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Original Article

Integration of a Shredding Shaft to the Autonomous Rotary Composter

Fatima Zahra Siti [1], Moha Arouch[2]

[1] *Laboratory of Engineering, Industrial Management & Innovation IMII, Faculty of Sciences and Technics (FST), Hassan 1st University of Settat, Morocco.*

[1]*Corresponding Author : f.siti@uhp.ac.ma*

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Abstract *- In this study, the design and sizing of a shredding shaft are presented. This shaft allows shredding the organic household waste inside the autonomous rotary composter before starting the composting process to accelerate the composting process, increasing the surface between the wastes to promote aerobic degradation and produce high-quality compost. In addition, this shaft of 30 mm diameter, made from stainless steel, does not consume much energy, 2,55 Kw. It rotates at a speed of 350 rpm for up to 5 min before the start of the composting process. The electric motor's power is transmitted to the shredder shaft through a pulley-belt transmission system. It allows the shaft to withstand maximum stress of up to 420.3 MPa, with a safety factor of 2,03. This design has been well studied and approved according to the 3D design software SolidWorks simulations.*

Keywords *- Autonomous Rotary Composter, Composting, Design, Shredding Shaft, Waste.*

1. Introduction

The production and generation of organic waste have increased excessively due to the rapid industrialization that the world has experienced, urban proliferation, and other human inputs, which threaten the environment and ecological balance [1-3]. Indeed, the mismanagement of organic waste leads to the soil, air and water pollution, land reduction, and the generation of high environmental and public health costs [4,5]. Thus, there are various sources of waste generation, including industrial, domestic, and agricultural [6]. Most of these collected wastes are disposed of in pits, landfills, and agricultural areas on the outskirts of cities [4]. However, the organic fraction of this waste can be considered a potential resource if converted into a value-added product. There are several methods of managing organic waste: incineration, landfilling, source reduction, recycling, and composting [3], [7,8].

On the other hand, composting remains the best technique for converting organic waste into compost that serves as a soil conditioner [9,10]. It offers the most benefits and causes the least environmental damage, with an acceptable and convenient cost for society in the long and short term [11]. Composting can treat a variety of organic wastes, such as food waste, leaf and green waste, paper, etc. It is the most environmentally friendly technique for treating organic waste [12]. Composting is a process of aerobic decomposition of organic materials by microorganisms into a biologically stable product without harmful effects on plants when used as a soil conditioner [13]. There are three categories of composting: vermin composting, windrow composting, and in-vessel composting [14,15]. Most of these composting methods are generally traditional and do not involve any technological process, which allows for improving the duration of the composting process. The quality of compost produced [16-18]. However, composting in vats or rotating drums allows to maintain the conditions favorable to the progress of the composting process and maintains the temperature necessary to produce a mature and hygienic compost [19]. In addition, composting in rotating drums is an efficient and promising technique because it allows the reuse of organic waste where it is generated, reducing the quantities of waste destined for the final landfill and the transport costs. The rotating drum provides agitation, aeration, and mixing of the substrate to produce a pathogen-free compost without odor or leachate [20]. It provides a perfect environment for the decomposition of organic matter by microbes, so it reduces the composting time from 2 to 3 weeks so that this composting time can be longer or shorter depending on the nature of organic waste and according to the size of the particles [21-25]. To further accelerate the composting process, facilitate aerobic degradation, and produce a rich, mature. Stable compost is recommended to grind the organic waste into small pieces before starting the composting process [26,27]. Indeed, the grinding process reduces the particles' size to facilitate aerobic degradation by the microorganisms.

Most often, the grinding is done by machines physically separated from the composting machine. In particular, in the literature, several shredders are designed and manufactured to facilitate the composting process of organic waste. The authors in [28] have developed a portable machine for shredding agricultural waste. Thus, the authors in [29] have designed a waste shredder, which shreds organic materials into small pieces to enable farmers to prepare vermin compost. In [30], the authors have developed and designed a machine for shredding coconuts, which extracts the fibers from the shell and uses them as a soil conditioner. In [31], a machine for shredding food waste, intended for restaurants, and colleges, was designed. In [32], the authors designed a machine that shakes and grinds the cow manure pile, improving fermentation efficiency, to produce organic fertiliser. However, all these studies focused on shredding organic waste outside the composter. The user would have to shred the waste elsewhere and then transport it to another machine to finally start the composting process, making the shredding-composting process more time-consuming, tiring, and costly. While the study discussed in this paper proposes the integration of a shredding shaft within the stand-alone rotary composter to shred the organic waste inside the composter before starting the composting process, which allows decreasing the duration of the shredding-composting process, to save energy and space occupied by the composter and the shredder, and it also allows to minimise the shredding and composting costs at the same time, which is the added value of the study proposed in this paper.

