Redesign and Simulation of a Hammer Mill to Minimize Consume of Iron Filings

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Abstract: The present study designed, constructed and undertook the performance evaluation of a hammer mill for milling cereals grains as an alternative to that of a traditional attrition mill which poses health challenges. The materials used for the study were galvanized steel, stainless steel 304, canvas, and electrodes. The study made use of Autodesk inventor professional 2020 for the modelling and ANSYS Workbench was used for numerical analysis. The performance test of the mill was done with three different cereal grains namely corn, guinea corn and millet with different sieve sizes. The quantity of cereal weighed to test run the machine was 15 kg, 20 kg and 25 kg for each sample. The result showed that its capacity is improved to mill cereals up to 1000 tons per day and can equally mill cereal grains into grades for animals' consumption. For the improved hammer mill, the iron filings contents produced had much lower iron filings contents of milled corn, guinea corn and millet as compared to the attrition mill. The improved hammer mill has an efficiency of 96%. The model remains safe with the induced deformation being lower which will not make it deteriorate faster. The crushing unit is shown to withstand the applied force which produced a von Mises stress lower than the yield strength of the material. The factor of safety based on the induced stress and the yield strength of the material is 2.49 with a margin of the safety factor of 1.49. The proposed mill after completion is safe to operate and easy to carry out maintenance therefore it is recommended for use as a milling unit for cereals.

Keywords: hammer mill, cereal grains, traditional attrition mill, numerical analysis and iron fillings.

1. Introduction

A hammer mill also known as a cereal miller, is a device consisting of a rotating head with free-swinging hammers or beaters which reduce grains or similar hard dry objects to predetermine sizes through a perforated screen [1]. During the operation of the hammer mill, the grains are placed into a holding hopper on top of the hammer mill, and a small control gate allows the grains to trickle into the grinding chamber. The grains feed into the path of the hammers either through the centre of the front plate or through the top side of the case [2]. The hammers strike the grains and shatter them before they can pass through the screen surrounding the hammers. The flour produced either falls by gravity into a chamber or sack or is propelled by air flowing up through a cyclone into a holding container. The airflow is provided by either the fan effect of the hammers or by extra fan blades mounted on the hammer shaft [3]. The hammers rotate inside a perforated metal screen through which the flour is drawn [4]. The hammers are driven by two or four sets of V-section belts between the engine and the mill [5]. The speed of the mill has to be matched to the size of the mill as a small mill needs to run at higher revolutions than a larger mill [6]. This is not commonly practiced in Africa, and screens have to be imported. Screen replacement represents one of the main running costs of the mill. Mills without transmission belts are well suited for local manufacture [7]. Simple hammer mills can have a small electric engine, but they also work well in petrol and diesel-driven mills [8]. Hammer mills work well for grains with a minimum moisture content of 12 percent. Dry crops are very dusty when grounded and can create health problems for mill operators. However, the drier the crop, the less power is needed for milling [9]. The cereals food consumed is mostly processed through grinding by either iteration or hammering means. It is, therefore, necessary to have an efficient means of achieving such goals, especially in developing countries like ours where industrial activities are low [10]. The design and construction of a hammer mill become imperative as that will go a long way in getting processed cereals grains easily within developing nations [11, 12]. The perforated metal screen covering the discharge opening of the mill retains coarse materials for further grinding while allowing properly sized materials to pass as a finished product. Hammer mills are grinders that work based on impact. In hammer mills, the size of a grind is controlled by built-in screens [13]. Kratky et al. [14] reviewed biomass size reduction using hammer mills. They reported that using a hammer mill had the advantage of low maintenance over other methods, including crushing, shearing and using roller mills [15]. Tub grinders are small mobile hammer mills often designed as pull-behind units for agricultural use or mounted on tractor-trailers for larger waste removal use. Attrition is used primarily for grinding tough organic materials such as wood pulp and corn grits [16]. Size reduction takes place between two smooth or abrasive plates, which may be aligned either horizontally or vertically. Product size is controlled by changing the distance between two plates. Stone grinders have been used for pulp making in pulp and paper industries [17, 18]. Consumption of cereal food is the most delicacy to the people from Ghana, among several varieties of foods, before this, cereals grains are sent for grinding to very fine flour powder by, the approach to grinding of these cereals is through attrition milling. Studies has confirmed that their high rate of wear during grinding operation by attrition milling, the worn-out particle are what is termed as iron filling, the iron fillings as a result of the wear ends up in the milled product and get into the food prepared for human consumption which poses long term health challenges like hemochromatosis leading to hepatoma, the root courses of the liver cancer.

