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FINITE ELEMENT ANALYSIS OF PLASTIC RECYCLING MACHINE DESIGNED FOR PRODUCTION OF THIN FILAMENT COIL

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ABSTRACT
This paper presents the conceptual design of plastic recycling machine for production of thin filament coil. The machine is meant to serve as a sustainable means of converting waste Polyethylene Terephthalate (PET) plastic materials into thin filaments to be used as feedstock material in Fused Deposition Modeling (FDM) machine. The machine design consists of a shredder hopper, two shredder shafts with knife-edge ring cutters, extruder hopper, extrusion barrel with heater jackets and extrusion auger shaft. The design analysis of each of the machine elements was done and structural integrity of the machine design was evaluated using finite element analysis (FEA) tool in Solid Works Computer Aided Design (CAD) application. The FEA result indicated that a maximum stress of 33 MPa was reached in one of the machine frame members when loads mounted on top and below the frame structure are 1204 N and 271 N respectively. The maximum resultant displacement in the member frame was 0.34 mm and the minimum factor of safety obtained was 8.3. Also, a minimum factor of safety value of 5.3 was obtained for shredder shaft between when subjected to a torque of 1000 Nm and it experienced an angle of twist of 0.42^o and a maximum stress of 46.8 MPa. The implication of the result is that the design of the machine is adequate and the machine will fulfill its intended purpose upon fabrication, as the yield strengths of selected materials for the fabrication of the machine members are not exceeded.

Keywords: *Plastics; Machine; Design; Recycling; Sustainability; Finite Element; Simulation*

1. INTRODUCTION

Plastics have become an integral part of society since 1950s when its mass production commenced and their usage have continued to increase with growth in population, standard of living and technological development [1]. Over the years, plastics have become choice materials for product designers and developers, owing to the fact that different shapes of components are easily manufactured from plastic materials, which are made to replace metal, wood, paper and glass components where appropriate for diverse engineering applications [2]. The tremendous uses range from domestic to industrial applications, which include: refrigerator parts, vehicle parts, credit cards, computers, calculators, milk jugs, shampoo and cosmetic bottles, detergent plastic bottles, plastic containers for storage of chemicals, lubricants and oil-based materials, cosmetics, toys, and patterns for investment casting amongst others etc.

However, the increasing usage of plastics has caused some substantial environmental pollution burden on both land and water habitats [3], as plastics, which are mostly non-biodegradable, takes up large space in landfills [4]. Hence, there is need for a process whereby some of the plastics, that are recyclable, are processed for reuse, which is the focus of this study. Hopewell, *et al.* [5] noted that majority of the plastic produced each year are for either disposable packaging materials or short-lived items, which are disposed within a short period of time, thus making plastic usage unsustainable. It has also been noted that recycling is the most promising action necessary to reduce environmental impact of plastic waste, as it reduces oil usage, carbon dioxide emissions and waste quantity to be disposed. Governments of different developed countries of the world have been legislating policies on plastics recycling waste management system to curb the menace of the increased waste plastics on their environment [2,6]. Amongst various plastic material, PET plastics are mostly recyclable and are been used to as container for bottled water, fruit juice and beverages, however, these plastic containers are sometimes left to litter the environment. Moreover, most of the used or waste plastics are burnt in incinerators or taken away for landfills which is not appropriate from the sustainability point of view.

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The production of new plastics from their raw materials requires a large amount of energy, and since majority of the plastics are non-biodegradeable, they often constitute nuisance to the environment after used [7]. In order to preserve our environment, there is a need for the development of sustainable means to manage plastic wastes generated from our local communities and industries, hence making recycling of plastics an important aspect of waste management [8]. For the recycling process to be sustainable, it must be cost-effective, i.e. economical, and must be able to solve the environmental problem created by the waste plastics without creating any new problems such as air, water or land pollution. Thus, an efficient recycling structure needs to be put in place to process some of these waste plastics, which are supposed to have been disposed by landfills or burnt in incinerators, into useful materials [9].

Majority of plastics recycling machine are imported and costly, hence there is need to locally develop a recycling machine from locally sourced materials to make their fabrication cheaper. In light of this, only limited work have been done on the development of plastic recycling machines. Ugoamadi and Ihesiulor [10] reported the design and fabrication of a plastic recycling machine using locally available materials, to recycle waste polythene bags, film sheets, PET bottles etc. In this study, gearing system was used to transmit power and it was suggested that for improved efficiency, belt and pulley system should be employed. It was also added that the finite element analysis should be used to simulate and analyse the reponses of the machine under the action of loads, which is one of the focus of this present study. It was claimed in the study that the machine recycling efficiency was 97% and its recycling capacity was 265 kg/hr. Odusote, *et al.* [11] reported the design and development of a motorised polythene and water nylon sachet recycling machine. The machine developed was able to achieve the shredding of polythene materials into flakes by heating up the polythene to soften them and then pass them through fixed and rotary blade assembly. The developed machine was able to produce 30-40 kg/hr of polythene shredded flakes in an hour. Odior, *et al.* [12] reported the development of polythene recycling machine from locally sourced materials. In this study, it was noted that heat required to soften the waste plastics to be shredded was generated as a result of friction during the operation of the machine. Kusekar, *et al.* [4] developed a pneumatically operated injection plastic moulding machine and the die assembly was simulated using ANSYS software to determine the stress, strain and temperature distribution across the die. The result obtained from simulation showed that the die assembly is approriate.

