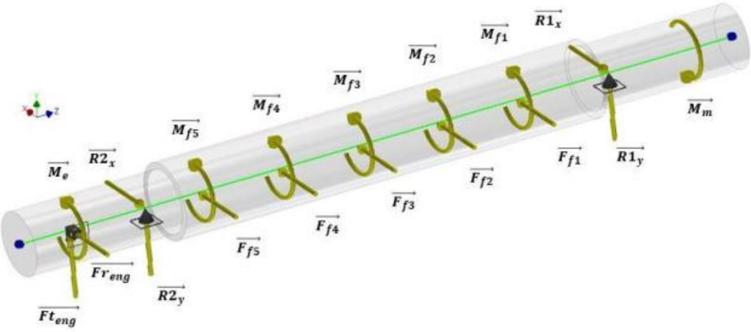

Figure 9. Distribution of loads and torques along the transmission shaft.

Figures 8 and 9 illustrate all the loads applied to the shaft, including forces resulting from the torque transmitted by the motor and the blades in operation. To simplify the analysis, it was assumed that the mass of the shaft and blades is negligible, as its influence on the generated stresses is insignificant compared to the applied cutting and torsional forces. This assumption allows the analysis to focus on the most relevant forces, ensuring the accuracy of the calculations for shaft sizing.

$\overrightarrow{M_m} - Motor\ torque;$

$\overrightarrow{M_e} - Torque\ transferred\ to\ the\ secondary\ shaft\ through\ the\ gear;$

$\overrightarrow{M_{f1}}\ \overrightarrow{M_{f2}}\ \overrightarrow{M_{f3}}\ \overrightarrow{M_{f4}}\ \overrightarrow{M_{f5}} - Torque\ for\ knifes\ 1,2,3,4,5;$

$\overrightarrow{F_{f1}}\ \overrightarrow{F_{f2}}\ \overrightarrow{F_{f3}}\ \overrightarrow{F_{f4}}\ \overrightarrow{F_{f5}} - Cutting\ force\ for\ knifes\ 1,2,3,4,5;$

$\overrightarrow{R1_x} - Horizontal\ reactive\ force\ (x - axis)\ \text{at}\ bearing\ 1;$

$\overrightarrow{R2_x} - Horizontal\ reactive\ force\ (y - axis)\ at\ bearing\ 2;$

$\overrightarrow{R1_y} - Vertical\ reactive\ force\ (x - axis)\ \text{at}\ bearing\ 1;$