Therefore, this study is aimed at redesigning a hammer mill to replace the attrition mill to minimize the consumption of iron filling in Ghana. Consumption of cereal food is the most delicacy to the people from Ghana, among several varieties of foods, before this, cereals grains are sent for grinding to very fine flour powder, the approach to grinding of these cereals is through attrition milling. Studies have confirmed that their high rate of wear during grinding operation by attrition milling, the worn-out particle is what is termed as iron filling, the iron fillings as a result of the wear end up in the milled product and get into the food prepared for human consumption which poses long term health challenges like hemochromatosis leading to hepatoma, the root courses of the liver cancer.

2. Materials and methods

2.1 Materials Selection

Galvanize metal plate was considered for the construction of Hoper because of periodic repainting due to corrosion resistance, abrasion resistance, formability, excellent surface appearance, and weldability. Harden stainless steel was selected for both the feed chamber and the screw shaft, due to their technical and economic advantages, as they are widely used in a variety of industrial applications, especially in the manufacture of domestic and pharmaceutical components.

The crushing chamber through the outlet was constructed by the use of stainless steel, stainless steel because in the grinding or crushing chamber cereals that are fed through are either dry or damp grains, and this can cause stains or rust on the chamber walls, and that can lead to consumption of particle that imposes health threats. The main support or stand is made from angle bars for firmness and mechanical rigidity capable of damping vibration and chatter when milling. The base of the machine is fabricated from U-channels and selected because when there is any spill of liquid, it can run through the channel easily, also this material is heavy enough to be used as the base of the machine to damp out vibration and chatter during operation. The stainless steel plate was carefully selected as the material for the screen, this is where cereal grains are graded and sieved after milling for final consumption, how fine or coarse the flour is, depends on the size of perforated holes in the screen. The table shows the material properties of Steel 304.

Table 1 Material properties of Steel 304 [19]

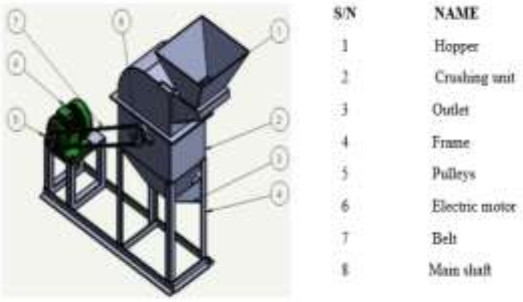
Properties	Value
Density	8.0kg/m^3
Modulus of Elasticity	193 GPa
Poison’s Ratio	0.27 – 0.30
Yield Strength	(540 – 750) MPa
Coefficient of Thermal Expansion	17.2 × 10^{-6} /k

2.2 Design Procedure

Design of any device/tool/Equipment or machinery, the size should be considered with both the body/frame and dimensions of the individual part or member which are expected to saddle the loads and withstand forces acting on them for effectiveness. Hence the dimensions should be given emphasis when a design problem is tackled. The design of the hammer mill took into consideration different design criteria and parameters, some of which are from the literature review, whiles others were determined by using an arithmetic approach. These design parameters include the availability of the materials within the locality, environmental condition of the locality, space to test run the machine, variety of cereal and availability of parts to be replaced.

