DEVELOPMENT AND PERFORMANCE EVALUATION OF A PLASTIC SHREDDING MACHINE

BY

SOLANKE, Oluwatoyin
MEng/SIPET/2018/8671

DEPARTMENT OF MECHANICAL ENGINEERING
FEDERAL UNIVERSITY OF TECHNOLOGY
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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF ENGINEERING IN MECHANICAL ENGINEERING (INDUSTRIAL AND PRODUCTION ENGINEERING)

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ABSTRACT

This research is focused on proffering solution to the problem of plastic waste management in our surrounding environment. Therefore, plastic shredding machine for the recycling of plastic wastes was designed, fabricated and evaluated for performance. The machine consists of the following components: hopper, main enclosure, the chute and the screen made of mild steel sheet; drive shaft and the gears made of mild steel rod; cutters made of mild steel plate; and electric motor which was bought from the market. Performance of the machine was evaluated for polyethylene therephthale (PET), expanded polystyrene (EPS) and high-density polyethylene (HDPE) and the shredding efficiencies for PET, EPS and HDPE were obtained as 69.8 %, 73.9 % and 89.7 % respectively. The machine developed is suitable for shredding of plastic waste materials in a small scale plastic recycling plant.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

Waste is naturally produced by all humans and possesses great health and environmental risks. Indiscriminate loitering of waste is prevalent in our streets due high rate of production and in adequate disposal mechanisms. Studies (Al-Gheethi *et al*., 2018) link the lack of proper waste disposal to water contamination in developing communities and cholera outbreak in those places. Aside from these serious risks in developing nations traffic congestion, drainage blockages are some of the problems caused by the lack of efficient waste management practice in Nigeria.

Plastic and non-degradable materials constitute most of the waste disposed in the present day (Jadhav *et al*., 2018). Plastics are made from petroleum products and if improperly disposed cause grave agricultural and environmental problems due to the long time it takes without degrading in the soil. Most of the plastic disposed take more 500 years without degrading (Canopoli *et al*., 2019; Akash, *et al*., 2019), presently the world over it constitutes a nuisance. Artificial islands formed by these non-degradable wastes can even be viewed from satellites. Recycling these types of materials seems to be the solution to this menace.

Thermoplastics do not undergo chemical change when heated therefore are good candidates for recycling (Olukunle, 2016). Recycling of plastics is the process of recovering plastic materials and reprocessing them into usable products. Various products can be made from recycling plastics, like polyethylene bin liners, and carrier bags, plastic bottles, flooring and window frames. The recycling process includes washing, sorting, shredding, heating, extruding and pelletizing. The recycling of plastics requires specialized machines.

The shredding process is crucial as the enormous volume of the waste is plastic is reduced to make it easy to undergo the rest of the recycling process and to ease transportation of raw materials. Machines available are bulky, costly, scarce and generally out of the reach (Akash, *et al*., 2019; Olukunle, 2016) if commensurate with amount of waste available.

Therefore, the need to develop a portable machine that will be cost effective, easy to operate, available and capable of shredding waste thermoplastic materials using locally sourced materials becomes a necessity.

1.2 Statement of the Research Problem

Waste thermoplastic materials release hazardous substances that are damaging to the environment hence, plastic waste management that will ensure sustainable clean environment had been a focus for attention (David and Joel, 2018). Plastic shredding machines plays a vital role in the waste plastic recycling process and this will benefit developing countries like Nigeria. Though there are few plastic shredding machines available but they are bulky, scarce and expensive (Akash *et al*., 2019). Hence, there is a need to develop a new portable machine as available machines developed locally have low efficiency and are often too cumbersome (Ejiko *et al*., 2022; Atadious and Oyejide, 2018). The affordability of this new developed machine will also enable easy start-ups in the waste thermoplastic materials recycling sector for the small-scale entrepreneurs. Also, The continuous development of plastic shredding machine is inevitable until there is locally produced shredder that will have competitive efficiency as the available ones in the market.

1.3 Aim and Objectives of the Study

The aim of the study is to develop a shredding machine that will be used for crushing thermoplastic materials. The objectives for achieving this aim are:

(i) To carry out design analysis of the shredding machine.

(ii) To fabricate the shredding machine.

(iii) To carry out the performance evaluation of the machine.

1.4 Justification of the Study

The volume of plastic waste materials generated in the country is very high causing serious environmental and health risks. The shredding machine will enable reduction in the volume of plastic waste and ease transportation and recycling process. The developed machine will also encourage establishment of small plants that will eventually aid in the overall reduction of plastic waste pollution in the society.

1.5 Significance of the Study

The plastic shredder plays a significant role in the recycling process. It aids in the preparation of waste into raw materials for recycling and converting the waste into manageable volume for further operation. With proper design analysis the shredder could be used to shred various types of plastic when developed thereby enhancing its efficiency and capacity.

1.6 Scope of the Study

The study focused on the design of the machine and fabricating it using locally sourced materials. The study will also carry out performance evaluation of the efficiency of the fabricated plastic shredding machine.

The availability and cost of machinery for handling the blades due to their special shapes and thickness posed a challenge. This caused minor deviations in the work that made the machine have more tolerance than anticipated from the working drawings and eventually affected the overall efficiency of the machine.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Theoretical Fundamentals of Plastic Materials

Olukunle (2016) defines plastic as a polymeric material that has the property of plasticity. When heat and pressure is applied can be moulded or shaped. Other notable properties mentioned by Olukunle (2016) are low density, low electrical conductivity, transparency, and toughness. Plastic can be into a great variety of products.

Popular products made from plastic materials are tough and lightweight beverage bottles made of polyethylene terephthalate (PET), flexible garden hoses made of polyvinyl chloride (PVC), insulating food containers made of foamed polystyrene, and shatterproof windows made of polymethyl methacrylate (Olukunle, 2016)

2.1.1 Classification of plastics materials

Plastics can be divided into two major categories: thermoplastics and thermosetting, some properties and application of plastics is given in Table 2.1a and Table 2.1b. Thermoplastics are recognized by their ability to be recycled as polyethylene and polystyrene (both types of thermoplastics) are capable of being moulded and remoulded repeatedly. The polymer structure is that of individual molecules that is separate from one another and flow past one another (Olukunle, 2016).

Thermosetting, on the other hand, cannot be reprocessed upon reheating (Campbell, 2011). During their initial processing, thermosetting resins undergo a chemical reaction that results in an infusible, insoluble network (Olukunle, 2016). Essentially, the heated plastic becomes

Table 2.1a: Properties and Applications of Commercially Important Plastics (Source: Olukunle, 2016)

Polymer Family and Type	**ρ (g/cm^3)**	**DOC**	**GTT (ºC)**	**CMT (ºC)**	**DT at 1.8 MPa (ºC)**	**TS (MPa)**	**EB (%)**	**FM (GPa)**	**Typical Products and Appl.**
Thermoplastics									
Carbon-Chain									
High density polyethylene (HDPE)	0.95-0.97	High	-120	137	-	20-30	10-1000	1-1.5	Milk, bottles, wire & cable insulation, toys
Low density polyethylene (LDPE)	0.92-0.93	moderate	-120	110	-	8-30	100-650	0.25-0.35	Packaging film, grocery bags, agric mulch
Polypropylene (PP)	0.90-0.91	High	-20	176	-	30-40	100-600	1.2-1.7	Bottles, food containers, toys
Polystyrene (PS)	1.0-1.1	Nil	100	-	-	35-50	1-2	2.6-3.4	Eating utensils, foamed food containers
Acrilonitrili-butadiene styrene (ABS)	1.0-1.1	Nil	90-120	-	-	15-55	30-100	0.9-3.0	Appliance housings, pipe fittings
Polyvinyl chloride, unplasticized (PVC)	1.3-1.6	Nil	85	-	-	40-50	2-80	2.1-3.4	Pipe conduit, home siding, window frames
Polymethyl methacrylate (PMMA)	1.2	Nil	115	-	-	50-75	2-10	2.2-3.2	Impact-resistant windows, sky lights, canopies
Polytetrafluoroethylene (PTFE)	2.1-2.2	Moderate -high	126	327	-	20-35	200-400	0.5	Self-lubricated bearings, non-stick cock-ware
Heterochain									
Polyethlene terephthalene (PET)	1.3-1.4	moderate	69	265	-	50-75	50-300	2.4-3.1	Transparent bottles, recording tape
Polycarbonate (PC)	1.2	Low	145	230	-	65-75	110-120	2.3-2.4	Compact disc, safety glasses, sporting goods
Polyacetal	1.4	moderate	-50	180	-	70	25-75	2.6-3.4	Bearings, gears, shower heads, zippers
Polyetheretherketone (PEEK)	1.3	Nil	185	-	-	70-105	30-150	3.9	Machine, automot. aerospace parts

Table 2.1b: Other Properties and Applications of Commercially Importance Plastics