In order to solve the environmental problems associated with waste PET plastics, there is a need to design an efficient recycling machine that will shred, melt and extrude to produce other form of plastic materials that can be reuse. Hence, an improved design of the locally existing machine is inevitable. In one of the previous works, it was suggested that belt and pulley transmission system should be used for an improved efficiency of the recycling machine [10] and this has been adopted in the design presented in this study. The improved design has a two-stage processing unit cascaded such that the shredding unit can be operated independent of the melting and extrusion unit. Other previous works have addressed the shredding of plastics into flakes to be stored and later reuse. However, the plastic recycling in this work is targeted at the production of reel of thin plastic filament, which can be used as feedstock for production of additively manufactured components from Fused Deposition Modelling (FDM) machine. Fused deposition modelling is one of the additive manufacturing technologies, which utilises plastic filament fed through its heater-equipped extrusion head nozzle to produce plastic components layer by layer [13]. Hence, the aim of this present study is to conceptualise and design a plastic recycling machine to be used for recycling of waste PET plastics for production of thin plastic filament which will serve as feedstock for FDM machine. In the study, the finite element modelling tool is employed to simulate and analyse the critical machine members under the action of load.

2. MATERIALS AND METHOD

2.1 Design Concept

The plastic recycling machine consists of the shredding and the extrusion sections, equipped with two electric motors, which are mounted on a two-level frame as shown in the assembly view of the machine in Figure 1 with the component part list in Table 1. The shredding section, mounted on the top level of the frame, is made up of the hopper and two shredding shafts rotating against one another which are equipped with knife edge rings for cutting of PET plastic materials loaded into the hopper into smaller pieces called flakes. It is noteworthy that one of the shredder shafts is driven by an electric motor with the aid of belt and pulleys and allowed to rotate against the other shredder shaft held stationary. The extrusion section, mounted on the beneath level of the frame, is made up of a hopper, a chamber and an auger screw shaft. The extrusion chamber is equipped with a heater jacket and a thermostat to raise the temperature of the shredded plastic in the chamber to a molten state and maintain the molten temperature.

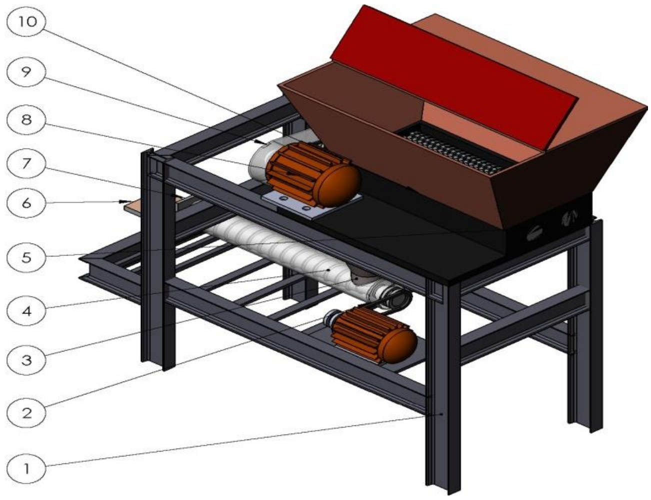

Figure 1: The assembly view of the recycling machine

Table 1: Bills of materials

S/N	Component part list	Quantity
10	Shredder Hopper	1
9	Motor Cover	1
8	1hp Electric Motor	2
7	Die breaker plate	1
6	Die plate	1
5	Shredder shaft	2
4	Auger screw shaft	1
3	Extruder hopper	1
2	Belt drive	2
1	Frame	1

The auger shaft is also driven by an electric motor with the aid of belt and pulleys. The plastic flakes are released through a channel below the shredder housing into the extruder hopper which allows the plastic flakes to be loaded into the extrusion chamber. The plastic flakes are heated to molten state in the extrusion chamber and with the rotation of the auger screw shaft in the chamber; the molten plastic is extruded through a hole in a die mounted in front of the extrusion barrel. The extruded thin plastic is made to pass through a water bath to cool its temperature and hence a reel of thin plastic filament is produced which would be used in Fused Deposition Modelling (FDM) machine. Figure 2 shows the orthographic view of the process plant.

2.2 Design Consideration

The followings were considered during the design of the plastic recycling machine:

(a) availability of local raw material for fabrication
(b) Simplicity in operation and easy to maintain
(c) Low cost of production

2.3 Material Selection

The selection of materials and component parts for the fabrication of the plastic recycling machine was based on the following considerations which include: physical and mechanical properties, availability of the materials, interchangeability, maintainability and cost. It is noteworthy that appropriate engineering materials were chosen to cope with the various load, stress, strain and torque to be experienced by various parts of the machine during operation. Table 2 shows the list of materials selected for the fabrication of the plastic recycling machine with the criteria for selection.