$\overrightarrow{R2_y} - Vertical\ reactive\ force\ (y - axis)\ at\ bearing\ 2;$

$\overrightarrow{Ft_{eng}} - Tangential\ force\ on\ the\ gear;$

$\overrightarrow{Fr_{eng}} - Radial\ force\ on\ the\ gear.$

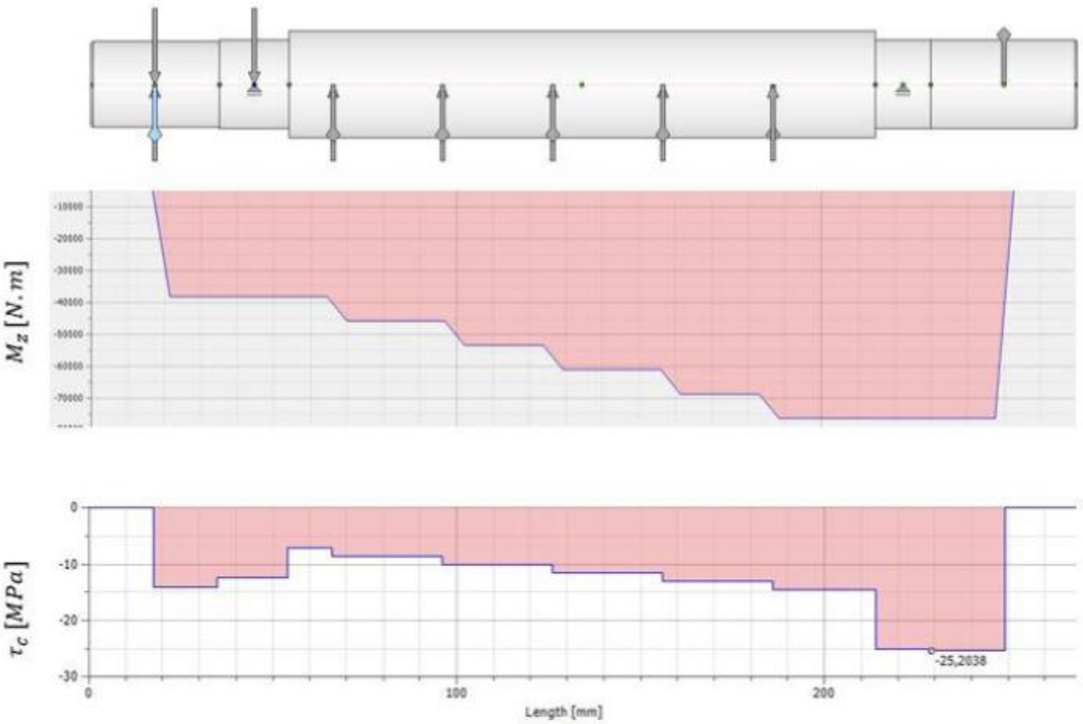

Figure 10. Free body diagram of the shaft, diagram of torsional moments and torsional shear stresses.

Mathematically confirming the maximum shear stress value involves calculating specific equations to analyze torsional forces. This procedure considers factors such as the polar moment of inertia of the shaft section, its diameter, and the applied torque. As a result, a precise shear stress value is obtained and then compared to the material's allowable limit, ensuring that the proposed design guarantees safety and reliability in the system's operation.

$$\tau_c = \frac{M_{shaft}}{I_0}.r \iff \tau_c = \frac{M}{\frac{\pi}{32}.D^4} * \frac{D}{2} \qquad \text{Equation 10}$$

$$\tau_c = \frac{76{,}4}{\frac{\pi}{32} * 0{,}0249^4} * \frac{0{,}0249}{2} \iff \tau_c = 25{,}20\ MPa$$

τ_c = Shear stress;

I_0 = Polar moment of inertia;

D = Shaft section diameter.

With an allowable shear stress of 85 MPa for CK45 steel, it is verified that the maximum shear stress in the shaft is significantly below the material's yield limit, ensuring a safety factor of 3.37. This factor provides an adequate safety margin for the system's operation under normal conditions. Additionally, the radial forces generated by the blade-cutting process result in combined shear and bending stresses in the shaft, further compounded by the radial and tangential forces arising from the gear-driven motion transmission. This integrated analysis confirms the shaft's robustness and reliability in meeting the system's demands.