Polymer Family and Type	ρ (g/cm^3)	DOC	GTT (ºC)	CMT (ºC)	DT at 1.8 MPa (ºC)	TS (MPa)	EB (%)	FM (GPa)	Typical Products and Application
Polyphenylene sulphide (PPS)	1.35	moderate	88	288	-	50-90	1-10	3.8-4.5	Machine parts, appliance, electrical equipment
Cellulosre decetate	1.3	Low	120	230	-	15-65	6-70	1.5	Photographic film
Polycaprolactam (nylon 6)	1.1-1.2	moderate	50	210-220	-	40-170	30-300	1.0-2.8	Bearings, pulleys, gears
Thermosets									
Hetrochain									
Polyester (unsaturated)	1.3-2.3	Nil	-	-	200	20-70	3	7-14	Boat hulls, automobile panels
Epoxies	1.1-1.4	Nil	-	-	110-250	35-140	4	14-30	Laminated circuit boards, flooring and aircraft parts
Phenol formaldehyde	1.7-2.0	Nil	-	-	175-300	90-125	1	8-23	Electrical connectors, appliance handle
Urea and metamine formaldehyde	1.5-2.0	Nil	-	-	190-200	35-75	1	7.5	Countertops, dinnerware
Polyurethene	1.05	Low	-	-	90-100	70	3-6	4	Flexible & rigid foams for upholstery, insulation

ρ = Density, DOC = Degree of Crystallinity, GTT = Glass Transition Temperature, CMT = Crystal Melting Temperature, DT = Deflection Temperature, TS = Tensile Strength, EB = Elongation at Break, FM = Flexural Modulus a single entity and subsequent application of heat only causes it to break rather than be reworked. Examples include vulcanized rubber, fiberglass (a fibre-reinforced polymer composite), polyester resin, polyurethane, melamine, Bakelite, silicone resin and epoxy resin (Campbell, 2011).

2.1.2 Analysis of polyethylene

Polyethylene (PE) was discovered in 1933 by Eric Fawcett and Reginald Gibson at the British Industrial giant, Imperial Chemical industries (ICI). Although it is more than 80 years since it was produced, it is still a very promising material. It is produced at high pressures and temperatures in the presence of any of the catalysts, depending on the desired properties of the end-use product. Other structure (leading to long and short branches) may be present, depending on the producer used in the synthesis. PE is the largest volume polymer consumed in the world. It is a versatile material that offers high performance compared to other polymers and alternative materials such as glass, metal or paper (VijayAnanth *et al*., 2018) Polyethylene plastics have the largest volume use of any plastics. They are prepared by the catalytic polymerization of ethylene at high pressure and temperature (vijayAnanth *et al.*, 2018). Depending on the mode of polymerization or the desired properties of the end-use product, molecular weight (MW), molecular weight distribution (MWD), as well as on the degree and type of branching there can be three basic types of polyethylene: high-density (HDPE), low-density polyethylene (LDPE) polymers, and linear low-density (LLDPE) (Yu et al., 2011). LDPE is prepared under more vigorous conditions, which result in short-chain branching. LLDPE is prepared by introducing short branching via copolymerization with a small amount of long-chain olefin. Other types of PE product are such a very-low density polyethylene (VLDPE), high molecular weight HDPE (HMWHDPE), ultra high molecular weight polyethylene (UHMWPE) and ultra-low-density polyethylene (ULDPE) (VijayAnanth *et al*., 2018).

2.1.3 Production processes of plastics

The processing of raw materials into usable forms is termed fabrication or conversion, plastic is converted from pellets into films or food containers.

2.1.3.1 *Compounding*

The first step in most plastic fabrication procedures is compounding (Rodriguez, 2019), the mixing together of various raw materials in proportions according to a specific recipe. Most often the plastic resins are supplied to the fabricator as cylindrical pellets (several millimetres in diameter and length) or as flakes and powders according to Cheremisinoff (2012). Other forms include viscous liquids, solutions, and suspensions.

2.1.3.2 *Forming*

The process of forming plastics into various shapes typically involves the steps of melting, shaping, and solidifying (VijayAnanth *et al*., 2018). Thermoplastics in general are solidified by cooling below transition temperature while thermosets are solidified by heating in order to carry out the chemical reactions necessary for network formation (VijayAnanth *et al*., 2018).

2.1.3.3 *Extrusion*

In extrusion, a melted polymer is forced through an orifice with a particular cross section (the die), and a continuous shape is formed with a constant cross section similar to that of the orifice as shown in Figure 2.1 (VijayAnanth *et al*., 2018). Although thermosets can be extruded and cross-linked by heating the extradite, thermoplastics that are extruded and solidified by cooling are much more common. Among the products that can be produced by extrusion are film, sheet, tubing, pipes, insulation, and home siding (VijayAnanth *et al*., 2018). In each case the profile is determined by the die geometry, and solidification is by cooling.

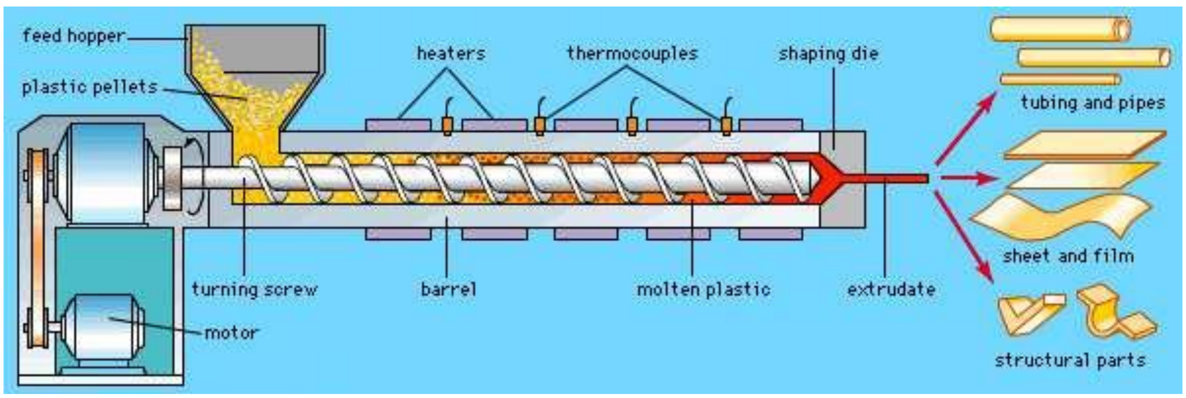

Figure 2.1: Longitudinal Section of a Screw Extruder of Thermoplastic Polymers (Source: VijayAnanth *et al*., 2018)

2.1.3.4 *Moulding*

The next step in the process is moulding; amongst the notable types are compression, injection and blow moulding processes (Olukunle 2016). Compression moulding is the process in which a moulding powder (or pellets, which are also sometimes called moulding powder) is heated and at the same time compressed into a specific shape, but is inefficient for thermoplastics (Helmi *et al*., 2011). In injection moulding this inefficiency is corrected, it involves liquefying of the resin and regulating its flow in a part of the apparatus that remains hot, while the shaping and cooling is carried out in a part that remains cool. Blow moulding (Figure 2.2) is the process of forming a molten tube of thermoplastic material and placing same within a mould cavity and inflating the tube with compressed air, to take the shape of the cavity and cool the part before removing from the mould (Olukunle, 2016; Belcher, 2017).

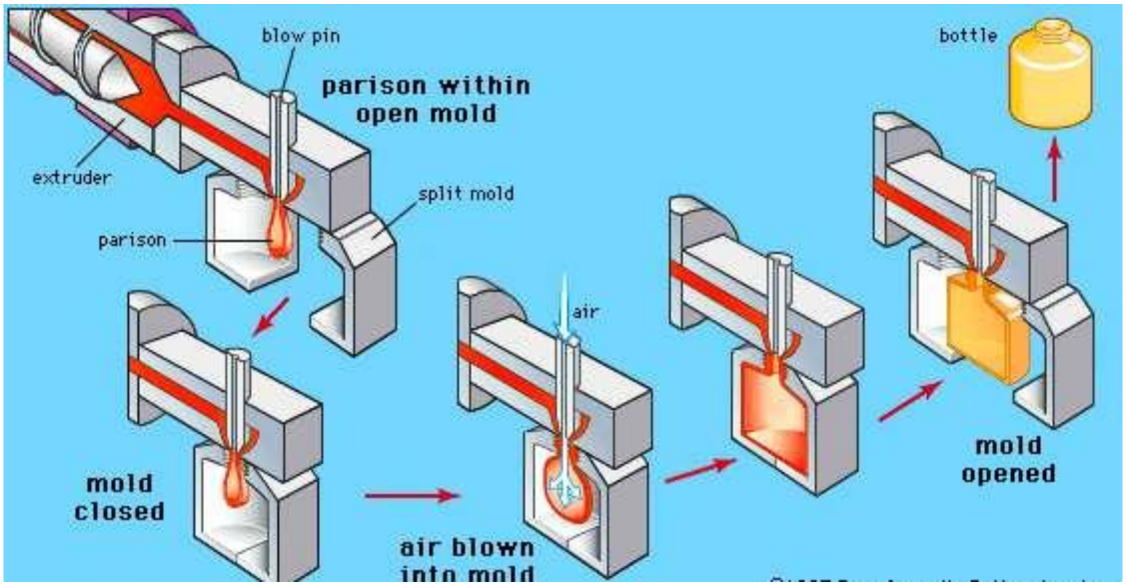

Figure 2.2: Blow Moulding of Plastic Containers (Source: VijayAnanth, 2018)

2.1.3.5 *Casting and Dipping*

Not every forming process requires high pressures. If the material to be moulded is already a stable liquid, simply pouring (casting) the liquid into a mould may suffice. Since the mould need not be massive, even the cyclical heating and cooling for a thermoplastic is efficiently done.

