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Failure Analysis and Performance Improvement of a Paper Shredder

*Danladi,Peter[1], Okoro, U. G.[1]
[1]Mechanical Engineering Engineering Department, Federal University of Technology, PMB 65 Minna Niger State, Nigeria
*Corresponding author email:peterdanladi79@yahoo.com+2348033940161

ABSTRACT
A paper shredder is a mechanical device used to cut paper into smaller particles leaving the content in a way that cannot be put to further use. It has been observed over time that paper shredding machine always jam during operation and causes inconveniencies. This research work used Failure Mode and Effect Analysis tool to analyze the causes of instantaneous paper shredding blade/cutter's failure. It identifies the causes of failure, the consequence of failure, and proposes process control i.e., what to monitor. The result showed that paper shredding machine problem always occur at the cutting region of the system and suggested that the blade/cutter should be redesign in order to eliminate or reduced the blade's failure. Furthermore, the study proposes a design modification paper shredder blade/cutter, to improve the performance. The comparative test conducted on the developed blade indicates an improvement of about 24% per time required to complete shredding of 1kg which translates to volumetric efficiency of 79.9%.

Keywords: *Cutter design modification, Failure mode and effect analysis, Paper shredder, Performance evaluation.*

1 INTRODUCTION

Many situations require that important information be made available on papers; letters are drafted, set examination questions or even write minutes of crucial meetings before getting them typed and these hand written ones are usually thrown into the waste paper basket. It is possible that wrong persons may have access to the waste papers, collect and use them in wrong or negative ways. Also, as competition between businesses grows, offices and people in general become more concerned about protecting their business and personal information to avoid identity theft, financial frauds and other security risks. Although in recent time information are stored digitally on computer servers, however important information that can compromise businesses and organizations is still widely available on paper. It is expected that every organization, irrespective of the size, should regularly destroy documents, which are not meant for the public eye (Ogbeide et al., 2017). This not only keeps the operations of the business safe, but also protects consumers and the members of the general public safe from identity theft, financial frauds and other security risks. Throwing whole pieces of paper containing such information into trash receptacles exposes businesses and organizations to great risk. One effective way preventing sensitive information falling into the wrong hands is to use a paper shredder.

A paper shredder is a mechanical device used to cut paper into chad, typically either strips or fine particles leaving the content in a way that cannot be put to further use. It is a machine used to shred papers into pieces in a way it cannot be pieced together. Government organizations, businesses, and private individuals use shredders to destroy private, confidential, or otherwise sensitive documents. Privacy experts often recommend that individuals shred bills, tax documents, credit card and bank account statements, and other items which could be used by thieves to commit fraud or identity theft (Nithyananth et al., 2014). Figure 1.1 shows the complete assembly of a paper shredding machine.

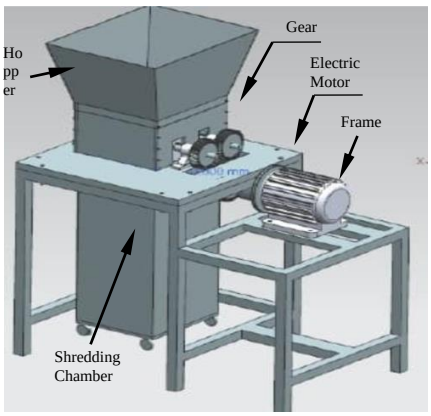

Figure 1-1 a paper shredding machine

According to Nithyananth et al (2014) it is a security device, which reduces paper to small strips or confetti-like pieces, making it difficult for the individual piece to be put back together. paper shredder is to crush sheet papers, especially confidential paper documents and other documents that are no longer required. Paper The main function of shredder can also be found in education sector such as schools tertiary, secondary or primary institutions. It could either be used in offices or for paper disposal on campuses.