This paper presents the design and manufacturing study of a shredding shaft integrated into the autonomous rotary composter to accelerate the composting process and produce high-quality compost. The integration of this shaft in the autonomous rotary composter will present an added value compared to what exists in the literature because it allows accelerating the composting process thanks to the addition of the shredding operation of the organic waste inside the composter before the launching of the composting process. In addition, the Autonomous Shredder Rotary Composter also allows for remote control and real-time monitoring of the composting process. It also saves energy and the cost of shredding-composting. This technological solution is an innovation in the world of composting and is intended mainly for households. The structure of this article is as follows: after the introduction, the materials and methods part will present the study's objective, the description of the shredder shaft composter, and the mechanical and electrical dimensioning of the shredder shaft. Then the results and discussion part will be devoted to the presentation of the results of the static study and the fatigue study of the shredder shaft, performed by the 3D design and simulation software, Solid Works. Finally, the conclusion.

2. Materials and Methods

2.1. Purpose of the Study

This study will describe the techniques used to analyse and design the shredder shaft of the autonomous rotary composter. In addition, the functioning of this shredder shaft will be determined and whether its design will be successful.

2.2. Description of Rotary Shredder Composter

The rotary composter with the crushing shaft is an automated machine with a solid helical shaft, which can shred and compost organic household waste into high-quality compost. As shown in (figure 1), the system consists of a rotating drum in cylindrical form with a length of 640 mm and a diameter of 600 mm. It is made from PVC. This composter ensures the shredding of organic waste into small pieces, thanks to a shredding shaft (figure 2), this shaft is in helical form with a length of 680 mm, a diameter of 30 mm, and it is made of stainless steel. A steel stand supports the rotating composter. It rotates at a speed of 4 rpm and is powered by a direct current motor, which is operated by a photovoltaic energy system. This system contains a polycrystalline solar panel, a voltage regulator and a solar battery. Aeration is provided inside the rotary composter through two vents located on the right and left walls of the drum. The composter presented in this work is designed to crush and compost a quantity of organic household waste of about 20 Kg in a short time that does not exceed 4 weeks maximum.

Moreover, the rotary composter, with a shredding shaft, is equipped with a remote management system, which allows one to supervise and control the composting parameters inside the rotary composter (Temperature, humidity, NH_3 gas) remotely and in real-time. The remote management system consists of three wireless sensors (temperature, humidity, and NH_3 gas sensor) installed in the rotary drum, which collects data related to the composting parameters and then transmits them to an Arduino Uno board to save and process these data, before communicating them to the end user via a mobile application so that he can manipulate the composting parameters inside the rotary drum, remotely and in real-time. This rotary shaft composter provides shredding, agitation, aeration and mixing of organic household waste to produce high-quality compost valid for agricultural use. It is an innovative technology in the world of composting and is mainly intended for household use.

2.3. Dimensioning of the Shredding Shaft

The shredding shaft is cylindrical and helical, with a circular cross-section. It supports the pulley-belt transmission system, ensures the positioning of the rotary composter about its support, and rotates to shred the organic waste. Depending on its role, the shredder shaft is subjected to various stresses, such as bending and torsion, and thus it is subjected to a complex load of torsion, bending, and axial load.

Fig. 1 Design of the self-contained rotating composter with shredding shaft by SolidWorks.

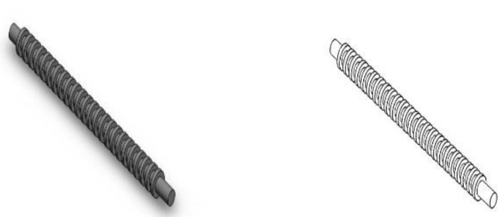

Fig. 2 Shredding Shaft

Therefore, to design a compliant grinding shaft, the following criteria must be considered: strength, stiffness, and critical speed. Since the shredder shaft is primarily intended for shredding organic household waste, we need to check its strength by calculating its adequate diameter.

2.3.1. Choice of Material

The grinding shaft is made from stainless steel grade, as it has the following criteria:

- Resistance to corrosion and oxidation;
- Aesthetic appeal;
- Economical and available;
- Total recyclability;
- Good mechanical strength-to-weight ratio.

2.3.2. Shredder Shaft Speed

This shredding shaft can shred organic household waste with a rotation speed of 350 rpm to ensure higher efficiency and output than what is available on the market.

2.3.3. Number of Helices

Since the particle size should be between 12 and 60 mm, the distance between two consecutive propellers should not exceed 30 mm. The shaft length is 680 mm, and the length of the helical part inside the rotary composter is 640 mm. It will have a set of 22 helices (640 mm/30mm = 21.34). A length of 30 mm separates each.