2.1.3.6 *Foaming*

Foams, also called expanded plastics, possess inherent features that make them suitable for certain applications. For instance, the thermal conductivity of foam is lower than that of the solid polymer. Also, a foamed polymer is more rigid than the solid polymer for any given weight of the material.

2.2 Generation of Plastic Waste

Waste generation is a natural and inevitable phenomenon as long as there is consumption by humans. An average of 42 million ton of waste is generated annually in Nigeria for example (Chinedu *et al*., 2018). Disposing of this waste is a major concern in developing countries. Most cities in Africa spend more than 50 % of their environmental budget on municipal waste management (David and Joel, 2018). The process is highly in efficient due to poor documentation of waste generation rates, lack of proper storage facilities, poor collection mechanisms and underutilization of dumpsites (David and Joel, 2018). Over 20 % of the waste generated is made up of non-degradable plastic materials (David and Joel, 2018) making the situation even worse.

Plastic can spend more 500 years without degrading (Canopoli *et al*., 2019; Akash, *et al*., 2019) causing numerous environmental pollution. With the nation's population over 190 million people, water plastic bottle generation alone can reach a rate of 100 million waste bottles generated per day (David and Joel, 2018). Since plastic takes long to degrade the best option is to recycle.

Plastics are widely used economical materials characterized by excellent all-round properties, easy moulding and manufacturing. Approximately 140 million tonnes of synthetic polymers are produced worldwide each year to replace more traditional materials, particularly in packaging ((Chinedu *et al*., 2018). Over 60% of post-consumer plastics waste is produced by households and most of it as single use packaging (Chinedu *et al*., 2018).

Plastics are manufactured and designed to resist the environmental degradation and also more economical than metal, woods and glasses in term of manufacturing costs and energy required (Chinedu *et al*., 2018). Due to these issues, plastics resins have become one of the most popular materials used in packaging. Plastics packaging has a cycle less than a year and continuously enter the waste stream on a short turnout of time. The continuous growth of plastics industries has led to the increase volume of plastics waste in the landfill.

2.3 Recycling of Polymers

The recycling of waste polymers can be carried out in many ways. Four main approaches have been presented (Achilias and Karayannidis, 2004)

1. Primary recycling refers to the 'in-plant' recycling of the scrap material of controlled history. This process remains the most popular as it ensures simplicity and low cost, dealing however only with the recycling of clean uncontaminated single-type waste.

2. Mechanical recycling (or secondary recycling). In this approach, the polymer is separated from its associated contaminants and it can be readily reprocessed into granules by conventional melt extrusion. Mechanical recycling includes the sorting and separation of the wastes, size reduction and melt filtration. The basic polymer is not altered during the process. The main disadvantage of this type of recycling is the deterioration of product properties in every cycle. This occurs because the molecular weight of the recycled resin is reduced due to chain scission reactions caused by the presence of water and trace acidic impurities. Strategies for maintaining the polymer average molecular weight during reprocessing include intensive drying, reprocessing with degassing vacuum, the use of chain extender compounds, etc.

3. Chemical or Feedstock recycling (tertiary recycling) has been defined as the process leading in total depolymerization of PET to the monomers, or partial depolymerization to oligomers and other chemical substances. The monomers could subsequently re- polymerize to regenerate the original polymer.

4. Energy recovery (Quaternary recycling) refers to the recovery of plastic's energy content. Incineration aiming at the recovery of energy is currently the most effective way to reduce the volume of organic materials. Although polymers are actually high-yielding energy sources, this method has been widely accused as ecologically unacceptable owing to the health risk from air born toxic substances such as dioxins (in the case of chlorine containing polymers).

Apart from the aforementioned methods, direct reuse of a plastic material (that is, PET) could be considered as a "zero order" recycling technique. In a lot of countries, it is a common practice to refill and reuse PET-bottles. However, this should be done with a great care since plastic bottles are more likely than glass to absorb contaminants that could be released back into food when the bottle is refilled. Moreover, refill of a PET-bottle with a high-alcoholic-degree drink may lead to degradation of the macromolecular chains with unexpected results (Achilias and Karayannidis, 2004).

The objective of a plastic management policy, in accordance with the principles of sustainable development (development that meets the needs of present generation without compromising the ability of future generations to meet their needs), should be not only the reuse of polymeric materials but also the production of raw materials (monomers), from which they could be reproduced, or other secondary valuable products, which could be useful as feedstock for a variety of downstream industrial processes or as transportation fuel. In this sense, among the techniques proposed for recycling of waste polymers the most challenging method is chemical or feedstock recycling and various technologies have been successfully demonstrated and continue to be developed (Achilias and Karayannidis, 2004).

2.3.1 Chemical recycling of polyethylene (LDPE and HDPE)

Under the category of chemical recycling of polyethylene, advanced process (similar to those employed in the petrochemical industry) appear e.g., pyrolysis, gasification, liquid–gas hydrogenation, viscosity breaking, steam or catalytic cracking (Achilias, 2006). Catalytic cracking and reforming facilitate the selective degradation of waste plastics. The use of solid catalysts such as silica alumina, ZSM-5, zeolites, and mesoporous materials for these purposes has been reported. These materials effectively convert polyolefin into liquid fuel, giving lighter fractions as compared to thermal cracking (Achilias, 2006).

In particular, polyethylene has been targeted as a potential feedstock for fuel (gasoline) producing technologies. PE thermally cracks into gases, liquids, waxes, aromatics and char. The relative amounts of gas and liquid fraction are very much dependent on the type of polymer used. Thus, higher decomposition was observed in PP, followed by LDPE and finally HDPE. It seems that less crystalline or more branched polymers are less stable in thermal degradation (Achilias and Karayannidis, 2004). Many papers have been published recently on this subject and excellent reviews can be found in the book by Achilias and Karayannidis (2004).

Polyethylene (as well as other vinyl polymers) degrade via a four-step free radical mechanism: radical initiation, de-propagation (as opposed to propagation in the case of polymerization), intermolecular and intra-molecular hydrogen transfer followed by β-scission (initial step in the chemistry of thermal cracking of hydrocarbons and the formation of free radicals) and, lastly, radical termination. β-scission and hydrogen abstraction steps often occur together in a chain propagation sequence. That is, a radical abstract a hydrogen atom from the reactant to form a molecule and a new radical. A bond β is then broken to the radical centre (β-scission) to regenerate an abstracting radical and to produce a molecule with a double bond (a molecule with a double bond involving the carbon atom that had been the radical centre). Sample size and surface area to volume ratio of the melt have a significant influence on the rate and relative importance of the various mechanisms of polymer degradation. In pyrolysis, which is normally done on micro-scale, only random initiation and intermolecular transfer were reported to be important. Conversely, on milligram scale of polyethylene charges and samples, intermolecular transfer of hydrogen atoms via abstraction by free radicals was considered to be the predominant transfer mechanism to produce volatiles. There is also a growing interest in developing value added products such as synthetic lubricants via PE thermal degradation.

The development of value-added recycling technologies is highly desirable as it would increase the economic incentive to recycle polymers. Several methods for chemical recycling are presently in use, such as direct chemical treatment involving gasification, smelting by blast furnace or coke oven, and degradation by liquefaction. The main advantage of chemical recycling is the possibility of treating heterogeneous and contaminated polymers with limited use of pre-treatment. Petrochemical plants are much greater in size (6–10 times) than plastic manufacturing plants. It is essential to utilize petrochemical plants in supplementing their usual feedstock by using plastic solid wastes (PSW) derived feedstock (Achilias, 2006).

2.3.1.1 *Thermolysis schemes and technologies*

Thermolysis is the treatment in the presence of heat under controlled temperatures without catalysts. Thermolysis processes can be divided into advanced thermo-chemical or pyrolysis (thermal cracking in an inert atmosphere), gasification (in the sub-stoichiometric presence of air usually leading to CO and CO_2 production) and hydrogenation (hydrocracking) (Achilias, 2006). Thermal degradation processes allow obtaining a number of constituting molecules, combustible gases and/or energy, with the reduction of landfilling as an added advantage (Panda *et al*., 2010).

i. Pyrolysis

The pyrolysis process is an advanced conversion technology that has the ability to produce a clean, high calorific value gas from a wide variety of waste and biomass streams (Achilias, 2006). The hydrocarbon content of the waste is converted into a gas, which is suitable for utilization in either gas engines, with associated electricity generation, or in boiler applications without the need for flue gas treatment. This process is capable of treating many different solid hydrocarbon based wastes whilst producing a clean fuel gas with a high calorific value (VijayAnanth *et al*., 2018). This gas will typically have a calorific value of 22–30 MJ/m^3 depending on the waste material being processed. Solid char is also produced from the process, which contains both carbon and the mineral content of the original feed material (VijayAnanth *et al*., 2018). The char can either be further processed onsite to release the energy content of the carbon, or utilized offsite in other thermal processes (VijayAnanth *et al*., 2018).