A paper shredder is driven by an electric motor which delivers power to the cutting system and reduces the electric motors speed to suit the needs of the blade rotation to destroy the paper. Paper shredder machine consists of three main parts which are the machine construction, transmission system and cutting system. The

paper shredding machine is a simple machine that can be operated. After assembling the components, the machine is operated electrically with the cutting shaft operated by electric motor. When the machine is switched on the speed of the electric motor is transmitted to the pulley via Vee belt and then to the shaft, which rotates the gears and the driven shaft the meshing of the two shafts brings about the cutting of the papers when it is fed into it. Paper shredder blade as shown in figure 1.2 is one of the important components found in paper shredding machine connected to the shaft which is used to rotate the blade in order to cut the paper in to pieces.

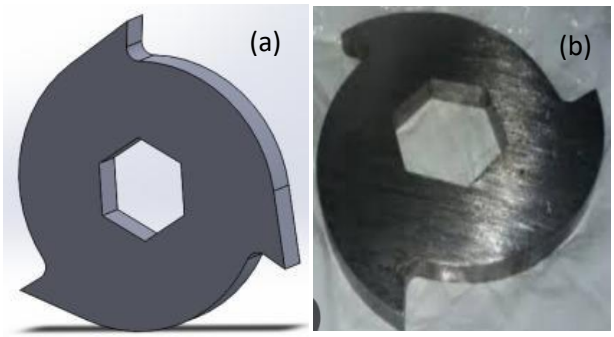

Figure 1-2 **a paper shredding machine's blade**

Failure mode and effect analysis is the process of reviewing as many components assemblies and subsystems as possible to identify potential failure modes in a system and their causes and effects. In this project, instantaneous causes of paper shredder's blade failure was determined using failure mode and effect analysis and the new blade was developed to meet up with efficient, reliable and full operational performance of paper shredder's blade was achieved.

2 METHODOLOGY

2.1 MATERIALS

Material selection is one of the most important aspect that demand the understanding of the functional requirement for the individual machine components as there are ever increasing varieties presently available and the development of new materials with unique properties and application (González-Viñas & Mancini, 2004). Material selection for any engineering design depend on the following factors; availability, strength, fabricability, appearance, cost and corrosion resistance. Before starting the actual paper shredding materials selection process, under listed questions must be answered. Every specific application required by paper shredding machine is characterized by a set of operation parameters, which dictate the necessity and accurate selection of the optional materials(Khurmi & Gupta, 2012).

According to Siddiqui (2017), material selection depends on some operating conditions. Some of the conditions or factors considered in selecting materials includes but not restricted to Pressure and load involved, Operating temperature, Availability,Cost and Functionality. With these above, material requirements and its properties was selected for the design of blade component. The material to be considered in this research work is low carbon steel.

2.2 LOW CARBON STEEL

Also known as mild steel is now the most common form of steel because its price is relatively low while it provides material properties that are acceptable for many applications. Low carbon steel contains approximately 0.05-0.25% carbon making it malleable and ductile. Mild steel has relatively low tensile strength, but it is cheap and easy to form, surface hardness can be increased through carburizing.(Gao et al., 2015).The heat transfer characteristics of a solid material are measured by a property called the thermal conductivity or λ,measured in w/m.k. it is a measure of a substance's ability to transfer heat through a material by conduction. Table 2.1 below shows the mechanical properties of low carbon steel.

Table2-1:THE MECHANICAL PROPERTIES OF LOW CARBON STEEL.

low carbon steel	Properties
Magnetic	This is due to the high amounts of ferrite and iron in mild steel bars.
Ductile	In comparison to other types of steel, it is more ductile and therefore can be used for a wide variety of purposes.
Weldable	Due to its low carbon content, it is more malleable and suitable for welding. The less carbon in the steel, the more weldable and machinable it becomes.
Affordable	Using mild steel is relatively cost-effective in comparison to some other steels.
Very little carbon	This makes cold-forming low carbon steel easier, and they are easier to handle as a whole.