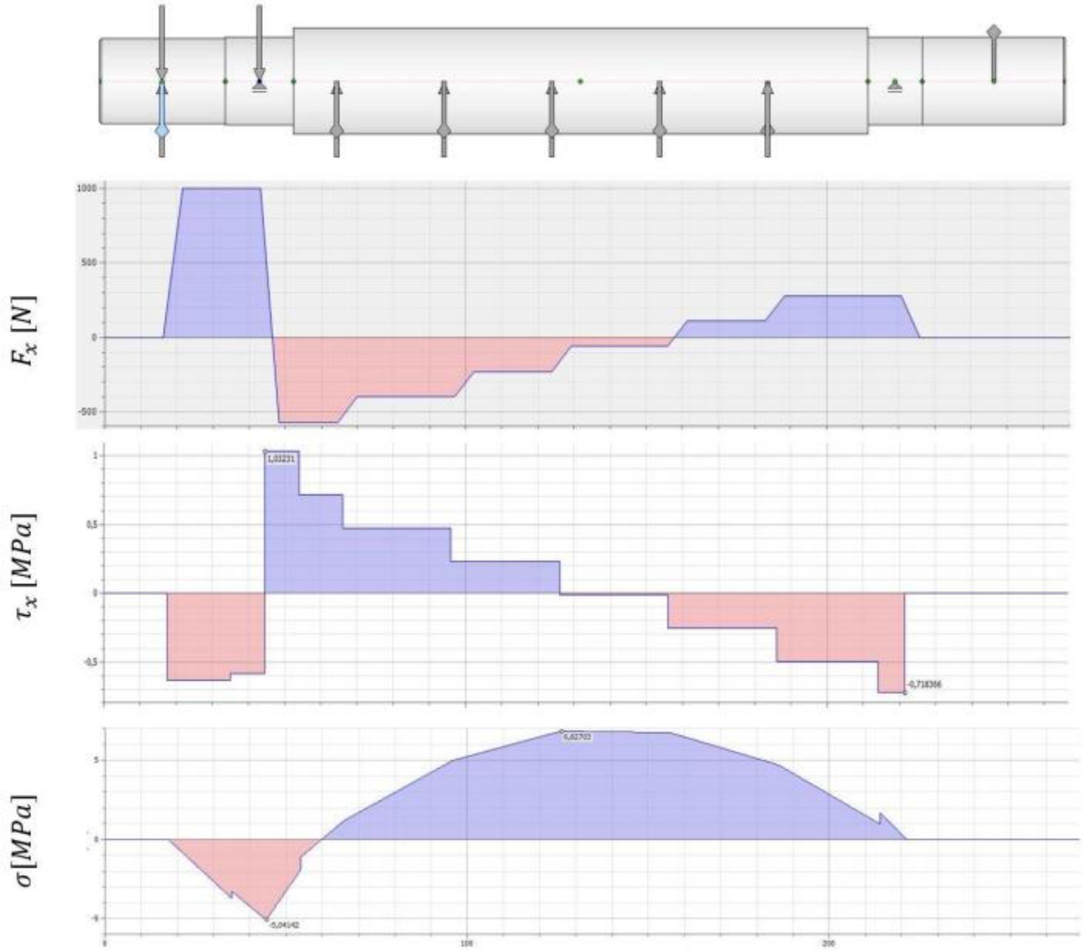

Figure 11. Shaft free body diagram, shear stress diagram, shear and bending stress diagram.

4.3 Motor

For the operation of this shredder, an electric motor was chosen. The selection of this motor required determining its necessary power, which was calculated based on the sum of the torque of the two shafts (M_{veio}) and their rotational speed (n). This sizing process ensures that the selected motor can provide the energy required for the system's efficient operation, meeting the operational requirements and guaranteeing the desired performance.

$$P_{motor} = (M_{shaft} + M_{shaft}) * n$$

$$P_{motor} = 76{,}4 * 27{,}23 \Leftrightarrow P_{motor} = 2080{,}4\ W \qquad \text{Equation 11}$$

Based on the calculated motor power and the predefined requirements, which include using a single-phase motor with a 220V power supply, the SEW-Eurodrive gear motor, model R27DRM100LS4, was selected. This asynchronous electric motor has four poles and a nominal power of 2200 W, features that ensure robust and efficient performance. The gearbox associated with the motor has a transmission ratio of 5.60, allowing the adjustment of speed and torque to meet the shredding system's operational requirements. This configuration guarantees reliability, energy efficiency, and compatibility with the project's specifications.

Table 2. SEW-Eurodrive R27DRM100LS4 gearmotor data [26].

Property	Value	Motor

Motor nominal speed	1450 [1/min]
Output speed	259 [1/min]
Transmission ratio	5.6
Output torque	81 [Nm]
SEW-FB service factor	1.20
Mounting position	M1
Base / Upper coating	7031 Blue-Grey (51370310)
Terminal box position	0 [°]
Cable/connector entry position	X
Output shaft	25x50 [mm]
Maximum permissible radial load at n=1400	1430 [N]
Lubricant quantity Reducer 1	0.25 [Litre]
Motor power	2.2 [kW]

5. Shredder Assembly

This chapter presents the assembly of the developed shredder, an equipment designed to produce plastic granules through the mechanical grinding of parts originating from 3D printing. Although intended primarily to reuse PLA polymer, the shredder is robust and efficient, enabling processing other common polymers, such as ABS, PETG, and PA.

The equipment stands out for its versatility and simplicity, which makes it capable of processing various materials, including plastics, wood, metals, and ceramics. Its robust and adaptable construction facilitates both operation and maintenance.

The shredder consists of a funnel-shaped hopper for the safe insertion of the material to be shredded, a set of rollers and blades responsible for the grinding process, and an electric motor with a gearbox to ensure the necessary motion. Additionally, it includes a perforated mesh that determines the size of the produced granules and a safety sensor that prevents access to moving parts during machine operation.