The main pyrolysis units and technologies on an industrial scale include PYROPLEQ (rotary drum), Akzo (circulating fluidized bed), NRC (melt furnace), Con Therm technology (rotary drum), PKA pyrolysis (rotary drum), Pyromelt (melt furnace), BP (circulating fluidized bed), BASF (furnace) and NKT (circulating fluidized bed). Details can be found in Yu *et a.,l* (2011).

Pyrolysis provides a number of other advantages, such as operational advantages, environmental advantages and financial benefits. Operational advantages could be described by the utilization of residual output of char used as a fuel or as a feedstock for other petrochemical processes. An additional operational benefit is that pyrolysis requires no flue gas clean up as flue gas produced is mostly treated prior to utilization.

Environmentally, pyrolysis provides an alternative solution to land filling and reduces greenhouse gas (GHGs) and CO_2 emissions. Financially, pyrolysis produces a high calorific value fuel that could be easily marketed and used in gas engines to produce electricity and heat. Several obstacles and disadvantages do exist for pyrolysis, mainly the handling of char produced and treatment of the final fuel produced if specific products are desired. In addition, there is not a sufficient understanding of the underlying reaction pathways, which has prevented a quantitative prediction of the full product distribution (Yu *et al.*, 2011).

ii. Gasification

Air in this process is used as a gasification agent, which demonstrates a number of advantages. The main advantage of using air instead of O_2 alone is to simplify the process and reduce the cost. But a disadvantage is the presence of (inert) N_2 in air which causes a reduction in the calorific value of resulting fuels due to the dilution effect on fuel gases. Hence, steam is introduced in a stoichiometric ratio to reduce the N_2 presence. A significant amount of char is always produced in gasification which needs to be further processed and/or burnt. An ideal gasification process for PSW should produce a high calorific value gas, completely combusted char, produce an easy metal product to separate ash from and should not require any additional installations for air/water pollution abatement (Yu *et al.*, 2011).

Early gasification attempts of plastics have been reported since the 1970s. The gasification into high calorific value fuel gas obtained from PSW was demonstrated in research stages and results were reported and published in literature for PVC, PP and PET. The need for alternative fuels has led for the co-gasification of PSW with other types of waste, mainly biomass (VijayAnanth *et al*., 2018).studied the fluidized bed co-gasification of PE, pine and coal and biomass mixed with PE. Yu *et al*. (2011) co-gasified five typical kinds of organic components (wood, paper, kitchen garbage, plastic (namely PE), and textile) and three representative types of simulated MSW in a fluidized-bed (400–800 ^{0}C). It was determined that plastic should be gasified at temperatures more than 500 ^{0}C to reach a lower heating value (LHV) of 10,000 kJ/N (VijayAnanth *et al*., 2018).

iii. Hydrogenation (Hydrocracking)

Hydrogenation by definition means the addition of hydrogen by chemical reaction through unit operation. The main technology applied in PSW recycling via hydrogenation technology is the Veba process. Based upon the coal liquefaction technology, VebaOel AG converted coal by this process into naphtha and gas oil. Major technologies are summarized in Yu *et al.*, 2011).

2.4 Plastic Waste Processing Machines

Recycling of paper as well as glass and aluminium containers have been recycled to some degree for many years now, and in more recent years plastic recycling has become common. In most plastic recycling operations, the first step after sorting is to shred and grind the plastic into chips, which are easier to clean and handle in subsequent steps (Adepo and Obanoyen, 2017). Plastic shredders are machines designed to cut or reduce large materials into tiny pieces for easy handling. The materials that can be shredded include syringe, glucose bottles, water bottles, pure water nylon, and many other items.

Some of the common types of plastic shredders are: single shaft plastic shredders, multiple shaft plastic shredders, high-speed-low torque plastic shredders, low-speed-high-torque plastic shredders, simple plastic shredders, and industrial plastic shredders (Adepo and Obanoyen, 2017).

Reddy and Raju (2018) developed a mini plastic shredding machine (Figure 2.3) which was powered with a 1.5 hp motor. Mild steel plate was used to produce the blades performing the shredding action. The blades were divided into two parts; the fixed and the movable blades. The movable blades are bolted on the blade carrying bars welded on the shaft while the fixed blades are bolt on the edge of the lower hemisphere of the cutting chamber.

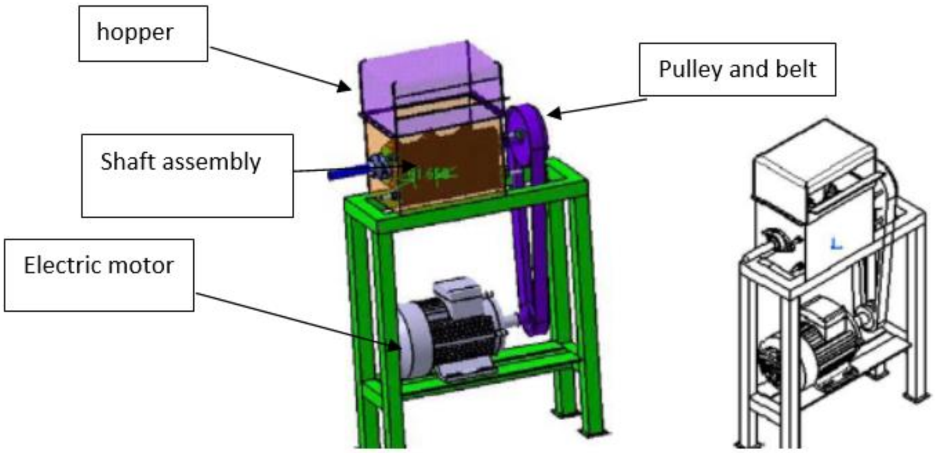

Figure 2. 3: Mini Shredder with Single Shaft (Reddy and Raju, 2018)

Adepo and Obanoyen (2017) developed a shredding machine whose optimum velocity needed to run it was found to be 11.5 m/s. The machine was designed to shred nylon materials and had 97 % efficiency recorded from the performance evaluation. However, results of the experiments were not presented. The efficiency was determined using Equation (2.1).

$$efficiency = \frac{output}{input} \times 100\ \% \tag{2.1}$$

Extensive design analysis was conducted while designing the machine. Part of the components designed for were drive pulley, belt tension, power determination using belt tensions and drive shaft diameter. Equation (2.2) was used to determine the power transmitted by the belt according to Adepo and Obanoyen (2017), while Equation (2.3) was used to determine the speed of the belt on the driven pulley.

$$P = (T_1 - T_2)V \tag{2.2}$$

Where T_1 and T_2 are the tension in tight side and slack side respectively and V is the speed of the driven pulley.

$$V = \pi \frac{d_2 N_2}{60} \tag{2.3}$$

Where d_2 is the diameter of the driven pulley, N_2 is speed of the driven pulley.

VijayAnanth *et al*. (2018) included gear in their design. The gears transmit the rotation between both shafts shown in Figure 2.4.

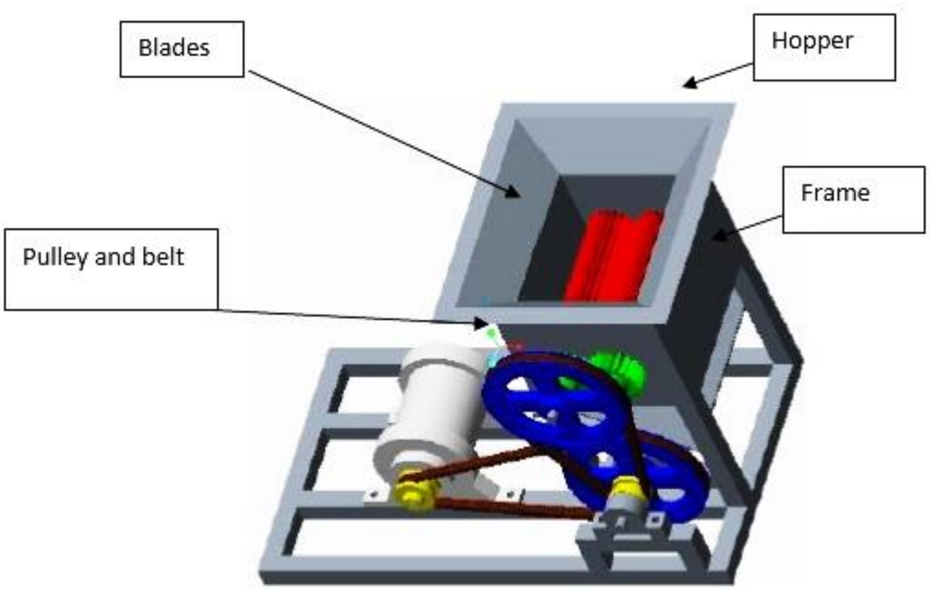

Figure 2.4: Isometric View of Shredder(VijayAnanth *et al*., 2018)

The number of driver and driven gear teeth are 50 and 70 respectively. A 2 hp motor was selected from after the necessary design analysis carried out. VijayAnanth *et al*. (2018) opted to use Equation (2.4) to determine power required to drive the machine.

$$P = \frac{2\pi NT}{60} \tag{2.4}$$

Where T is torque and N is speed of electric motor. Equation (2.4) can also represented in terms of force as shown in Equation (2.5).

$$P = \frac{2\pi mrN}{60} \tag{2.5}$$

Where m is the mass of shaft and r is the distance of blade end from centre of shaft. VijayAnanth *et al*. (2018) suggested that the blade tips be strengthened by coating with the help of a carbide tool. The blades were arranged on both shafts in such a way that each had a total of nine blades. A space was provided between the blades in the design to allow the shredded materials to fall.