2.3 PAPER MATERIAL

Paper is a thin sheet material produced by mechanically or chemically processing cellulose fibres derived from **w**ood, rags, grasses or other vegetable sources in **w**ater draining the **w**ater, through fine mesh leaving the fibre evenly distributed on the surface, followed by pressing and drying. It is a versatile material with many uses, including printing, painting, graphics, signage, design, packaging, decorating, **w**riting and cleaning. It may also be used as filter paper, wallpaper, book, endpaper, conservation paper, laminated **w**orktops, toilet tissue or currency and security paper, or in a number of industrial and construction processes.In this study the material to be cut is selected to be paper material with mechanical properties given in the Table 2.2.

Table 2-2MECHANICAL PROPERTIES OF PAPER

Office copy	Bulk density(g/cm□)	Ultimate tensile strength(kgf/cm²)	Ultimate tensile strength(Mpa)
A4 – 1	0.632	232.5	22.81
A4 -2	0.635	271.8	26.7
A4 – 3	0.637	255.5	25.05

2.4 FAILURE MODE EFFECT ANALYSIS (FMEA)

FMEA is an efficient tool for identifying the potential failure modes and their effects in order to increase the reliability and safety of complex systems and gathering the data that is necessary to decide about how to manage risks. In fact, the purpose of this technique is to identify failure modes and their effects and corrective actions to eliminate or reduce the probability of failure (redesign) and finally the development of efficient maintenance system, to reduce the occurrence of potential scenarios (Kmenta & Ishii, 2000).

The first phase of this research work was to investigate the paper shredding blade's failure using failure mode and effect analysis as a tool used to carried out the analysis. This investigation was carried out with the help of experts (paper shredding machine's operator and their maintenance personnel) from different locations across the country that came up with the same opinion on the component's failure mode, failure consequences and process control / what to monitor. The detailed information was given in the table 2.3 below. It was opined by some of these experts on the paper shredding blade's that the blade should be re-redesign in order to eliminate or reduced the instantaneous of failure of the blade/cutter as low as possible that can be of a help to increase the paper shredding blade's efficiency.

Table 2-3FAILURE MODE AND EFFECT ANALYSIS OF PAPER SHREDDING MACHINE'S BLADE/CUTTER

S/N	Component / Sub component	Component / Sub component Function	Failure Mode	Failure consequences	What to monitor/process Control
1	Paper shredder blade/cutter	Paper shredder blade/cutter is a major component found in paper shredding machine used to shred the paper in to pieces with the help of rotating shaft connected to the blade	Blade / cutter broken at the edges	Paper flying out from the shredding housing completely	- regular inspection oat the edges of the blade
			Blade /cutter bent at its periphery	Paper jamming at the shredding housing	Daily internal/ external inspection of the blade's periphery
			Blade /cutter worn out at the edges	Partial shredding of the paper	-daily inspection on the edges of the blade
			Blade /cutter fractured around the blade hole	Partial jamming and shredding of the paper	-regular inspection of the blade/cutter's hole
			Blade /cutter hooked without rotation	Total loss of shredding during the process	Regular inspection on the entire cutting system
			Blade /cutter out worn around blade's hole	Partial jamming and shredding of the paper	Regular internal /external inspection
			Blade/ cutter broken, worn out, fractured and bent around its periphery	Total loss of shredding during the process	-regular inspection -weekly / monthly maintenance

2.5 DESIGN CONSIDERATION

The second methodology adopted for the second phase of this research work is the process that starts with design of the concept, selection of material and design analysis, and lastly fabrication and testing of the blade/cutter.