2.3.4. Strength Criteria of the Shredder Shaft

In this case, study, since the solid shaft is cylindrical helical, it is a uniform torsion. The stress is zero at the center and maximum at the periphery. Therefore, to make this crusher shaft torsionally strong, the minimum diameter of the crusher shaft and the angle of rotation between the two sections of the crusher shaft must be determined.

The diameter

It is known that the torsional strength condition is such that:

$$\boldsymbol{\tau_{max}} \leq R_{pg} \quad (1)$$

With $R_{pg} = \tau_e / s \quad (2)$

Thus, the maximum stress for a solid shaft of circular cross-section is as follows:

$$\tau_{max} = C \times r / I_0 = 2 \times C / \pi \times r^3 = 16 \times C / \pi \times d^3 \quad (3)$$

Using the resistance condition (1), then:

$$16 \times C / \pi \times d^3 \leq \boldsymbol{\tau_e / s}$$

so $d \geq \sqrt[3]{16 \times C \times S / \pi \times \tau_e} \quad (4)$

Table 1. Diameter calculation

Data	Results
C = 66 N.m	d= 18,67 mm
S = 4	
τ_e = 206,5 MPa	

According to the calculation result, a diameter of 30 mm should be chosen.

Angle of rotation θ

The angle of rotation between the two sections of the grinding shaft that are L apart is given by the following formula:

$$\theta = \alpha \times L \tag{5}$$

Thus, the rotation angle α per unit length is:

$$\alpha = C/\mu \times I_0 \tag{6}$$

With $\mu = E/2(1 + \nu)$ (7)

Table 2. Angle calculation

Data	Results
E = 205 000 MPa	$\boldsymbol{\theta}$ = 0, 41 deg
ν= 0,3	
L = 680 mm	
C = 66 N.m	
d= 30 mm	

2.3.5. Calculation of the Motor Power

Study of the Resistive Forces

The organic household waste is inserted into the rotating shredder shaft composter through a door on the longitudinal side of the drum. The shredding shaft is helical and contains 22 helices. The motor torque must be sufficient to rotate the shredder shaft properly. Since there is no procedure for determining the force required to cut the organic waste, and since the organic waste falls randomly onto the shredder shaft, the force must be determined experimentally. Therefore, it is assumed that 20 Kg = 200 N is the force applied to the helical shaft.

Power Calculation

The following formulas determine the engine power and torque:

$$P = C \times w \tag{8}$$

$$C = F \times r \times n \tag{9}$$

Table 3. Results of the calculation

Data	Results
N = 350 rpm	w= 36,65 rd/s
F = 200 N	C = 66 N.m
n = 22	P = 2,5 Kw
r= 15 mm	

The engine torque required to turn the grinding shaft is equal to the resistive torque at a constant speed, so

$$C_m = C_r \tag{10}$$

The motor power is therefore given by:

$$P_m = P_{nécessaire}/\eta_{global} \tag{11}$$

And since η_{global} = 0, 98 then the engine power

P_m= 2, 55 Kw.

Therefore, to drive the grinding shaft in rotation, a DC electric motor with the following characteristics should be selected:

Motor type: LAK 2112 A

P (Kw) = 3 Kw
N = 1750 rpm
Ua = 320 V
Ia = 11,5 A
Uext = 360 V
Iext= 0,84 A

2.3.6. Transmission-Reduction System

The pulley-belt system transmits the rotational movement from the motor shaft to the grinding shaft by reducing it.

Diameter of the Drive Pulley

Let d_b be the diameter of the driven pulley (grinding shaft pulley) such that:

$$d_b = d_m \times N_m/N_b \tag{12}$$

And the reduction ratio is such that:

$$r_b = d_m/d_b \tag{13}$$

Length of the Belt

The following formula determines the length of the belt:

$$L = (\pi/2) \times (d_b + d_m) + 2C + (d_b - d_m)^2/4C \tag{14}$$

The pulley-belt transmission system between the electric motor and the grinding shaft reduces the speed transmitted by the motor and increases the force.

Reduction Ratio

This formula gives the total reduction ratio:

$$r_{st} = N_b / r_b \times N_m \tag{15}$$

Table 4. Calculation of the transmission system characteristics.

Data	Results
N_m = 1750 rpm	d_b = 175 mm
N_b = 350 rpm	r_b = 0,2
d_m= 35 mm	L = 717,1 mm
C = 180 mm (car $d_b < C < 3(d_b + d_m)$)	r_{st} = 1

3. Results and Discussion

3.1. Static Study of the Shredder Shaft

The grinding shaft was analyzed, and the maximum stress that this shaft must withstand inside the rotary composter is 206.5 MPa. Thus from the stress analysis performed by the 3D design software SolidWorks (Figure 3), the shredder shaft can withstand maximum stress of 420.3 MPa, resulting in a safety factor of 2.03.