The motor is controlled by a switch for the forward and reverse rotation of blades. This is done by controlling the Double Pole and Double Throw switches that operate in forward as well as in reverse directions of the motor. Then the motor is switched on to the forward rotation and the power is transferred to the smaller pulley by means of the shaft coupled to it.

The shredder developed by David and Joel (2018) was capable of delivering an end product of 10 – 20 mm size. With a hopper size determined to be 0.0063 $m^3$the machine was able to accommodate over 25 kg of waste and shred within 43 s using a shredding force of 690 N. The shredding rate and efficiency were determined using Equations (2.6) and (2.7).

$$shredding\ rate = \frac{Average\ weight}{Average\ time} \tag{2.6}$$

$$shredding\ efficiency = \frac{mean\ weight\ of\ shredded\ plastic\ wastes}{mean\ wreight\ of\ plastic\ wastes} \tag{2.7}$$

2.5 Components of Plastic Wastes Recycle Machine

The major components in the machine are hopper made from mild steel plate of 0.22 mm and angle bar of 0.33 mm for rigidity, a shredding chamber made with thick mild steel plate of 0.610 mm thickness and that of 0.33 mm thickness, a mesh made of steel wires used to regulate the shredded plastic sizes, a cover plate and a fly wheel. The flywheel was incorporated to resist changes in speed and help steady the shaft rotation and uneven torque. The fly wheel as defined by David and Joel (2018) is a hevy material attched to a drive shaft having most of its weight concerntrated at the circumference. David and Joel (2018) used Equation (2.8) to determine the volume of the machine hopper unit.

$$machine\ hopper\ volume = \frac{weight\ of\ plastic\ material}{bulk\ density\ of\ plastic\ material \times g} \quad (2.8)$$

Jadhav *et al*. (2018) used a speed of 50 rpm to drive the main shaft of their machine, the speed was reduced from a motor speed of 1440 rpm. Th study was also able to determine the percentage reduction in volume of the waste plastic using Equation (2.9).

$$percentage\ rdeduction\ in\ volume = \frac{initial\ volume - final\ volume}{initila\ volume} \quad (2.9)$$

Yu *et al*. (2011) carried out performance analysis of the designed and fabricated plastic crushing machine from locally sourced materials. The machine made used belt drive mechanism with single shaft. The results of the analysis showed that the machine has efficiency of 85.16 % while the average machine through put capacity was calculated to be 0.112 kg/s. the machine can be considered efficient enough to be used for domestic and industrial purposes from the results obtained.

VijayAnanth *et al*. (2018) developed a plastic shredding machine which uses gear mechanism for its operation. The machine was meant to shred low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP) and polystyrene (PS) based plastics to smaller flakes with the dimension of about 10 mm long and 1 mm wide. The power needed to cut the plastic was determined to be 2.34 hp. However, no information about the efficiency of the machine was given.

Bansal (2010) developed a waste plastic shredder whose drive mechanism combined the belt and gear drives to provide greater efficiency. The machine performance was evaluated for four categories of waste plastic. These include low density polyethylene (LDPE), high density polyethylene (HDPE), polyvinyl chloride (PVC) and polyethylene therephthalate

(PET). The machine was observed to have low shredding efficiency of 60 % for LDPE and high efficiency ranging between 90-96 % for HDPE, PVC and PET.

Bansel (2010) designed and fabricated a low-cost plastic shredding machine which made use of belt drive mechanism with a single shaft. Compressed plastic bottles and other plastic waste materials were used to evaluate the performance of the machine after fabrication. It was observed that the efficiency of the machine remains relatively constant at at 97 % with the variations in the mass of the plastic waste introduced into the machine for shredding.

Bansel (2010) designed a plastic shredding machine to obtain small plastic waste to help to be dedicated to the recycling industry in an automated way. The machine was designed to shred either of the following types of plastic: polyethylene therephthalate (PET), high density polyethylene (HDPE), low density polyethylene (LDPE), polyvinyl chloride (PVC) or others (plastic mix).

2.5 Summary/Research Gap

Shredding of plastic is a crucial step in the recycling process of plastic materials and the machines available for the execution of this task are bulky, expensive and scarce hence, the need to develop portable machine like this project that can be affordable by small scale entrepreneurs and perform the shredding operation properly becomes necessary. The continuous development of plastic shredding machine is inevitable until there is locally produced shredder that will have competitive efficiency as the available ones in the market.

This machine has been developed with less moving parts to reduce the cost and deliver higher torque required for shredding. For example, the machine does not have pulley system but rather a geared electric motor assembly directly attached to the shafts.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

The materials used for fabrication of the machine are:

1. Mild steel sheet for the hopper, main enclosure the chute and the screen.
2. Mild steel plate for the cutters.
3. Mild steel rod for the shafts.
4. Angle bars for the frame.
5. Electric motor

The equipment used for the fabrication and testing of the machine are an electric welding machine (MAXMECH TG/MMA-400,400A, 380 volts) to make permanent joints in the machine parts, a centre lathe for turning and facing operations of various machine components such as the blades, and an angle grinder (CTWIN model with 125 mm grinding disc diameter) for grinding rough welded surfaces of the machine.

3.2 Methods

3.2.1 Description and working principle of the machine

The shredder has a double shaft design where the blades are attached to. The shafts are rotated in the opposite direction to one another via a gearbox assembly, as the rotation occurs the blades rip and shred the plastic introduced to the hopper into pieces. The major components of the machine are the hopper, crushing chamber containing the shafts and blade assembly and gearbox to deliver the required high torque for the shredding.

3.2.1 Design analysis of the shredding machine

The design analysis involves the design specification, determination of the power required for shredding and power required for driving the machine components, determination of the shaft diameter and selection of the size of the bearings to be used.

3.2.1.1 *Design specification*

Waste plastics of high-density polyethylene (HDPE) with density 960 kg/m^3 (Khalaf, 2012) were collected from refuse dump site, Panteka, Bida, Niger State for analysis and evaluation. Table 3.1 showed the material properties of high-density polyethylene. The machine is capable of shredding HDPE to the desired dimension. The schematic sketch of the designed shredding machine is depicted in Figure 3.1; it is driven by two shafts with blades arranged in such a way to provide optimum shredding. Standard shaft diameters provided by Khurmi and Gupta (2005) will be selected for the machine as appropriate.

Table 3.1: Material Properties of HDPE

S/N	Property	Value
1	Melting point	110-140 ^{0}C
2	Specific gravity	0.9-1.0
3	Density	0.9-1.0 g/cm^3
4	Volatile matter (wt)	<0.1%
5	Water absorption(wt)	0.05%
6	Melt flow index	6 g/10 min (2.16 kg at 190 ^{0}C)

(Source: Khurmi and Gupta (2005)

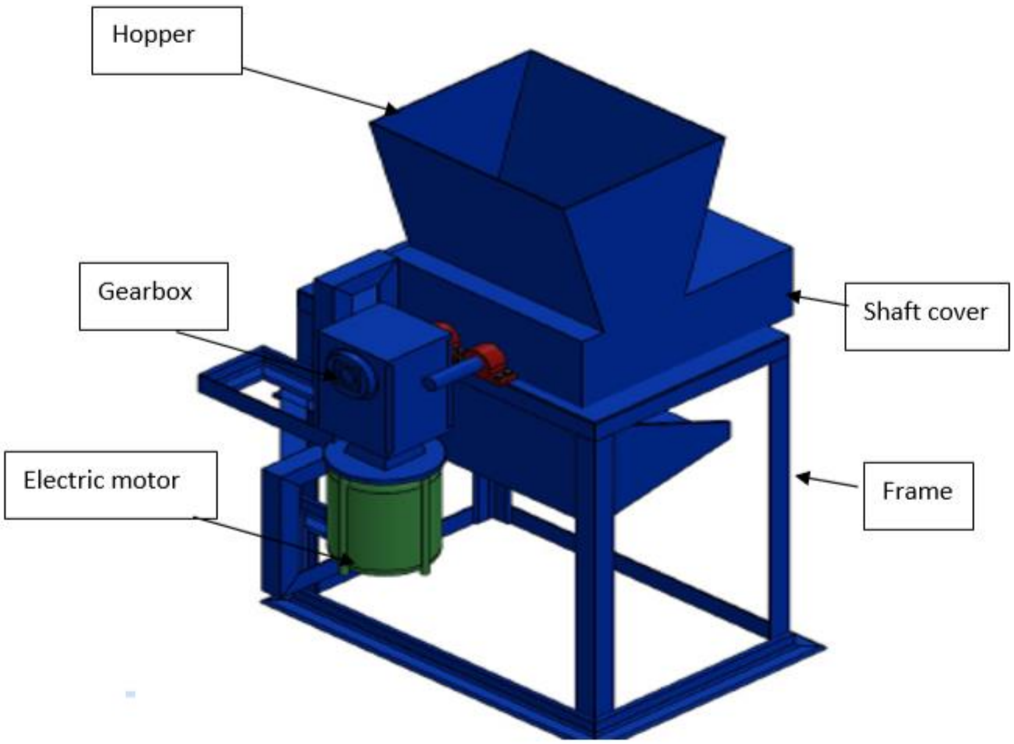

Figure 3.1: Schematic of the Designed Plastic Shredder

3.2.1.2 *Determination of hopper volume*

The volume of the frustum shaped hopper depicted in Figure (3.2) can be determined using Equation (3.1) as given by Olukunle (2016).

$$v_{hopper} = \frac{h}{3}\left(Area_{big} + Area_{small} + \sqrt{Area_{big} \times Area_{small}}\right) \tag{3.1}$$

Where v_{hopper} is the hopper volume in m^3, $Area_{big}$ is the area of the upper pyramid base in m^2, $Area_{small}$ is the area of the lower pyramid base in m^2. The pyramid bases are rectangular shaped.