2.2.1 Conceptual Design One

Figure 1 shows a typical design of a hammer mill with a 20-horsepower (hp) motor powered by a hydroelectric generator. The cons of the design are the large amount of power needed to effectively run the machine and also the high amounts of manufacturing required.



S/N	NAME
1	Hopper
2	Crushing unit
3	Outlet
4	Frame
5	Pulleys
6	Electric motor
7	Belt
8	Main shaft

Fig. 1 Concept Two

2.2.2 Conceptual Design Tow

The mill machine in Figure 2 is of low capacity, and cannot be used for commercial purposes, adopting this design; one has to improve on the design for high production of cereal grain like Ghana. Also, this design is based on grinding animal feed, no emphasis is laid on how to mill fine flour for human consumption.

Fig. 2 Concept Three

2.3 Detail Drawing of Selected Design

From the design concept, the concept selected is based on the advantages it has. The front view, the right view, the left view and the plan of the proposed machine are clearly shown in

Figure 3 a, b c and d with part names and dimensions.

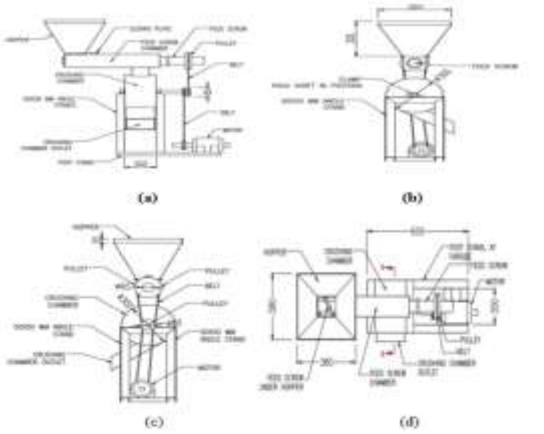


Fig. 3 Selected Design (a) Front view, (b) Right view, (c) Left View and (d) Plan

Table 2 Fabrication Processes

Table 2 shows the various stages under which the Hammer Mill was constructed

S/N	STAGES	TOOLS
1	Marking out of parts	Steel rule, scriber, straight edge, try-square, gauges
2	Cutting and filling of parts	Hacksaws, Set of files,
3	Folding	Folding bar, Bending machine
4	Drilling	Drilling machine, Drill bits, reamers
5	Aligning and welding of parts	Engineering vice, set of welding equipment
6	Grinding and Sanding of parts	Grinding machines and emery cloth
7	Assembling of parts	Set of spanners, mallets, bolts and nuts, screws
8	Spraying of final Artefact	Paint, spraying gun, masking tape, thinner

2.4 Procedure for the Numerical Methods

This section of the study presents the procedure for the numerical analysis using ANSYS software 2021 for meshing of the component, grid independence test and the boundary conditions set for this study.

2.5 Meshing of Component

Figure 4 shows the meshing which is a very important step in the static structural and modal analysis process. Meshing is an integral part of the engineering simulation process where complex geometries are divided into simple elements that can be used as discrete local approximations of the larger domain. The mesh influences the accuracy, convergence and speed of the simulation. If meshing is accurate, then the results are also anticipated to be feasible. The meshing details of the model are the number of nodes 117,298 and the element size 34,939.

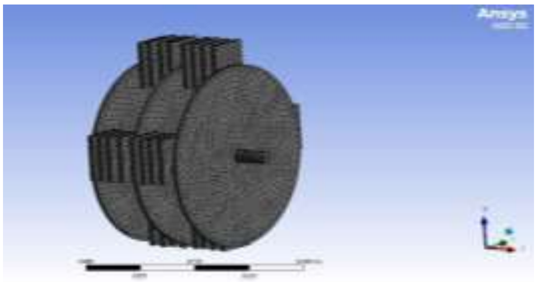


Fig. 4 Meshed Geometry

2.5.1 Grid Independence Test

The mesh size of the model was carefully selected since the validity of the mesh can influence the results. Independent tests for five (5) iterations were conducted with mesh sizes 3 mm, 4 mm, 5 mm, 6 mm and 7mm and the best iteration number was selected as the mesh size. The mesh size that yielded the best induced von Mises stress was 5mm. It was observed that all the mesh sizes from 6 upward yielded almost the same magnitudes of deformation. The maximum induced deformation of 3.5119 x 10^{-4} mm was adopted for this simulation to ensure that the result is closer to reality.

