

# DEVELOPMENT OF A FUSED DEPOSITION MODELLING MACHINE FOR PLASTIC-BASED ADDITIVE MANUFACTURING PURPOSES

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**Abstract:** *In this work, the development of a Fused Deposition Modelling (FDM) machine was successfully carried out and reported. The machine was designed to boost local manufacturing capabilities in Nigeria by promoting the use of additive manufacturing techniques for production of plastic-based prototypes, functional components and casting patterns. The machine consists of a heater bed, hot-end extruder, machine frame, controller and electrical circuitry and it was designed to have a working envelope with maximum build volume of 200 x 200 x 200 mm<sup>3</sup>. The design of each machine component parts was analysed and the structural capacity was assessed using finite element analysis (FEA) tool in Autodesk Inventor and COMSOL Multi-physics applications. The simulation result showed that a maximum stress of 3.669 MPa was attained in one of the machine stand when component aggregate load of 301.29 N was exerted on the frame structure. The machine component with maximum resultant displacement of 0.04 mm was also observed while the minimum factor of safety was 12.5. This result shows that the design of the machine is satisfactory for its development since the yield strengths of the selected materials for the individual components were not surpassed by the stresses obtained from the FE analysis. Upon the machine development, it was able to produce prototypes of some vehicle logos which confirms its capability to perform the intention of its development.*

**Keywords:** *Additive, Manufacturing, FDM, Machine, Design*

## 1. INTRODUCTION

Additive manufacturing (AM) has been described as a new advance technology, capable of producing or reproducing 3D structures in one piece (Vojislav et al., 2011). Additive manufacturing is the process of joining materials to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to conventional manufacturing process, such as traditional machining and formative manufacturing techniques (ASTM/ISO, 2015). There are several classifications of AM technologies, however there are some fundamental features which are common to them all, and these are: the use of computer to digitalize object to be produced and to generate electronic command signal which controls the fabrication system and delivery of feedstock as specified by the control signals (Bourell *et al.*, 2017).

Additive manufacturing process comprises of two stages which include: conversion of software data to printed structures and repeated setting of the print head in all three directions in space in order to print layer by layer the whole object. However, for the purpose of this study, Fused Deposition Modelling (FDM) is considered as one of the most commonly used rapid prototyping technology, after stereolithography (Wong and Hernandez, 2012). To improve upon the level of popularity of additive manufacturing technology in Nigeria, it was

recommended that local fabrication of additive manufacturing equipment can help to increase the awareness of the technology.

Hence, the main objective of this work is to establish the local development of Fused Deposition Modelling machine in Nigeria. The significance of this development is to promote the level of awareness of additive manufacturing and also to enhance manufacturing capabilities in Nigeria.

### **1.1 Purpose of the study**

The purpose of the study is to report the development of Fused Deposition Modelling machine which was locally fabricated to promote application of additive manufacturing technology in Nigeria and also to enhance the manufacturing capabilities associated with the production of miniature functional and prototype plastic-based parts.

## **2. LITERATURE REVIEW**

Additive manufacturing (AM) technology has been gaining popularity over the last two decades as it offers numerous advantages over the conventional, subtractive manufacturing techniques (Sharon 2014). There are several classifications of this AM technology and these include: stereolithography (SLA), fused deposition modelling (FDM), direct energy deposition (DED), laminated object manufacturing (LOM), inkjet printing, selective laser sintering/melting (SLS/SLM) and others. However, fused deposition modelling is considered to be widely used for production of plastic-based prototypes and functional parts (Mkhemer 2016, Bhandari & Regina 2013).

FDM involves the use of a plastic material which is extruded through a nozzle to enable the construction of three-dimensional objects. The RepRap (a self-Replicating Rapid prototyper) has been described as the first open source 3-D printer which was released under the GNU General Public License led to the rapid technical growth of RepRap 3-D printers (Gwamuri *et al.*, 2016). This category of 3-D printer referred to herein generally uses a FDM process with thermopolymers for part fabrication. The free and open source hardware (FOSH) nature of the RepRap project led to rapid growth in the number of FDM printing firms competing in the FDM printing market, which has helped to reduce the costs of FDM printers from more than \$20,000 to about \$1,000 within a couple of years (Prusa 2013).