$Area_{big}$ =0.5 ×0.42 = 0.21 m^2

$Area_{small}$ = 0.42×0.36 = 0.1512 m^2

The values are substituted into Equation (3.1).

$$v_{hopper} = \frac{0.2}{3}\left(0.21 + 0.1512 + \sqrt{0.21 \times 0.1512}\right)$$

v_{hopper} =0.036 m^3

3.2.1.3 *Determination of power required for shredding*

The design commenced by determining the power required to shred the HDPE material. First the volume that will be fed to the machine for a single operation is determined from the hopper and crushing chamber volume.

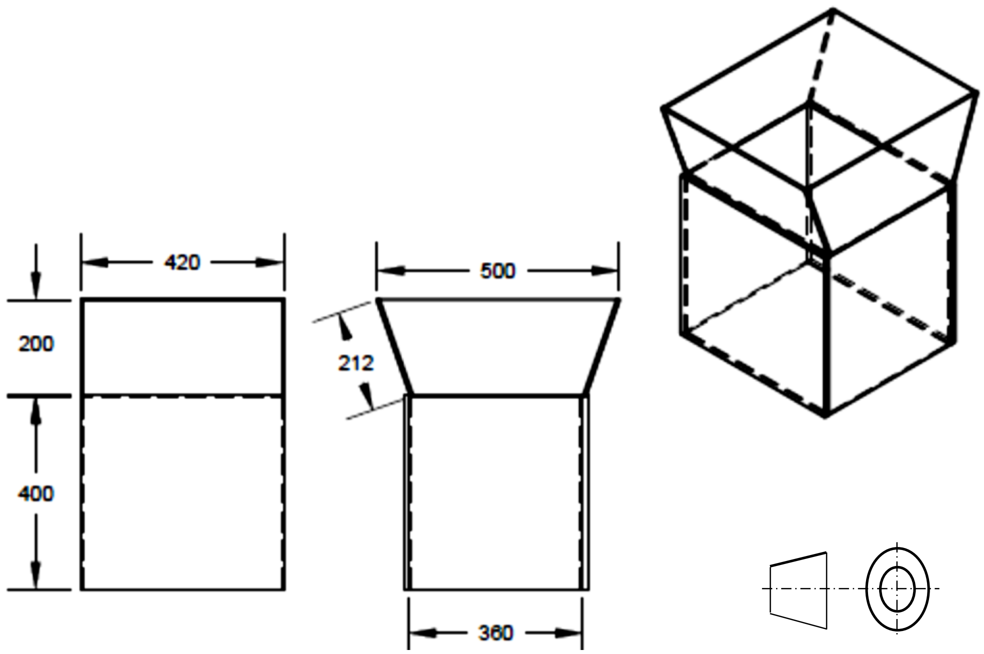

Figure 3.2: Hopper and Crushing Chamber (all dimensions are in mm)

The shredding chamber is assumed to be filled to about two-third giving room for the blade assembly. The shredding chamber is rectangular shaped, the volume given by multiplying the three lengths.

Shredding chamber volume = 0.4 × 0.42 × 0.36 = 0.06048 m^3

Two-thirds of that is 0.06048 × 0.67 = 0.0405 m^3

The total volume of plastic to be shredded at a single operation v_t,

v_t = 0.036 + 0.0405 = 0.0765 m^3.

The weight of HPDE plastic to be shreddedw_{HDPE} is given by Equation (3.2) as provided by Olukunle (2016).

$$w_{HDPE} = v_t \times \rho_{HDPE} \times g \text{ (N)} \tag{3.2}$$

Where,

ρ_{HDPE} = the density of HDPE plastic (960 kg/m^3 (Khalaf, 2012))

g = acceleration due to gravity (9.81 m/s^2).

$w_{HDPE} = 0.0765 \times 960 \times 9.81$

$w_{HDPE} = 720.45$ N

Assuming blade is not to shear relative to plastic (to be shredded) then the force required to shred must be greater than or equal to the weight obtained (Sulaiman *et al*., 2017). That is,

$\text{Force}_{\text{shredding}} \geq \text{Force}_{\text{HDPE}}$

Shredding force is determined to be ≥ 721 N

The blade torque, T_b is obtained according to Akash *et al*. (2019) using Equation (3.3).

$$T_b = \text{Force} \times \text{Perpendicular distance} \tag{3.3}$$

The blade length as shown in Figure 3.3 is the perpendicular distance.

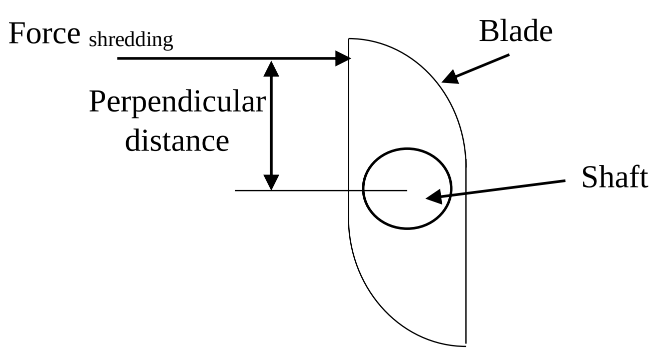

Figure 3.3: Shredding Force Acting on Blade Edge

Perpendicular distance and force are 0.075 m and 721 N respectively, the torque is obtained as 54.075 Nm. (Olukunle, 2016) provided the required shredding speed as 300 rpm, so the power required can be obtained using Equation (3.4) as provided by Khurmi and Gupta (2005).

$$P = \frac{2\pi N T_b}{60} \tag{3.4}$$

Where N is the shredding speed.

$P = \frac{2\pi \times 300 \times 54.075}{60} =$ 1698.8W or 2.28 hp

The minimum required power to shred the plastic is 2.28 hp, but considerations must be given to the power required to drive the machine components.

3.2.1.4 *Power required for driving machine components*

The material considered for the blade and shaft is mild steel with density of 7860 kg/m^3 (Manik *et al*., 2012). Mild steel was considered due to its high strength and availability. The blade is machined from a cylindrically shaped mild steel plate of radius 0.075 m and thickness of 0.004 m. The volume of a cylinder is given by Equation (3.5) (Barderas *et al*., 2016).

$$V = \pi r^2 h \ (\text{m}^3) \tag{3.5}$$

Where r is the radius in m and h is the thickness in m (in this case). The volume is obtained as 7.07× 10^{-5}m^3. The mass can be obtained from the relation given in Equation (3.6) as given by Manik *et al*. (2012).

$$m = \rho V \tag{3.6}$$

Where ρ is density of the blade material (7860 kg/m^3) and m is the mass of the blade in kg. The mass is therefore obtained as 0.56 kg. From the design drawing, a total of 14 pieces will be needed for the blade assembly, so 0.56 × 14 = 7.84 kg.

The total weight is 7.84×9.81 m/s^2 = 5.5 N

Using Equation (3.3) and radius 0.075 m, the torque is 0.4125 Nm and using Equation (3.4) the power can be obtained as 12.96 W or 0.017 hp. Adding both powers obtained gives 1698.8 + 12.96 = 1711.8 W or 2.3 hp.

Considering a service factor is paramount so that enough power will be designed for to avoid overheating of electric motor and premature motor failure; the design power can be obtained using Equation (3.7) as provided by Sulaiman *et al*., (2017). Service factor of 1.5 is used.

Design power = Service factor × required power (3.7)

Design power = 1.5 × 1711.8 = 2567.7 W or 3.44 hp

The efficiency of an electric motor is given by Equation (3.8) (Sulaiman, *et al*., 2017).

$$\eta_m = \frac{P_{out}}{P_{in}} \quad (3.8)$$

Where P_{out} and P_{in} are powers input and output of the electric motor in Watts. For a 2.6 kW motor efficiency of 78 % (Yu *et al*., 2011) was adopted.