2.5.2 The Boundary Conditions Set for the Analysis

Analysis of the crushing unit made with structural steel material was done in Ansys software version 2021 R2 using static structural analysis. The parameters that were considered during the static structural analysis were total deformation, directional deformation, equivalent elastic strain, equivalent (Von

Mises) stress, maximum principal stress, minimum principal stress, maximum principal strain, minimum principal strain, and factor of Safety, maximum shear stress, fatigue life and Damage.

3. Results and Discussion

3.1 Proposed Design of Hammer Mill

The improved hammer mill has the highest motor speed of 6.284rpm, with 32 hammers to improve crushing efficiency; the shaft is incorporated with an auger to improve the fast feeding of cereal grains, with different sieve sizes the improved hammer mill can mill varieties of food texture from coarse grade to very fine grade. This is used to blind chemicals in both pharmaceutical and herbal industries and makes it a multipurpose machine. It is built with a strong frame and base to dump out vibration and chatter.

3.2 Iron Filling Content Analysis

The three grains, thus maize/corn, Guinea corn and Millet were milled either wet or dry using a local/Attrition milling machine. Samples of the milled grains were taken and analyzed for elemental iron. Results show that iron particles from milling plates contaminate the milled grains and that the level of contamination increases with the number of milled grains as shown in Table 4.1. However, when the three grains were milled using the improved hammer mill machine with the same masses, the results showed a massive reduction of the iron filling content in the milled products as a result of the increase in the number of hammers which doesn't have friction between the crushing chambers.

3.3 Comparative Test Analyses of the Iron Filling Content in the Various Grains after Milling

For the Attrition Mill, the corn had iron filings content of 1.95g, 1.96g, and 1.97g per 15 kg, 20 kg, and 25 kg of corn flour milled which gives an average value of **1.96g**. The guinea corn had iron filings content of 0.07g, 0.06g, and 0.05g per 15 kg, 20 kg, and 20g of guinea flour milled with an average value of **1.09g**. The millet had 0.90g, 0.91g, and 0.91g with an average value of **0.91g** of iron filings contents per 15 kg, 20kg, and 25kg of millet flour milled. For the Improved Hammer Mill, the iron filings contents were; 0.10 g, 0.08g and 0.07 g per 15 kg, 20 kg, and 25 kg of flour of corn milled with an average value of 0.083g. For guinea corn, the iron filing content was 0.07g, 0.06g, and 0.05g per 15kg, 20 kg, and 25 kg of flour milled with an average value of 0.06g. For millet, the iron filing contents were 0.06g, 0.05g and 0.05g respectively per 15Kg, 20Kg, and 25Kg of flour milled with an average value of 0.053g compared with, the improved hammer mill produces a much lower iron filings contents of milled corn, guinea corn and millet as compared to the Attrition Mill as shown in Figure 5. This implies that the Improved Hammer Mill has fewer wear particles and is much safer to use as compared to the Attrition Mills. This result agrees with the study carried out by Manaye et al. (2019)[20].

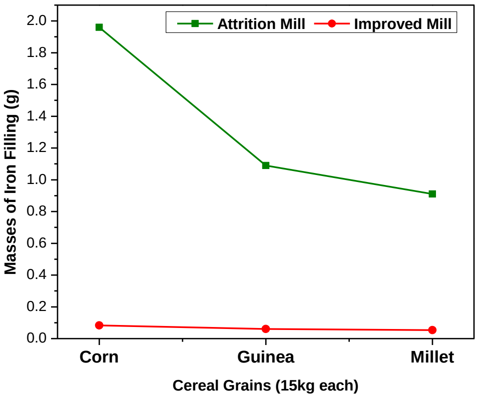


Fig. 5 Mass of iron filings in attrition mill and improved mill

3.4 Static Structural Analysis of a Hammer Mill Crushing Unit

The static structural analysis results help to identify weak areas with low strength and durability which allows engineers to modify structures to meet desired requirements.