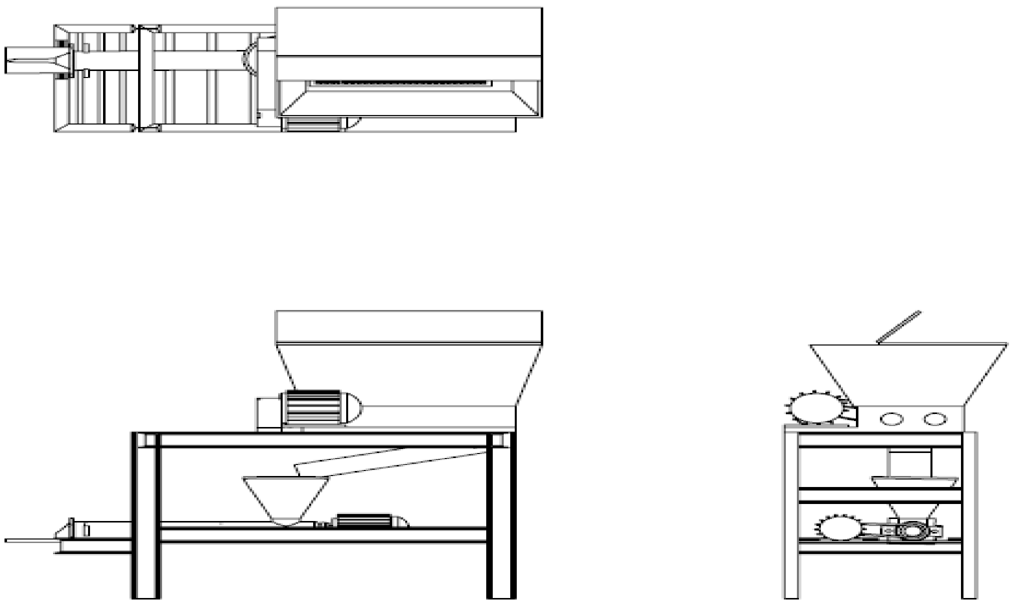

Figure 2: Orthographic view of the plastic recycling machine

Table 2: A list of the materials selected for fabrication of the plastic recycling machine

S/N	Machine component	Material selected	Selection criteria
1	Frame	Malleable steel	Adequate strength, hardness, toughness, readily available
2	Belt	Rubber	Good corrosion resistance, low cost and readily available
3	Hopper	Galvanised mild steel plate	Adequate Strength, corrosion resistance, cheap and readily available
4	Auger screw shaft	Galvanised mild steel	Adequate strength, cheap and readily available
5	Shredder shaft	Mild steel	Adequate strength, cheap and readily available
6	Shredder shaft blade	High speed steel	High strength, toughness, wear resistance and readily available
7	Die plate and breaker plate	Stainless steel	Adequate strength, corrosion resistance, and readily available
8	Extrusion barrel	Galvanised mild steel	Adequate Strength, corrosion resistance, cheap and readily available
9	Pulley	Mild steel	Adequate strength, cheap and readily available
10	Motor cover	Mild steel	Adequate strength, cheap and readily available

2.4. Design Analysis

2.4.1 Shredder Hopper

The shredder hopper is a truncated rectangular based pyramid which is placed on the chamber that houses the shredder shafts as shown in Figure 1. The volume of the shredder hopper, V_{sh}, through which the plastic materials to be recycled are fed is obtained from equation (1).

$$V_{sh} = \frac{1}{3}(BH - bh) \qquad (1)$$

where, B is the area of the rectangular base for the big pyramid, H is the height of the big pyramid, b is the area of the rectangular base for the small truncated pyramid, and h is the height of the small truncated pyramid. Taking B as 281533 mm^2, b 150242 mm^2, H 930.85 mm and h 680.85 mm, the volume of the shredder hopper is 53257488 mm^3. It is aimed that the PET plastic to be recycled will occupy 75% of the hopper volume due to space between independent plastic materials and knowing that the density of PET plastic is 1380 kg.m^{-3}, the mass of the PET plastic to be loaded in the shredder hopper is evaluated to be 55.12 kg (540.74 N).

2.4.2 Shredder Shaft

The shredder shaft is a rotating part housed in the shredder chamber and it is equipped with knife-edged rings. This knife-edge rings allow shredding of the waste plastic materials to be possible as it rotates against another fixed shaft in the chamber. The shredder shaft speed, V_{ss}, is obtained from equation (2).

$$V_{ss} = \omega_{ss}.r_{ss} = \frac{2\pi N_{ss}}{60} r_{ss} \qquad (2)$$

where, ω_{ss} is the angular velocity of the shredder shaft pulley, r_{ss} is the radius of the shredder shaft pulley, and N_{ss} is the speed in revolutions per minute of the shredder shaft pulley.

The shredder shaft is designed to withstand both torsional and bending loads which it is subjected to during operation, as it is being supported at its near end by two bearings. Hence, the shredder shaft diameter, d_{ss}, is obtained from equation (3) [14].

$${d_{ss}}^3 = \frac{16}{\pi S_s}\sqrt{(K_b M_b)^2 + (K_t M_t)^2} \qquad (3)$$

where, S_s is the allowable shear stress, K_b and K_t are the combined shock and fatigue factors as applied to bending moment and torsional moment respectively, M_b is the bending moment and M_t is the moment due to torsion. Given that the values of K_b and K_t are 1.5 and 1 respectively [10], the turning moment experienced by shaft is 1000 Nm and the maximum bending moment due to the PET plastic loaded into the hopper (540.74 N) is 45.29 Nm, and the allowable shear stress is 7.6 x 10^{10} N.m^{-2}, the shredder shaft with diameter of 60 mm was obtained.