$P_{in} = \frac{2567.7}{0.78}$ =3291.9 W or 4.4 hp

The power determined is 4.4 hp therefore a 5 hp motor is selected for the machine.

3.2.1.5 *Determination of shaft diameter*

The diameter of a shaft can be determined from the American Society of Mechanical Engineers ASME design code as used by Egbe and Olugboji (2016).

$$d^3 = \frac{16}{\pi S_s}\sqrt{(Mk_b)^2 + (T_s k_t)^2} \quad (3.9)$$

Where, S_s is the shear stress, and it is taken as 42 MN/m^2. M and T are bending and twisting moments respectively. Egbe and Olugboji (2016) combined shock and fatigue bending (K_b)

and torsion (K_t) factors for suddenly applied load, minor shock are 1.5-2 and 1-1.5 respectively (Egbe and Olugboji, 2016).

The bending moment was first obtained by ascertaining the total weight acting on the shaft, which was obtained as 721 + 5.5 = 726.5 N. This weight is considered to be uniformly distributed on the shaft as the blade distances are minimal. The forces acting on the shaft are depicted in Figure 3.4).

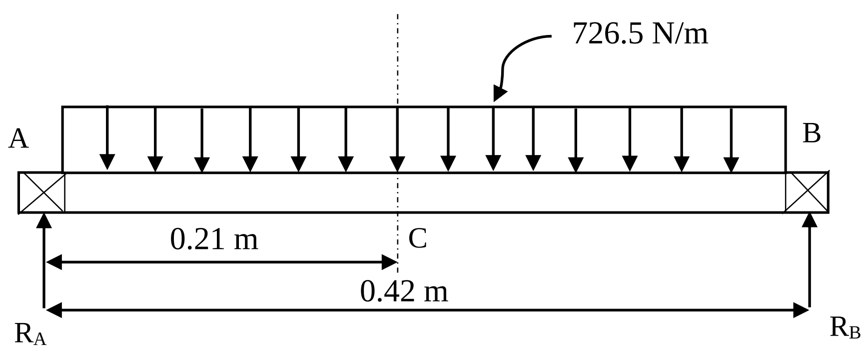

Figure 3.4: Free Body Diagram of forces acting on the Shaft

Reactions at point A and B are given by Equation (3.10) as stated by Bansal (2010).

$$R_A = R_B = \frac{wL}{2} \tag{3.10}$$

Where R_A and R_B are reactions at point A and B, w is the load acting on shaft and L is the length of shaft. So, R_A and R_B are obtained as 152.6 N. The shear force at a point say 0.105 m is given by Equation (3.11) as derived by Bansal (2010).

$$F_{0.105} = +R_A - w(0.105) \tag{3.11}$$

$$F_{0.105} = 152.6 - 726.5(0.105) = 76.32 \text{ N}$$

Shear forces at point A, B and C are described in Equations (3.12), (3.13) and (3.14) as given by Bansal (2010).

$$F_A = +\frac{wL}{2} \tag{3.12}$$

$$F_B = -\frac{wL}{2} \tag{3.13}$$

$$F_C = 0 \tag{3.14}$$

Therefore, the shear forces at points A, B and C are 152.6, -152.6 and 0 N respectively.

For the bending moment analysis, bending moment at a point say 0.105 m is obtained using Equation (3.15) as derived from Bansal (2010).

$$M_{0.105} = +R_A(0.105) - \frac{w(0.105)^2}{2} \tag{3.15}$$

$M_{0.105}$ = 16.023 – 4.0048 = 12.02 Nm

For points A and B their bending moments are 0 Nm and for C the bending moments is given by Equations (3.16) as derived from Bansal (2010).

M_A = 0 Nm

M_B = 0 Nm

$$M_C = +\frac{wL^2}{8} \tag{3.16}$$

M_C =16 Nm

The diagrams for shear force and bending moment for the shaft are given in Figure 4.1.

From Equation 3.20 the diameter of the shaft can be determined using bending moment, M = 16 Nm and twisting moment, T = 54.075 Nm as determined earlier using Equation (3.3). The K_b and K_t are selected as 1.5 and 1.2 as the shock on the shaft is minor.

$$d^3 = \frac{16}{\pi \times 42 \times 10^6}\sqrt{(16 \times 1.5)^2 + (54.075 \times 1.2)^2}$$

$d^3 = 0.00000838881$

d = 0.02032 m or 20 mm

Two shafts of 25 mm diameter are selected for the machine from standard shaft dimensions provided by Khurmi and Gupta (2005).

3.2.1.6 *Material selection and costing*

For this design, mild steel was selected for the frame and major components like the hopper and cutters. Khurmi and Gupta (2005) have suggested the consideration of three factors when selecting a material for design; its availability, suitability for the working condition and the material cost. Metals have excellent strength, stiffness and ductile properties desired for this machine. Mild steel can be easily shaped to form different components and machined with considerable ease. The cost of mild steel is also low, hence the choice for selecting it for the machine. The shaft diameter selected was 25 mm, so a bearing of type 205 was selected from Table 3.2 as provided by Khurmi and Gupta (2005).

Table 3.2: Principal Dimensions for Radial Ball Bearings

Bearing No.	Bore (mm)	Outside dia. (mm)	Width (mm)
205	25	52	15
305	25	62	17
405	25	80	21

(Khurmi and Gupta, 2005)

3.2.2 Fabrication of the shredding machine

3.2.2.1 *Frame*

An angle iron of 50 × 50 ×4 mm was used for the frame. The frame is where all other parts are fixed by means of bolts and nuts for easy maintenance. Hacksaw was used to cut the bars to specification and the electric arc process was used to create permanent joints between the bars (drawing number 004 in the appendix).

3.2.2.2 *Hopper*

The hopper is the component that is used to feed the machine. It is shaped like a funnel, so that easy and controlled movement of plastic feed can be maintained. 1.5 mm sheet metal was used for fabricating the hopper; the edge of the hopper was hemmed to prevent injury during feeding (drawing number 004 in the Appendix).

3.2.2.3 *Shaft*

Two sets of shafts of 25 mm diameter were used in the machine. The shafts are designed to carry the cutters. The cutters are to rotate inward simultaneously so as to 'clutch' the plastic and shred consequently. The shaft was machined on the lathe using orthogonal cutting method for machining (drawing number 005 in the Appendix).

3.2.2.4 *Cutters*

Mild steel of diameter 140 and thickness 8 mm was used to fabricate the cutters. A set of 10 cutters each have been arranged on each shaft, totalling 20. Additional stationary fixtures are welded in the shredding chamber to aid with the shredding process. The cutters were cut to shape using a mechanical saw and then grinding thereafter. It was then machined on the lathe using orthogonal cutting method (drawing number 005 in the Appendix).

3.2.2.5 *Gears*

A set of 100 mm involute spur gears have been incorporated in the system to deliver the opposite directional movement required for the cutters via the shafts. The gears power the first cutter (say) clockwise the second cutter will be driven anticlockwise alternately.

3.2.2.6 *Screen*

This was fixed underneath the cutters assembly. The shredding must go through a complete cycle multiple times till the shredded particles have reached the desired dimension before they can be allowed to pass down from the shredding chamber. The holes for the screen were made using a hand drilling machine.

3.2.2.7 *Electric motor*

This is required to provide the power that drives the whole system. To increase the torque a geared motor was selected for the machine.

3.2.3 Bill of engineering measurement and evaluation

The cost incurred during fabrication of the machine is given in Table 3.3, however, the details are indicated from 1 to 10 respectively.

Table 3.3: Bill of Engineering Measurement and Evaluation

S/N	Material	Quantity	Unit cost (₦)	Cost (₦)
1.	Shredding teeth	10	5,000	50,000
2.	Shaft	1	12,000	12,000
3.	Angle iron	3	5,000	15,000
4.	2mm plate	½ sheet	7,500	3,750
5.	Gear motor 3hp	1	60,000	60,000
6.	Bolt and Nuts		1,000	1,000
7.	Cutting/grinding disc	3	1,000	3,000
8.	Electrode	1 pack	3,000	3,000
9.	Bearing	4	2,000	8,000
10.	Painting	2 tins	4,000	8,000
	TOTAL			136,250

3.2.4 Performance evaluation procedure of the shredding machine

2 kg of each of polyethylene therephthalate (PET), expanded polystyrene (EPS) and high-density polyethylene (HDPE) were collected for the testing. The test samples were divided into two samples for the performance evaluation. Each of the 1 kg samples were shredded in the machine with a gearbox of ratio 1:15 and ratio 1:22 using speed ranges suggested by Ejiko *et al*. (2022). Hence, the machine was tested to evaluate its shredding performance at

constant driving shaft speed of 194 rpm and 132 rpm respectively. This speed was reduced from a motor speed of 2910 rpm.

The different quantities of these plastic categories were measured before and shredding to determine the efficiency of the machine for each category. The efficiency (η) of the shredding machine for each of the categories of the plastic materials was calculated using Equation (3.17).

$$\text{Efficiency } (\eta) = \frac{Output\ Quantity}{Input\ Quantity} \times 100\ \% \tag{3.17}$$

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Results

4.1.1 Results of the design calculations

The results of the design calculations are shown in Table 4.1 while the shear force and bending moment diagrams are depicted in Figure 4.1.