The RepRap open source project presents the users with vast knowledge and technical ideas to transform, vary and enhance the physical designs of their FDM printers to meet their needs which include basically cost reduction and efficiency improvement. Thus, the unstable prices of FDM printers, together with the continuous innovation and development of the Reprap open source project, has afforded educational researchers the opportunity to develop their own FDM printers to be used for educational purposes especially in countries where there is little awareness of this technology (Mercuri & Meredith 2014, Canessa *et al.*, 2013)

FDM has a number of advantages over traditional manufacturing methods which include the ability to easily produce customized parts since it requires no special tooling (Farayibi *et al.*, 2015). In order to continue to leverage on the advantages of FDM, however, the mechanical properties and performance of the materials that are used need to be fully optimized (Gross *et al.*, 2014). According to Khatwani, 2016, all rapid prototyping processes have different input variables that affect the features of the product corresponding to the surface roughness strength, dimensional accuracy. The study further noted that basic printing parameters used on an FDM machine during printing processes such as layer thickness, build orientation, part bed temperature, nozzle diameter, raster angle and width, hatch spacing *etc.* affect greatly the quality of a built part produced.

Farayibi and Abioye (2017) conducted a research that promote the level of awareness on additive manufacturing technology in south-western Nigeria and noted that the awareness of this technology is not too high (40%), as there was only one research institute with an inkjet/3D printing AM system within the region. It was therefore recommended that the level of awareness of this technology can be significantly improved when concerted efforts are made towards buying AM systems from overseas and by local fabrication/manufacturing to promote rapid product development. However, the procurement of brand new one of AM machine from abroad is relatively expensive and hence local fabrication of these systems is a good choice to enhance the availability of this technology in Nigeria. Therefore, the aim of this study is to develop a fused deposition modelling (FDM) machine for the purpose of producing plastic-based components.

### **3. METHODOLOGY**

#### **3.1 Design concept**

The Fused Deposition Modelling machine consists of two major components which are the mechanical and the electrical components mounted on the frame structure as indicated in the assembly view of the machine with front and plan views in Figure 1. The machine was designed to have a working envelope of 200 x 200 x 200 mm<sup>3</sup>. The structural frame of the machine is made up of eight rectangular aluminium bars assembled together with bolts and nuts and the edges of the frame were properly aligned to ensure stability of the machine upon the mounting of the critical components such as stepper motors, extruder, etc., on the frame. The mechanical components of the machine include: five (5) NEMA-17 stepper motors which are required for the control of all motions of the machine on the x-, y- and z-directions. Whilst the machine is designed to employ one of the stepper motors for feeding plastic filament as feedstock through the extruder head, two of the stepper motors are used for controlling the motion along the z-axis, and one each is employed for motion control in the x- and y- directions. Two linear shafts are mounted on the four (4)-beam structure serving as the machine base to hold the heater bed in position and as well serve as guide rail when traversed to and fro in the y-direction. The rotary motion of the stepper motors are linearized using lead screw shafts which are attached with a coupling unit to each of the motors in the direction of motions to be achieved. Three (3) end-stop switches are mounted at the extreme of each axis of the machine to limit motion beyond the points specified by the switches. A Wansen's (S-250-12) power-pack unit with input of 220V, 50/60Hz and output of 12V/20A was used for the power supply device of the machine. The device is capable of satisfying the machine energy demands. A Rep-Rap's BT7272A RAMPS Arduino Mega board was employed as the motherboard of the machine which coordinates the entire operation of the FDM machine. The Arduino board is equipped with a cooling fan to prevent its overheating. The electrical configuration of the machine involves connection of all the stepper motors, the cooling fan, the liquid crystal display (LCD), the heater bed and the power supply to the Arduino board. An aluminium plate of 200 x 200 mm<sup>2</sup> is used as the heater bed of the machine on which objects can be printed. Four (4) hardened plastic parts are fixed beneath the machine base on which the machine stands. It is noteworthy that the feeder motor is expected to continuously feed the printing filament to the hotend in the extruder head where it is melted and extruded out from the nozzle unto the machine heater bed.