2.4.3 Shredding Chamber

This cuboid chamber housed the shredder shafts and shredding of the plastic material also takes place inside it before the shredded plastic material is deposited into the extrusion hopper through an orifice beneath the chamber. The volume of the shredder chamber, V_{sc}, is obtained from equation (4).

$$V_{sc} = b.H_{sc} \quad (4)$$

where, b is the area of the rectangular base for the truncated pyramid which is the same as that in Section 3.1, and H_{sc} is the height of the shredding chamber.

2.4.4 Electric Motor Selection for the Shredding Section

The selection of the electric motor for the shredding section is based on the shredding load, and it is worthy to note that the power is transmitted through a belt-pulley system. Hence, the speed in revolutions per minute, N_m, power, P_m, of the required electric motor and torque in the shaft are determined by equations (5) and (6). The power is transmitted through a belt-pulley system.

$$\frac{D_{ss}}{D_m} = \frac{N_m}{N_{ss}} \quad (5)$$

$$P_m = (T_1 - T_2).v_m = \frac{2\pi N_m r_m}{60}(T_1 - T_2) = T_{ss}.\omega_{ss} \quad (6)$$

where, D_{ss} and D_m are the diameters of the shredder shaft pulley and electric motor shaft pulley respectively, N_{ss} is the speed in revolutions per minute for the shredder shaft pulley, v_m is the velocity of the electric motor pulley, r_m is the radius of the electric motor shaft pulley, and T_1 and T_2 are tensions in the tight side and slack side of the power transmission belt respectively, which can be obtained from equation (7).

$$2.3\log\left(\frac{T_1}{T_2}\right) = \mu\theta.cosec\beta \quad (7)$$

where, μ is the coefficient of friction, θ and β are angle of inclination and wrap of the belt with the pulley respectively. Also, the tension in the tight side of the transmission belt, T_1, can be obtained from equations (8-10).

$$T_1 = T - T_c \quad (8)$$

$$T = \sigma_b.\sigma_b \quad (9)$$

$$T_c = m_b.v_b \quad (10)$$

the maximum tension in the belt, Tc is the centrifugal tension in the belt, σ_b is the allowable stress in the belt, ab is the cross section area of the belt, m_b is the mass per unit length of the belt, and v_m is the peripheral velocity of the belt on the electric motor pulley.

The angle of twist, θ that the shaft would experience due to the torque is obtained from equation (11-12).

$$\frac{T_{ss}}{J} = \frac{G\theta}{l_{ss}} \quad (11)$$

$$J = \frac{\pi D^4}{32} \quad (12)$$

T_{ss} is the torque applied to the shaft, G is shear modulus of the shredder shaft material, J is the polar moment of cross sectional area of the shredder shaft, l_{ss} is the length of the shredder shaft and D is the diameter of the shredder shaft. With the choice of a one-horsepower (746 W) electric motor which s to deliver a torque of 1000 Nm, the angular speed of the shaft is 0.746 rad.s^{-1}, and given that the diameter of the shredder shaft pulley is 100 mm, then the linear speed of the shaft is 0.0373 m.s^{-1}.

Hence, the design capacity of the shredding unit, DC_{su} is estimated by the product of the weight of the loaded PET plastic to be recycled, W_p of 540 N, the shredder shaft linear speed, V_{ss} of 0.0373 m.s^{-1} and the reciprocal of the effective length of the shredder shaft, $l_{eff,ss}$ of 600 mm, which gives a value of 3.43 kg.s^{-1} (≈ 12000 kg.hr^{-1}).

2.4.5 Extrusion Hopper Design

The extrusion hopper through which the shredder plastic is fed into the extrusion chamber is a truncated cone, as shown in Figure 1. The volume of the extrusion hopper, V_{eh}, is obtained from equation (13).

$$V_{eh} = \frac{1}{3}\pi(R^2 H_{eh} - r^2 h_{eh}) \quad (13)$$

where, R is the radius of the circular base of the cone, r is the radius of the circular section where the cone was truncated, H_{eh} is the full height of the cone and h_{eh} is the height of the truncated section of the cone. With R equal 109 mm, r 39 mm, H_{eh} 630 mm and h_{eh} 221 mm, the volume of the extrusion hopper is 7487269.75 mm^3. With 95% of the extrusion hopper filled with the shredded plastics, the mass of the plastic to be in the hopper is 9.816 kg.

2.4.6 Extrusion auger Shaft

The extrusion auger shaft is a rotating part housed in the extrusion chamber where the shredder plastic loaded through the hopper is first heated to molten state before it is extruded through a die-orifice. The velocity of the auger shaft which conveys and force the molten plastic through the orifice and the diameter of the shaft can be obtained by adopting equations (2) and (3).

2.4.7 Extrusion Chamber

The extrusion chamber is cylindrical and houses the extrusion auger shaft. Also, the shredded plastic materials are heated, at temperature range of 250 – 265^{o}C [9], in this chamber to molten state with the aid of electric heater jacket wrapped around the chamber. The volume of the extrusion chamber, V_{ec}, can be obtained from equation (14). The mode of heat transfer to the plastic materials inside the extrusion chamber is by conduction, and the rate of heat transfer, Q, from the heater jacket through the cylindrical wall of the extrusion chamber is obtained from equation (15) [15].

$$V_{ec} = \pi.R_{iec}^2 L_{ec} \quad (14)$$

$$Q = -k.A\frac{dT}{dr} = -2\pi.R_{iec}.k\frac{(T_{oec} - T_{iec})}{In\left(\frac{R_{oec}}{R_{iec}}\right)}\frac{1}{R_{iec}} \quad (15)$$

where, R_{iec} and R_{oec} are the inner and outer radii of the circular cross section of the extrusion chamber respectively, L_{ec} is the length of the extrusion chamber, k is the thermal conductivity of the extrusion chamber material, and T_{iec} and T_{oec} are inner and outer surface temperatures of the cylindrical extrusion chamber.