2.6 DESIGN THEORY AND CALCULATION OF THE REDESIGNED BLADE

Breaking strength can be assumed as the ultimate strength multiply by a factor of safety 1.5.Breaking strength (τ_{br}) of paper material:(τ_{br}) =25.05 ×1.5=37.58 MPa.The cross-sectional area (A) of the material to be cut is:

$$A = w \times t \quad \textbf{(1)}$$

Where; w = width of the cutting edge, t = thickness of the paper material. Similarly, the shear stress is express by:

$$\tau = {}^{F}/_{A} \quad \textbf{(2)}$$

Where: $\boldsymbol{\tau}$: shear stress (N/mm^2), F, Force applied the blades (N), A : Cross-sectional area(mm^2).The cutting force ($\boldsymbol{F_c}$). The cutting force (F_c) required for shredding paper material;

$$F_c = \tau_{br} \times A \quad \textbf{(3)}$$

Torque (T) exerted on the blade as well as shaft is given by the equation

$$T = F_c \times r \quad \textbf{(4)}$$

Where; T = Paper cutting torque (N-m), r = Radius of the blade from the center (mm). Power (P) transmitted by the shaft is given by:

$$P = M \times \omega \quad \textbf{(5)}$$

Where; ω = angular speed (rad/s)

Description of the Geometry of The Shredder Blade:
The detailed blade geometry is as shown in figure 2.1. The blade has a width (w) of $0.006\ m$, centre radius(r) of 0.06m, and hole (Hexagonal circle) of radius 0.02m. The cutting area (A) made by edge of the blade is given by equation (1) and calculated as follows;

$$A = 6 \times 5 = 30mm^2$$

where;w = width of cutting edge, t = thickness of 10 sheets of A4 paper.

Force Acting on Cutting Edge of The Blade:
The force acting on the cutting edge of the blade can be estimated from the relationship between the shear strength and the area as expressed in equation 3. Given that the shear strength is$37.58MPa$, the force, therefore becomes;

$$F_c = breakingstrength \times Area$$

$$F_c = 37.58 \times 30 = 1127.4N$$

From the estimate of the force F_c. the torque exerting on the blade as well as shaft can be computed from equation 4 as follows;

$$T = F_c \times r$$

$$T = 1127.4 \times 0.06 = 67.644\ Nm$$

Power (P) required for torque transmission of the shaft:
The power transmitted by the torque is given by equation (5) and depicted as follows;

$$P = T \times \omega$$

Substituting the values of T and ω into equation (5) yields the following expressions

$$P = 67.644 \times 2\pi$$

$$P = 67.644 \times (2 \times 3.142)$$

$$P = 425.07\ watt, or P = 0.43\ Kw$$

2.7 FABRICATION AND ASSEMBLY

The fabrication, production and fixing of the paper shredding blade / cutter was carried out in order to achieved the desired units blade /cutter.The paper shredder blade /cutter was fabricated from 6mm thick plate. The metal plate was cut using a hand cutting machine to dimension specified in the appendix A. the cut plate was then finally plain and sharp at the edges to form a complete paper shredder blade/ cutter.

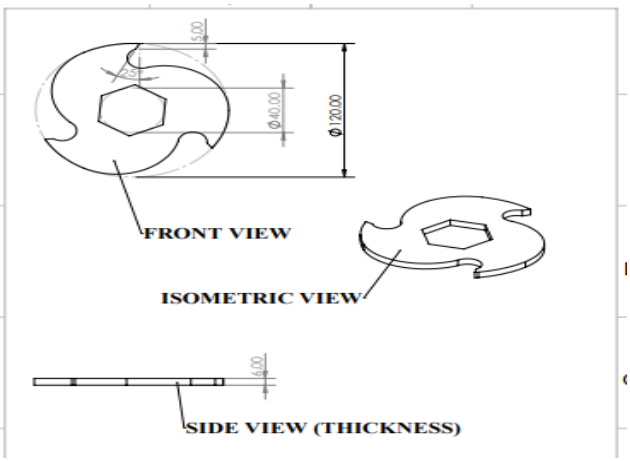

Figure 2-1 Detail geometry of shredder blade and dimensions

3 RESULTS AND DISCUSSION

The initial study of this research work was to investigate the existing paper shredding blade/ cutter's failure using one of the most popular risk analysis tool "the Failure Mode and Effect Analysis" to analyze the instantaneous failure of the blade in paper shredding machine. This investigation was carried out with the help of four (4) men of experts who have been operating paper shredding machine from different locations across the country. The result proved that paper shredding machine problem always occurs at the blade/cutter's region especially at the cutter's edge where the concentration of stress is high during the operation process. Therefore, the failure mode and effect analysis tool was not only designed to check "the causes of failure", "the