3.4.1 Total maximum deformation

The Total maximum deformation induced in the model when a rotational velocity load of 160N was applied is 3.5119 x 10^{-4} mm. The maximum deformation was observed to have occurred at the middle part of the hammers where the load was applied while the minimum deformation was found to be around 3.9021 x 10^{-5} mm which occurred at both ends of the shaft. The two plates at the ends of the model did not suffer any visible form of deformation as shown in Figure 6. The model remains safe with the induced deformation; however, the study result of the total deformation is lower as compared to that shown in the study of Moiceanu et al. [21]. The significance of this is that the deterioration rate of the model under the condition is minimal.

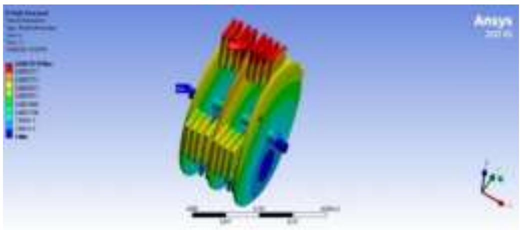


Fig. 6 Total deformation of the model

3.4.2 Maximum directional deformation

The maximum directional deformation induced in the model moves from the tips of the hammers towards the parts fixed to the shafts with a magnitude of 4.4098 x 10^{-5} mm and a minimum directional deformation of -4.3084 x 10^{-5} mm. The directional deformation on the tips of the hammers was observed to be more pronounced and spread through towards the middle portion as shown in Figure 7. Since the directional deformation is not pronounced at the middle part of the model which is suspended then the model will remain safe with the induced directional deformation in the model. The model remains safe with the induced deformation; however, the study result of the total deformation is lower as compared to that shown in the study of Moiceanu et al. [21].

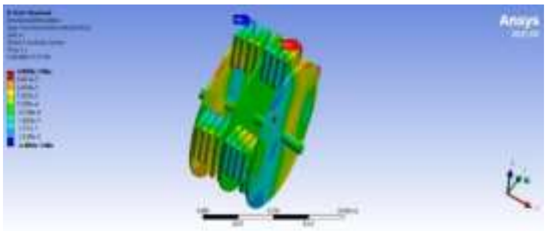


Fig. 7 Directional deformation of the model

3.4.3 Maximum equivalent (Von Mises) stress

The maximum equivalent (Von Mises) stress induced in the model has a magnitude of 2.1707 x 10^{8} Pa (217.07 MPa) for the given loading condition. The minimum yield strength of stainless steel 304 is 540 MPa. The stress distribution in the model was observed to be high at the portion of the plates that have been welded to the shaft close to the fixed supports at both ends of the model. The middle portion was observed to have the minimum induced von Mises stress with a magnitude of 989.41 Pa as shown in Figure 8. The induced stress in the model is lower compared to the yield strength of the material which led to the conclusion that the crushing unit will not fail under the conditions applied. This result is supported by the result of the study conducted by Kumar (2013). The factor of safety based on the induced stress and the yield strength of the material is 2.49 with a margin of the safety factor of 1.49, therefore the model is considered to be fit for purpose since it can withstand the given load. The significance of this is that engineers can predict acceptable stress levels to determine the life span of machines.