2.4.8 Electric Motor Selection for the Extrusion Section

The selection of electric motor to drive the extrusion auger shaft is based on the extrusion load, and equations (5-10) can be adopted to determine the speed and power of the electric power required for the extrusion process. A one-quarter horsepower electric motor is selected for the extrusion process with the aim of achieving angular speed of 0.2 rad.s^{-1}, and with an extrusion shaft pulley diameter of 100 mm, the linear speed is obtained to be 0.01 m.s^{-1}. With the extrusion chamber length of 716 mm, speed of 0.01 m.s^{-1} and plastic load of 9.816 kg, the design capacity for the extrusion process is 0.137 kg.s^{-1} (≈ 490 kg.hr^{-1}). It is aimed that the plastic filament should be of diameter 1 mm, hence the extrusion orifice of 1 mm diameter and velocity of flow of molten plastic as 0.01 m.s^{-1}, the extrusion process is expected to take place at a volumetric rate of 7.855 mm3.s^{-1} (≈ 28000 mm^3.hr^{-1}).

2.4.9 Design of the Standing Columns against Buckling

The structural standing columns of the machine are designed against buckling effect. This was achieved by determining the slenderness ratio of the columns and the critical load required for buckling to occur. The slenderness ratio, λ, of the standing columns was investigated using equation (16), to determine the classification of the loaded column as short ($\lambda < 50$), intermediate ($50 \leq \lambda \leq 200$) or long ($\lambda > 200$) column.

$$\lambda = \frac{L_{eff}}{R_g} = \frac{KL}{\sqrt{\frac{I}{A}}} \quad (16)$$

where, λ is the slenderness ratio, L_{eff} is the effective length of the column under compressive load, R_g is the radius of gyration of the I-section column, K is the column effective length factor, L is the unsupported length of the column, I is the second moment of area of the I-section, and A is cross sectional area of the I-section column. The critical load to be reached for buckling to occur is obtained using equation (17).

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} \quad (17)$$

where, E is the modulus of elasticity, I is the second moment of area of the column cross section, K is the column effective length factor and L is the column unsupported length.

2.4.10 Design Factor of Safety

The overall integrity of the machine design can be established by ensuring that the factor of safety, which can be obtained using equation (18), is greater than 1. This will guarantee that the machine will not collapse structurally under the action of loads.

$$FoS = \frac{YS}{WS} \quad (18)$$

In (18), FoS is the factor of safety, YS is the yield strength of the selected material for the machine frame, and WS is the working stress or the maximum stress.

3. RESULTS AND DISCUSSION

3.1 Design Evaluation

The CAD model of the plastic recycling machine was subjected to stress analysis to determine the adequacy of the conceptual design for fabrication. The stress variation, buckling, and factor of safety analyses on the machine frame members, and torsional analysis of the shredder shaft, which are considered as critical parts, were investigated using finite element (FE) modeling tool in Solid Works CAD application software.

3.2 Machine Frame Assembly

In the FE domain, the solid mesh of the entire frame was generated by discretizing the frame model into 358 elements with 368 nodes and the mesh was jiggled for refinement to enhance the mesh quality and hence the simulation results to be obtained. On the top level of the frame, the assembly of the hopper, shredder shaft and shredding chamber amounted to a load of 1203.59 N, which was normally acting and uniformly distributed on the top of the frame, and the extrusion assembly on the beneath level of the frame amounted to a load of 271.05 N, which was also normally acting and uniformly distributed on that level of the frame as indicated in Figure 3. The mechanical properties of malleable steel selected for the machine frame members are listed in Table 3.

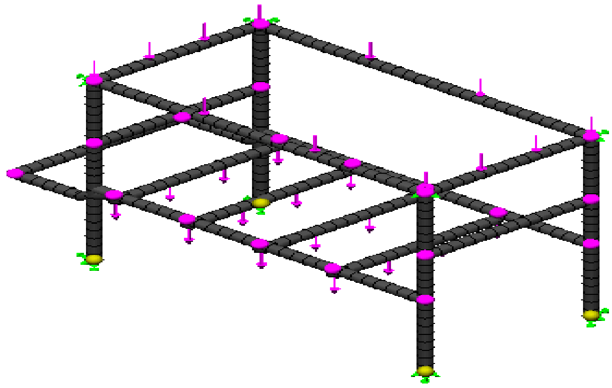

Figure 3 Frame solid mesh model with normally acting uniformly distributed load

Table 3 Mechanical properties of the malleable steel selected for machine frame

Properties	Malleable steel	Mild carbon steel
Mass density	7300 kg.m^{-3}	7800 kg.m^{-3}
Tensile strength	4.136 x 10^{8} N.m^{-2}	4.825 x 10^{8} N.m^{-2}
Elastic modulus	1.9 x 10^{11} N.m^{-2}	2.0 x 10^{11} N.m^{-2}
Poisson ratio	0.27	0.32
Shear modulus	8.6 x 10^{10} N.m^{-2}	7.6 x 10^{10} N.m^{-2}
Yield strength	2.757 x 10^{8} N.m^{-2}	2.482 x 10^{8} N.m^{-2}

The simulated FE analysis of the stress distribution in the machine frame member is shown in Figure 4. The simulation result indicated that the maximum stress of 3.3065 x 10^{7} N.m^{-2} (33.065 MPa), which is a combination of axial and bending stresses, is experienced by one of the members of the beneath level of the frame on which the extrusion assembly is mounted. However, this maximum stress value obtained is lower than the yield strength of the malleable steel selected as material for the frame members as seen in the Table 3.