consequence of failure", "what to monitor / process control but may also lead to the redesigning ofnew product (blade/cutter) after the completion of the work. The new blade was redesigned with the radius of an arc at the edge to be 20mm to reduce the stress concentration and the cutting angle of $25^0$for instantaneous shredding which is differ from the existing one with the radius of an arc 60mm at the centre and cutting angle of 120^0, that was consider in this research work to eliminate or reduced the amount of failure on the blade's/cutter in order to meet up with a credible performance.

The second phase of this research work was to redesign a new blade/cutter that can shred paper for a period of a term without developed any symptom of failure. The new blade/cutter was redesigned, fabricated and constructed while the results were recorded from the design analysis and calculations are itemized in table 3.1.

TABLE 3-1 DESIGN ANALYSIS AND CALCULATION RESULT

The cutting area (A) made by edge of the blade	$30mm^2$
Force acting (F) on cutting edge of the blade	751.5N
Torque(T) exerting on the blade as well as shaft	45.09Nm
Power (P) of the required torque transmission shaft	0.47KW
The volumetric efficiency	79.9%

The blades were been replaced, tested and it took about 6.08minutes for the machine to shred 4.78× 10¯5m□.During testing, the volumetric flow rate of the shredded paper was measured using the weighing machine and $\rho = m/v$ at the interval of 60secs,while the volumetric efficiency was gotten as 79.9%.Therefore,it was observed that radius at the new blade/cutter's edge when compare with the existing blade/cutter tend to reduce stress concentration and increase the redesigned blade/cutter's efficiency and the instantaneous failure of the machine become minimal during the testing operation when compare with the existing blade/cutter. The experimental test result table and graph showing relationship between discharge and time is described in table 3.2 and figure 3.1 respectively.

TABLE 3.2: EXPERIMENTAL TEST RESULT

S/No	T(min)	V($\times 10^{-5}m^3$/min)
1	0	0
2	1	1.2
3	2	1.62
4	3	2.24
5	4	3.20
6	5	4.01
7	6	4.78

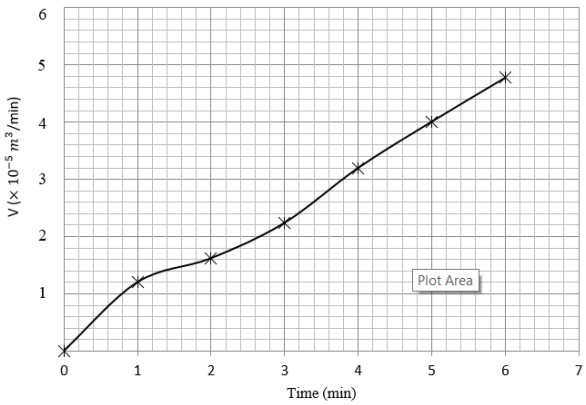

Figure 3-1Relationship between discharge and time which is linear with a slope

4 CONCLUSION

This research work used Failure Mode and Effect Analysis tool to analyze the causes of instantaneous paper shredding blade/cutter's failure and the result proved that paper shredding machine problem always occur at the cutting system region. Therefore, the causes, the consequence, and the process control are been determined. It was also observed that there is need for a new blade/cutter should be redesign in order to eliminate or reduced the blade's failure. The paper shredder blade/cutter's was designed, fabricated and tested using the existing machine to shred some quantities of papers. The blades ware designed for strength, rigidity, and the performance evaluation shows that the redesigned blades during the machine operation have a volumetric efficiency of 79.9%. The comparative test conducted between the new blades and the existing blades indicates that the machine takes 6.08minutes to complete shredding of 1kg in new blades and it took the existing blades 8.01minutes to shred 1kg of the papers.
Therefore, low carbon steel was chosen for the construction and the written papers of different size are also selected to be shredded.

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