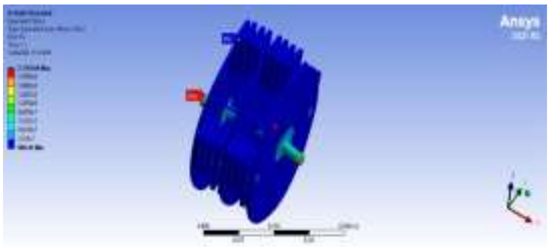


Fig. 8 Equivalent (Von Mises) stress of model

Table 5 Summary of results of structural steel material model

PARAMETERS	MAXIMUM	MINIMUM
Total deformation	3.5119 x 10^{-4} mm	3.9021 x 10^{-5}mm
Directional deformation	4.4098 x 10^{-5} mm	4.3084 x 10^{-5} mm
Equivalent Von Mises Stress	2.1707 x 10^{8} Pa	989.41 Pa

Max. Principal Von Mises Stress	2.7989×10^8 Pa	-5.3758×10^7 Pa
Equivalent Elastic Strain	1.0958×10^3 m/m	4.9471×10^{-9} m/m
Maximum Principal Elastic Strain	1.1545×10^3 m/m	-1.6121×10^{-6} m/m
Maximum shear stress	1.1882×10^8 Pa	570.94 Pa
Fatigue life	1×10^6	190.48
Damage	52,499	1,000
Factor of Safety	15	0.39711

3.5 Milling efficiency

Crushing/mill efficiency was calculated using this formula

Mass of corn before grinding was = 5000 g = 5 kg

Mass of corn after grinding = 4700 g = 4.7 kg

$$effeciency = \frac{Mass\ out\ material}{Mass\ input\ materials} \times 100\%$$

$$= \frac{4800}{5000} \times 100\% = 96\% effeciency$$

Now to achieve all that was inputted into the machine, losses were also calculated as; $\frac{\mathrm{Mb}-\mathrm{Ma}}{Mb}$,

Where; Mb is the mass before grinding, and Ma is the mass after grinding.

$$\frac{5000-4800}{5000} - 4\% \text{ as losses.}$$

A similar test was successfully carried out using guinea corn and millet which resulted in the same 4% losses when corn was milled, and that has also proven 96% efficiency which is a significant improvement upon the design of Workalemahu et al. [20].

Figure 8 shows pictures of milled corn, guinea corn and millet by the hammer mill.

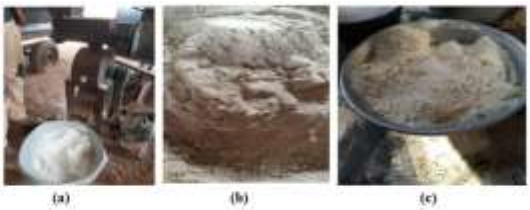


Fig. 8 Test ran (a) using corn grains (b) using guinea corn and (c) using millet

4. Conclusion

The main purpose of the study was to redesign and manufacture a hammer mill for the crushing of cereal grains to reduce the consumption of iron filings. However, the proposed hammer mill is to improve upon operational efficiency, make it a multifunctional machine as well as ensure safe operation and cost-effective maintenance. Consumption of cereal food is the most common among the people of Ghana.

- The study confirmed that a high rate of wear occurs during grinding operation by attrition millings, the worn-out particles are what is termed as iron filling; and the wear ends up in the milled product and gets into the food prepared for human consumption thereby poses long term health challenges like hemochromatosis leading to hepatoma, the root courses of liver cancer.
- For the Improved Hammer Mill, the iron filings contents produced had much lower iron filings contents of milled corn, guinea corn and millet as compared to the Attrition Mill.
- The model remains safe with the induced deformation being lower which will not make it deteriorate faster. The crushing unit is shown to withstand the applied force which produced a von Mises stress lower than the yield strength of the material. The factor of safety based on the induced stress and the yield strength of the material is 2.49 with a margin of the safety factor of 1.49.
- A similar test was successfully carried out using guinea corn and millet which

resulted in the same 4% losses when corn was milled, and that has also proven 96% efficiency which is a significant improvement upon the design of Workalemahu et al. [20].

The following recommendations are made;

(i) The parameters of the hammer mill should be increased alongside the motor capacity for commercial purposes.

(ii) The hammers should be carefully designed and spaced to avoid undue wear and to improve upon the crushing capacity of the machine.

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