Furthermore, the resultant displacement of the machine frame members was assessed under the action of the loads both on the top level and the level beneath. Figure 5 shows the distribution of the resultant displacement of the frame members. A maximum resultant displacement of 0.34 mm was observed on one of the members of the beneath level of the frame. The position where the maximum resultant displacement was observed on the member of the frame coincides with the position where maximum stress has been previously observed in Figure 4. The effect of this maximum resultant displacement may be considered negligible on the stability of the machine frame, since the maximum stress observed at that same position is below the yield strength of the malleable steel selected for the fabrication of the frame. Thus, the maximum displacement is tolerable within the elastic limit of the selected material which has not been exceeded.

The structural stability of the I-section columns for the machine standing supports under the action of the axial load was assessed to determine their suitability as leg support for the machine assembly. Figure 6 shows the resultant displacement of the machine frame after the buckling test has been conducted. The maximum resultant lateral displacement under the axial load is 2.186 mm on some members of the machine frame. Using equation (16), with the length of the unsupported standing columns of the machine assembly as 840 mm, second moment of area of the I-section as 1.059 x 10^{6} mm^{4}, and cross sectional area of the I-section column as 1040 mm^{2}, and taking column effective length factor to be 1, the slenderness ratio for the standing columns of the machine frame is calculated as 26.33, thus the axially loaded columns are considered as short columns.

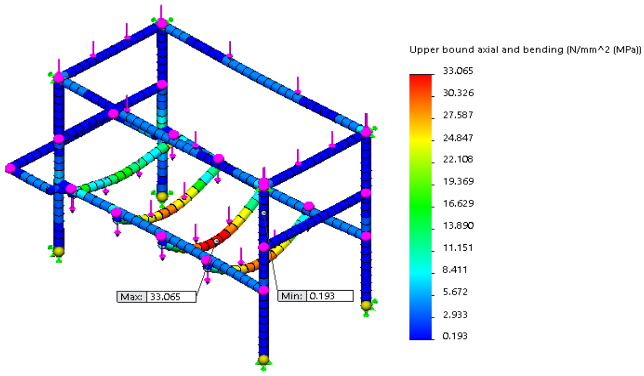

Figure 4: FE analysis of the stress distribution within the machine frame members

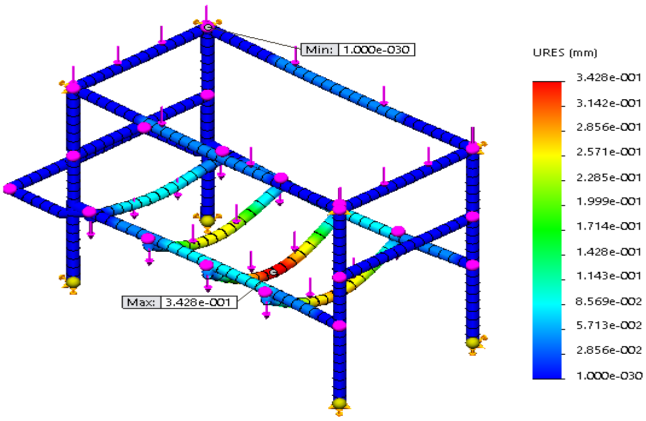

Figure 5: Distribution of the resultant displacement of the machine frame members