With this configuration, the shredder is an efficient, safe, and user-friendly solution, promoting the recycling of 3D printing waste and contributing to a more sustainable management of polymeric materials.

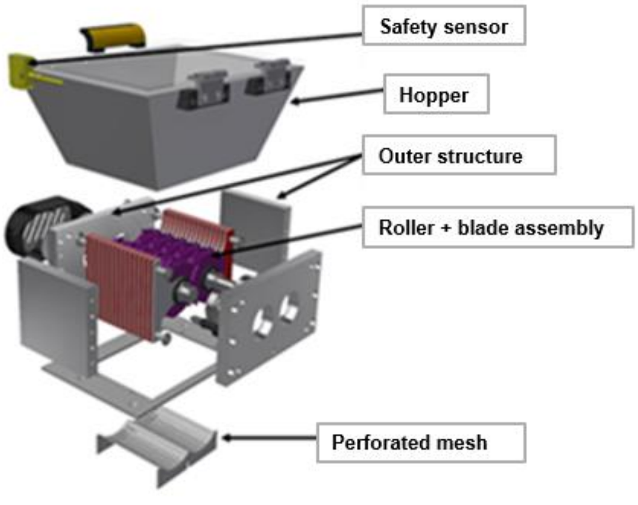

Figure 12. Exploded view of the crusher.

The funnel-shaped hopper serves as a reservoir for shredding materials and protects against access to moving parts, preventing serious injuries to people or animals. At the top, it features an access door made of

10 mm polycarbonate, a material that combines mechanical and impact resistance with the advantage of being translucent. This characteristic allows the operator to monitor the shredding process while ensuring their protection safely.

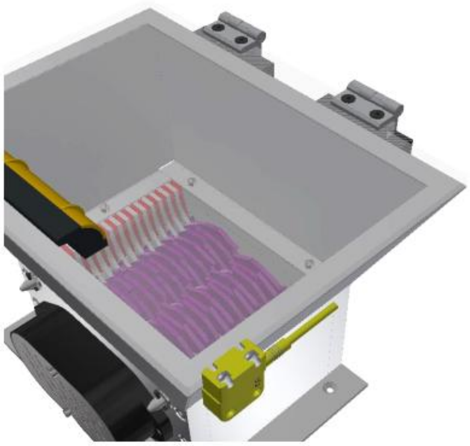

Figure 13. Hopper detail.

The set of rollers and blades forms the functional parts of the machine. It consists of the blades, spacer washers, contrast plates, hexagonal shafts, bearings, and transmission gears.

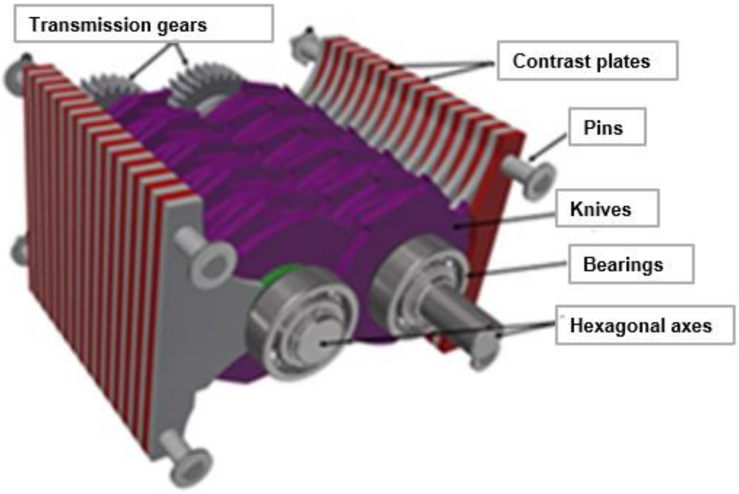

Figure 14. Detail of rollers and knives.

The rotational movement of the blades is generated by a gearbox connected to an electric motor. The gearbox and the hexagonal shaft are connected using a key/keyway system. The shafts transmit motion to the blades, which have a specific geometry suited for shredding material. They are organized in groups of fifteen and arranged in parallel.