Table 4.1: Results of the Design Calculations

S/N	Design Parameter	Value
1	Volume of hopper	0.036 m^3
2	Volume of plastic to be shredded in single operation	0.0765 m^3
3	Shredding force	721 N
4	Blade torque	54.075 Nm
5	Shredding power	2.28 hp
6	Machine parts driving power	0.017 hp
7	Design power	3.44 hp
8	Shaft diameter	25 mm
9	Maximum shear force	152.6 N
10	Maximum bending moment	16 Nm
11	Bearing selected number	205

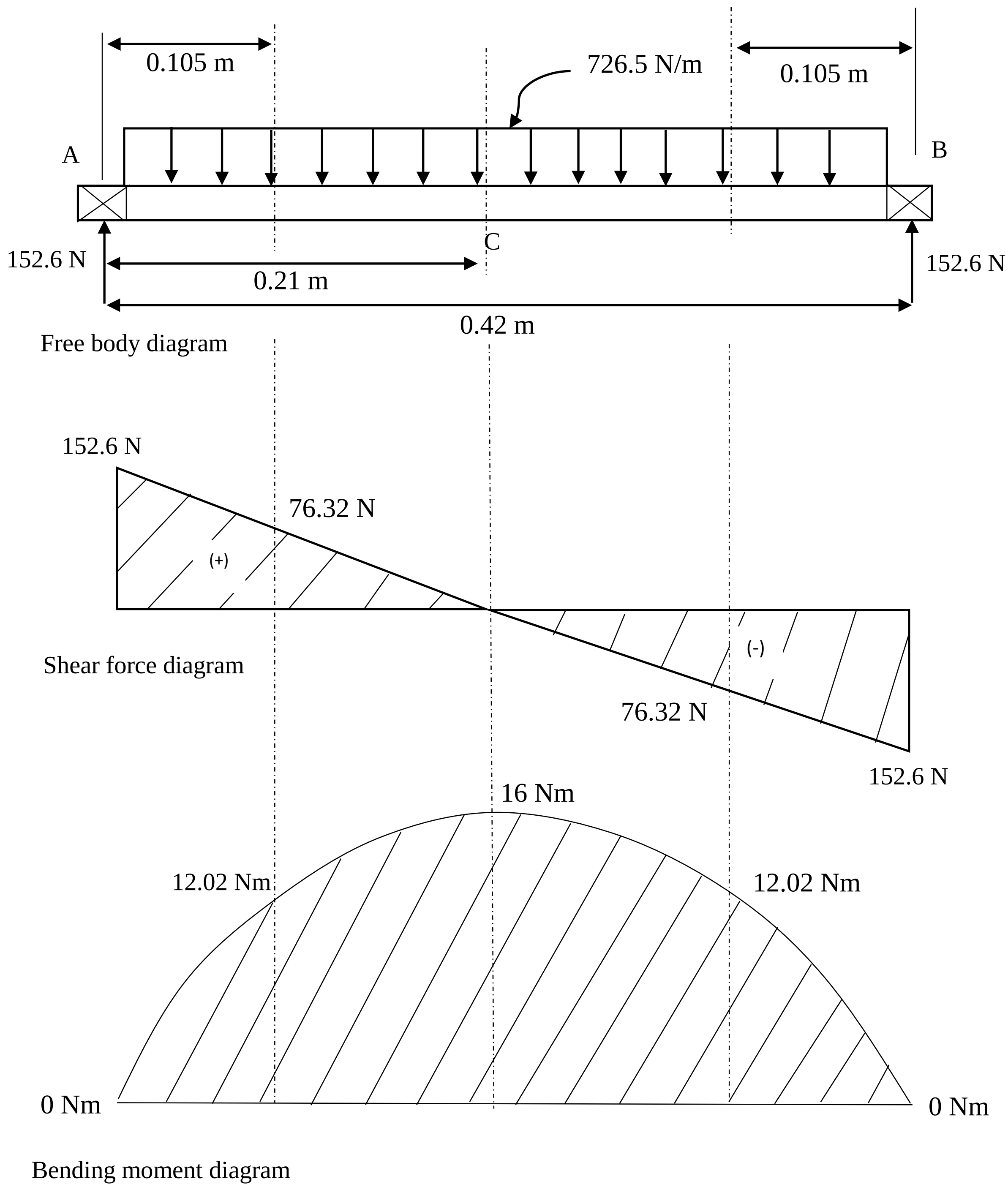

Figure 4.1: Shear Force and Bending Moment Diagrams for the Shaft

4.1.2 Assembly of the machine developed

Plate I showed the assembly of the developed shredding machine.

Plate I: Assembly of Developed Shredding Machine

4.1.3 Results of the performance evaluation of the machine developed

Table 4.2 showed the results of the performance evaluation of the machine developed.

Table 4.2: Performance Test Results of the Shredding Machine using of 194 rpm

S/NO	Plastic Category	Input Quantity (kg)	Output Quantity (kg)	Efficiency (%)
1	PET	1	0.6975	69.75
2	EPS	1	0.7385	73.85
3	HDPE	1	0.8974	89.74

Table 4.3: Performance Test Results of the Shredding Machine using of 132 rpm

S/NO	Plastic Category	Input Quantity (kg)	Output Quantity (kg)	Efficiency (%)
1	PET	1	0.7320	73.20
2	EPS	1	0.7410	74.10
3	HDPE	1	92.24	92.24

4.2 Discussion of Results

4.2.1 Shear force and bending moment diagrams

Figure 4.1 is an example of simply a supported beam carrying uniformly distributed load of w/m over the whole span of the shaft. By symmetry each support reaction is equal. That is, reactions at both ends of the shaft are the same. This was calculated to be 152.6 N from Equation (3.10). The shear force (S.F.) at mid-position of the shaft (where x=L/2) equals zero. This was determined using Equation (3.14). It is observed from Figure 4.1 that the shaft continually resists a maximum shear force of 152.6 N.

Bending moment (B.M.) at both ends of the shaft equals zero while the B.M. at mid-position is maximum with a value of 16 Nm. These values were determined using equations (3.15) and (3.16) respectively.

4.2.2 Assembly of the machine developed

The hopper of the machine was bolted to the cutting unit housing. The shaft and the cutting blades assembly were placed in the cutting unit housing and supported on bearings that were bolted to the frame of the machine. The shaft assembly is rotated by the gearbox which is also driven by the electric motor that serves as the prime mover. The meshing gears should be lubricated periodically to avoid wearing of the gear teeth and to eliminate or reduce noise that will be produced from meshing gears when in operation.

4.2.3 Performance evaluation of the machine developed

It could be observed from Tables 4.2 and 4.3 that the efficiencies of the fabricated plastic shredding machine for PET, EPS and HDPE are 71.5 %, 74.0 % and 91 % respectively. The variations in the values of the efficiency of the machine for the different plastic materials may be attributed to the disparities in their mechanical properties (Raji *et al*., 2020). The different quantities of the waste plastics introduced into the machine for shredding was based on the quantities available as at the time of testing. However, regardless of the variations in the mass of the waste plastic introduced into the machine for shredding, the efficiency of the machine will remain relatively constant as observed by Chinedu (2018). Also seen from comparing the results in both tables, the values obtained using 132 rpm produced higher efficiencies, hence the optimum speed is 132 rpm for the machine.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The following conclusions were drawn:

A shredding machine for crushing thermoplastic materials and having a hopper of volume of 0.036 m^3 was successfully designed.

The designed machine was successfully fabricated. This was aimed at eliminating the problem of environmental pollution caused by indiscriminate littering and dumping of plastic waste materials.

The developed shredding machine was tested to evaluate its shredding efficiency. The shredding performance of the machine for PET, EPS and HDPE gave efficiencies as 69.75 %, 73.85 % and 89.74 % respectively. These results showed that this machine will be suitable for small scale waste plastic recycling plant.

5.2 Recommendations

The followings are recommendations further work:

1. The machine developed is recommended for shredding of plastic waste materials in a small scale plastic recycling plant.
2. Environmental pollution caused by indiscriminate littering and dumping of plastic waste materials should be prohibited.
3. The developed machine could be further calibrated with varying quantities of batching testes.

5.3 Contributions to Knowledge

This work has been able to use locally sourced materials to develop a shredding machine for crushing waste plastics, shredding efficiency of 89.74 % for high density polyethylene (HDPE).

The publications from this work could serve as literature material for research studies in related areas.

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APPENDIX A
ISOMETRIC VIEW OF THE SHREDDING MACHINE

APPENDIX B
ORTHOGRAPHIC VIEWS OF THE SHREDDING MACHINE

APPENDIX C
EXPLODED VIEW OF THE SHREDDING MACHINE

APPENDIX D
ISOMETRIC VIEW OF THE MACHINE COMPONENTS (NO. 004)

APPENDIX E
ISOMETRIC VIEW OF THE MACHINE COMPONENTS (NO. 005)

APPENDIX F
ISOMETRIC VIEW OF THE MACHINE COMPONENTS (NO. 006)