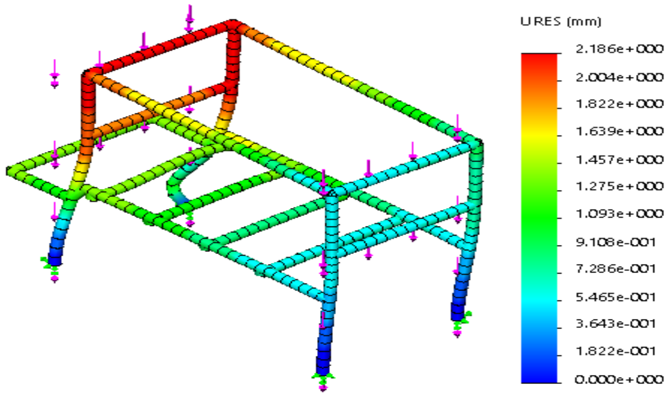

Figure 6 Resultant displacement of the machine frame during buckling test

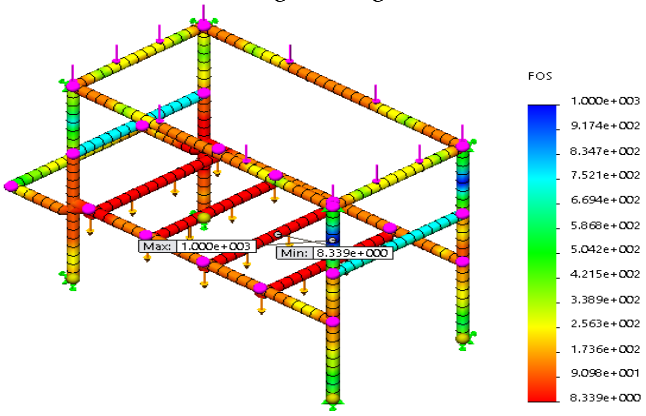

Figure 7: Factor of safety distribution on the machine frame members

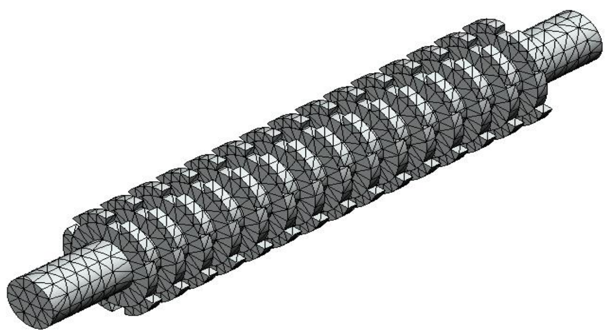

Figure 8: Solid mesh model of the shredder shaft

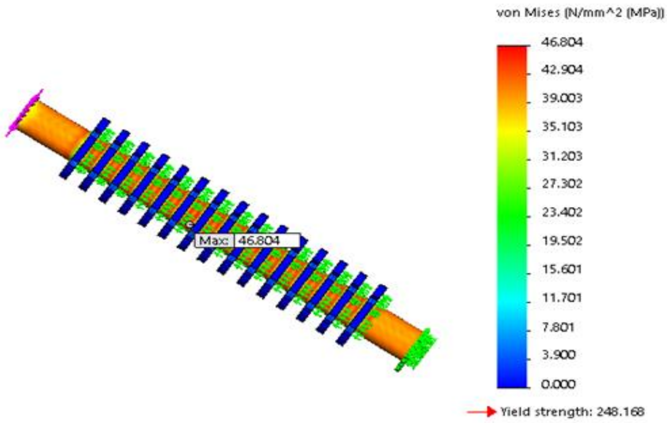

Figure 9: FE model of the stress distribution in the shredder shaft due to torsion

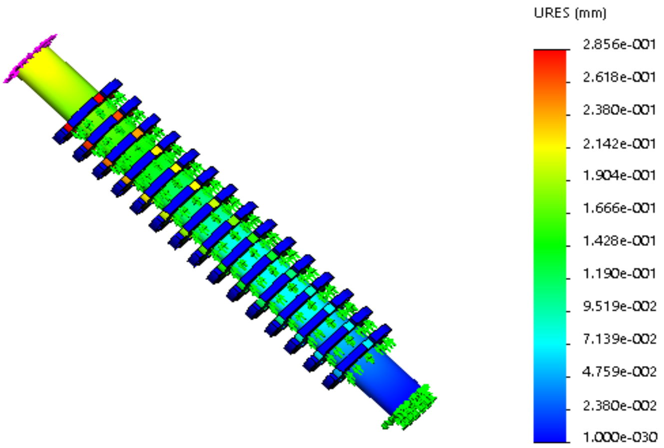

Figure 10: FE model of the resultant linear displacement variation due to torsion

Moreover, it is noteworthy to establish if the axial loads on the standing columns have exceeded the critical load for buckling of the column to occur. The overall load supported by the four standing columns is 1474.64 N, indicating that each standing column leg is axially loaded with 368.66 N with an assumption of uniform distribution. Using equation (17), the critical load, P_{cr}, is calculated as 2,365 kN, which is the expected load that can be mounted on each column for buckling to have occurred. The critical load value is far greater than the entire load of 1474.64 N that was axially acting on the standing columns; hence, the maximum resultant lateral displacement of 2.186 mm obtained from the FE simulation run can be considered negligible.

The overall structural integrity of the machine frame assembly was investigated by running the FE simulation run for factor of safety of the assembly. Figure 7 shows the distribution of the factor of safety from one element to another for the machine frame members. The minimum factor of safety observed from the distribution is 8.339, which was found on one of the beneath level frame members. This frame member coincided with the member that experienced maximum resultant stress of 3.3065×10^7 N.m^{-2} and maximum resultant displacement of 0.34 mm as shown in Figure 4 and Figure 5 respectively.

In order to validate the effectiveness of the FE simulation runs on the machine frame structural integrity, the factor of safety obtained using equation (18) for the maximum stress obtained from the stress distribution was evaluated. With yield strength of 2.757×10^8 N.m^{-2} (Table 3) and maximum stress of 3.3065×10^7 N.m^{-2}, the calculated factor of safety is 8.338, which is the same as the value of factor of safety obtained from the FE simulation run in Figure 7. Hence, the structural integrity of the design of the plastic recycling machine is guaranteed and it is acceptable for fabrication.