And since the design criterion for a machine component must satisfy F > 2, the grinding shaft studied above can be designed and operated inside the rotary composter without failure since its safety factor is equal to 2,03.

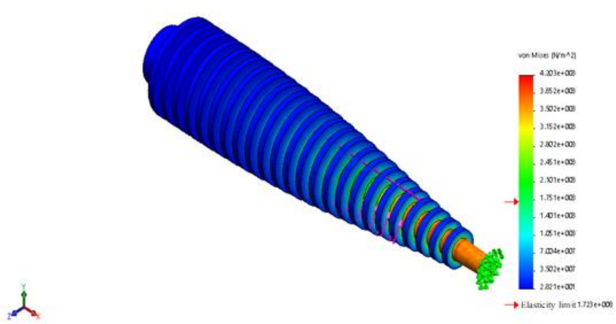

Fig. 3 Stress analysis of the grinding shaft

Table 5. Results of stress analysis.

Maximum applied stress	206,5 MPa
Maximum stress before failure	420,3 MPa
Minimum stress	$2{,}821 \times 10^{-5}$MPa

FOS = Maximum stress before failure / Maximum applied stress = 420,3MPa/206,5MPa = 2,03 > 2.

3.2. Fatigue Study of the Shredding Shaft

3.2.1. Design Material Properties

The SN curve shown in (Figure 4) shows the stress level under which the stainless steel (the grinding shaft's material) will resist cyclic stresses indefinitely without failure. Thus, the realistic reference stress on which to base the design of the grinding shaft is 2.065×108MPa which corresponds to a life cycle of 106 N/A. The choice of stainless steel for the design of the grinding shaft is better and well justified.

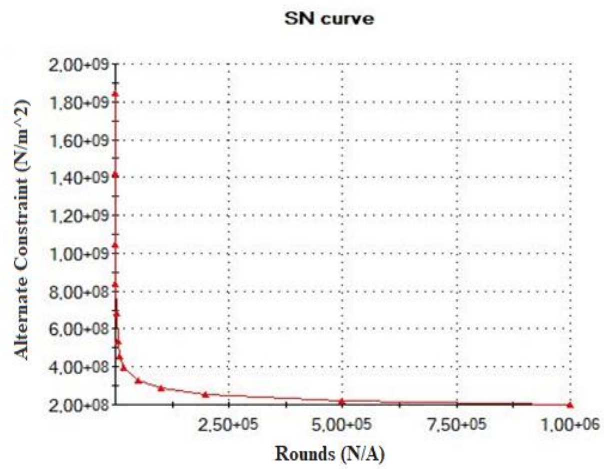

Fig. 4 Material properties

3.2.2. Fatigue simulation of the shredding shaft

The fatigue simulation of the grinding shaft (Fig. 5) shows that as the number of cycles increases, the stress required to maintain the deformation limits decreases. Thus, the damaging effect appears, which takes a minimum value of 102 at Node 54 and reaches its maximum value of 1.241×104 at Node 8641.

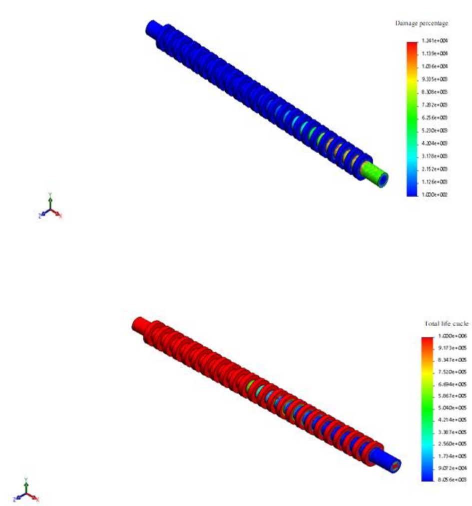

Fig. 5 Fatigue simulation

4. Conclusion

In this paper, the shredding shaft integrated into the autonomous rotary composter was studied and validly tested. This shaft was designed by the 3D design software SolidWorks. The implementation of this shredding shaft inside the autonomous rotary composter allows shredding the organic household waste in small pieces to accelerate the composting process and improve the quality of the produced compost. This shaft rotates at a speed of 350 rpm, consumes little energy, about 2.55 KW, and is made from stainless steel. Thus, the static study and the study of fatigue of the shaft of grinding were carried out by the tool of design and simulation SolidWorks, and the results of the simulation prove the effectiveness and the reliability of the operation of this shaft of grinding and justify the choice of stainless steel for its manufacture. This study's added value is the shredding system's design and integration into the autonomous rotary composter. In terms of the perspectives of this work, a component that concerns the remote management of the shredding system integrated into the autonomous rotary composter will be added to the mobile application for remote management of the autonomous rotary composter already realized.

Conflicts of Interest

The authors declare that they have no competing interests.

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