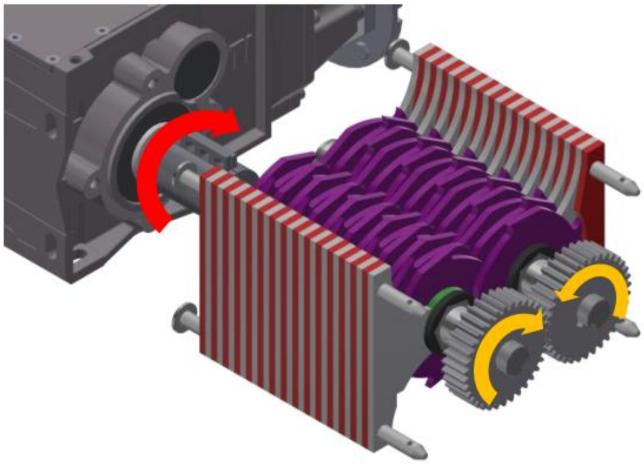

Figure 15. Joint operation of rollers and knives.

The blades are spaced 120 mm apart to make the shredding process more gradual, reducing the torque and power required by the electric motor. This configuration also minimizes mechanical stresses, particularly on the shafts and bearings.

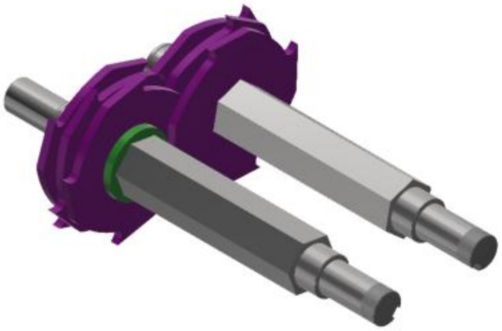

Figure 16. Arrangement of knives at 120º.

6. Discussion

Developing a polymer shredder, such as PLA, has proven to be an efficient and sustainable solution for recycling 3D printing waste. The 30° offset blade configuration and the use of a gearbox allowed for optimizing both energy and mechanical performance, reducing stress on the components and increasing the system's durability.

Compared to previous studies, such as [22], which utilize simpler shredders powered by electric motors, this project stands out due to its ability to adjust granule size and optimize torque, ensuring greater energy efficiency. Compared to the work of [21], which focuses on industrial waste shredding, the present shredder demonstrated greater versatility by processing different polymers, such as ABS, PETG, and PA.

Structural validation through finite element analysis confirmed the robustness of the equipment, ensuring that the applied stresses remained below allowable limits. Reusing waste in the form of granules contributes to the circular economy, reducing waste and dependence on virgin raw materials.

Despite the positive results, the equipment can be further improved through process automation, including continuous material feeding and real-time monitoring, to enable greater industrial scalability.

Compared to existing solutions, the developed shredder combines energy efficiency, robustness, and adaptability, presenting itself as an innovative and practical solution for the sustainable management of 3D printing waste.

7. Conclusions

This article focused on developing a polymer shredder to promote sustainability in the context of 3D printing through the efficient recycling of polymer waste, such as PLA. The project aimed to create a robust and efficient piece of equipment capable of transforming waste into reusable granules for the printing process itself, thus contributing to implementing a circular economy.

The equipment development involved a detailed analysis of the main components, such as the blades, transmission shafts, and motor, ensuring compliance with technical and operational requirements. Rigorous calculations were carried out to determine essential parameters, such as cutting force, applied torque, and material resistance, ensuring the system's structural robustness and energy efficiency. Additionally, safety devices were integrated to protect operators and provide safe and reliable operation.

The design of the shredder demonstrated high efficiency, particularly with its ability to adjust the granule size to meet the specific needs of the recycling process. The innovative configuration of the offset blades and the incorporation of a gearbox optimized the system's mechanical and energy performance, minimizing stress on components and significantly increasing their durability.

The results confirm that the developed shredder is a practical, efficient, and technically viable solution for managing polymer waste from 3D printing. In addition to reducing environmental impact, the equipment is adaptable, with significant potential for processing other polymers, such as ABS, PETG, and PA, thus broadening its application range.

For future work, it is recommended to explore improvements in the equipment's design and system automation to enhance scalability and operational efficiency. Integration into larger-scale industrial processes and development of complementary solutions could further strengthen the system's feasibility and positive impact, promoting an innovative and sustainable approach to polymer recycling.

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