3.3 Shredder Shaft

It is expected that the rotating shredder shaft is subjected to torque due to the power transmitted through the belt-pulley system obtained from equation (6). The torque applied to the shredder shaft, T_{ss}, can also be obtained from equation (6). The behaviour of the rotating shredder shaft under the torque is analysed in the FE domain of the CAD application software. The CAD model of the shredder shaft with the knife-edge ring cutters was discretised into a solid mesh having 10134 elements and 19808 nodes as shown in Figure 8. One end of the shaft was fixed while the other end was subjected to torque of 1000 Nm. The torque experienced by the shaft is expected to result from the plastic materials to be shredded in the shredding chamber, since the shaft is mounted on bearings at both ends and freely rotating. The mechanical properties of the mild carbon steel selected as material of the shaft are listed in Table 3.

The result of the FE simulation study of torsion on the stress distribution in the shredder shaft assembly is shown in Figure 9. The result indicated that a maximum stress of 4.6804×10^7 N.m^{-2} is experienced in the shaft when subjected to a turning moment of 1000 Nm.

Moreover, the yield strength of the mild steel selected for the shaft is greater than the maximum stress obtained from the simulation; hence, the shaft will be able to resist permanent deformation due to torsion when subjected to the torque of 1000 Nm. With a torque of 1000 Nm, shear modulus of 7.6 x 10^{10} $N.m^{-2}$, shaft length of 710 mm, shaft diameter of 60 mm, and polar moment of shaft cross sectional area of 1.27 x 10^6 mm^4, the angle of twist is 7.34 x10^{-3} radian (0.42°). The angle of twist of 7.34 x10^{-3} radian resulted in a linear displacement of 0.2202 mm, as shown in Figure 10, which is the yellowish red region on the modelled shaft, while the maximum resultant linear displacement of 0.2856 mm is experienced by the knife-edge ring cutter mounted on the shaft near the end of the shaft where maximum angle of twist was observed.

Furthermore, the fitness of the shredder shaft for the shredding purpose was examined by running the FE simulation to determine the factor of safety distribution in the shaft. The result showed that the minimum factor of safety was 5.3, which indicate that the shaft is fit to be used for as the shredder shaft and the linear displacement of 0.2202 mm due to the torque may be considered negligible.

3.4 Discussion

The entire FE simulation results for the stress distribution and resultant displacement variation in the machine frame members gave an insight to location experiencing maximum stress and maximum displacement. This location on the frame is a potential position where structural failure may likely begin when the machine is fabricated and put to use. However, the maximum stress value was far lower than the yield strength of the malleable steel selected for the fabrication of the frame, which made the minimum factor of safety obtained to be as high as 8.3.

The factor of safety is a good index to ascertain the structural integrity of the machine frame. Moreover, it may seem that the machine frame has been over-designed due to the high value of factor of safety; hence the selection of material for the frame can be reviewed such that the factor of safety value is reduced to 1.5. Generally, steel, most especially mild steel, is one of the most common, locally available and cheap engineering material often used for fabrication and construction. However, their use may result in high value of factor of safety. Materials such as Aluminium alloys and Titanium alloys possess lighter weight when compared to ferrous alloys, but these materials are not as cheap and readily available as steel. Wood may have as well be considered for construction of the machine frame, however, putting environmental conditions into consideration, it may not be durable enough. Hence, steel is still considered as the best choice, but hollow steel pipes may be considered as well in design re-evaluation. The material selection review can be made, provided there is cost saving associated with the newly selected material and it is also readily available. It is suggested that mild steel I-section columns may be used for the fabrication of the frame as its yield strength is lower than that of malleable steel (Table 3). Furthermore, the buckling test analysis indicated that the machine column legs are short columns which will not buckle under the axial load on them. This corroborates the structural fitness of the machine frame assembly.

The FE simulation on the shredder shaft to investigate torsion showed that the mild steel chosen as the shaft material is adequate, as obtained maximum stress on the shaft after the simulation did not exceed the material yield strength and a small angle of twist of 0.42° is experienced by the shaft under the twisting moment of 1000 Nm. Hence, the shaft is expected to be able to withstand a twisting moment that may have resulted from the shredded plastic in the shredder chamber which may create a resistance against the direction of rotation of the shaft during operation. It is not expected of the extrusion auger shaft in the extrusion section to experience a severe twisting moment, as the plastic material in the chamber would have been heated to a molten state which will offer a low resistance against the direction of rotation of the auger shaft. Hence, the auger shaft design is considered appropriate and fit for fabrication.

4 CONCLUSIONS

In this study, a PET plastic recycling machine has been successfully conceptualized and designed. The machine was design to have a shredder hopper, two shredder shafts with knife-edge ring cutters, an extruder hopper, an extrusion chamber and an extrusion auger shaft. The design analysis of each of the machine elements was done and structural integrity of the machine design was evaluated using FE modeling tool in SolidWorks CAD application. Under the action of axial loads of 1204 N and 271 N on top and below the frame structure, the simulation result indicated that a maximum stress of 33 MPa was reached in one of the machine frame members, which is lower than the material yield strength. The structural integrity of the designed machine frame was confirmed by the buckling analysis and a minimum factor of safety of 8.3. Upon the subjection of the shredder shaft to a torque of 1000 Nm, the shaft experienced a small angle of twist of 0.42° and a maximum stress of 46.8 MPa and a minimum factor of safety of 5.3, indicating that the shredder shaft design is appropriate. Hence, the conceptual design is considered fit for fabrication based on the design analysis and evaluation, using locally available and cheap materials. It is expected that the machine will fulfill its intended purpose upon fabrication.

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