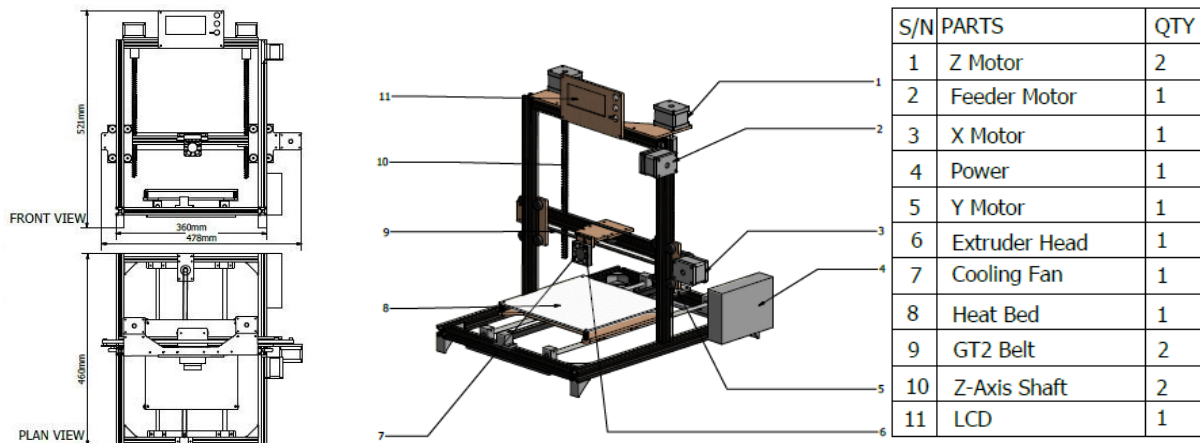


Figure 1: Fused Deposition Modelling machine (assembly view)

### 3.2 Design consideration

The followings were considered during the design of the FDM machine: (a) availability of component parts locally; (b) Simplicity in operation of the machine and easy to maintain; and (c) low cost of the machine.

### 3.3 Material selection

The materials selection and component parts for the development of the FDM machine was based on their physical and mechanical properties, availability, ease of use and cost. Table 1 comprises of materials selected for the development of the FDM machine with the justification for material selection.

Table 1: Material Selection for the FDM Machine

S/No.	Machine Components	Materials Selected	Justification for Material Selection
1	Support Frames	Aluminium T6-6061 (Anodized)	Adequate strength to withstand loads, Good strength to weight ratio, Cheap and its availabilities
3	Bearings	Mild Steel	Enough strength to withstand torque and readily available
4	Arduino Board (Motherboard)	Rep-Rap's BT7272A Ramps 1.4 Plus	Easy to program, ability to drive and control NEMA-17 stepper motors
5	Power Supply	Wansen's computer with input of 220V, 50/60Hz and output of 12V/20A.	Capable of satisfying the energy requirements of the FDM Machine
7	Heat-Bed (Printing Bed)	Aluminium Alloy	Good strength-to- weight ratio. Capable of withstanding temperature changes.
9	Belt Drive	Rubber	Ability to drive the machine gears, low cost and Readily available
10	Hotend Cooling Fan	12V Plastic Fans (4cm Diameter)	Ability to cool Hotend very quickly. Ease of use and very portable.
11	Stepper Motors	NEMA 17 Stepper Motors	Capable of meeting machine torque demands.
12	LCD Function	Rep-Rap's BT7262A LCD 2004	Can be easily configured, readily available and cheap.
13	Printing Filament	PLA (Polylactic acid or Polylactide)	Low toxicity, Biodegradable, Environmentally Friendly, Good Stiffness.

### 3.4 Design analysis

#### 3.4.1 Machine frame

The machine frame is made of aluminum rods with the dimensions of 460 × 400 × 420 mm and held together by M4 nuts and bolts. The aluminum rods that is used in the design of the FDM machine is a 20 mm thick profile. They are made from 6061-T6 aluminum and has a black hard anodized coat on it to make it more resistant to wear. The main function of the frame is to provide mounting points for the stepper motors, the printing bed and extruder parts. The frame absorbs forces and torques resulting from the motion of some parts during operation. The frame also provides the needed rigidity for the machine.

### 3.4.2 Selection of microcontroller (Arduino) board

RepRap Arduino Mega Pololu Shield (RAMPS) was selected for the development of the FDM machine. The RAMPS (12V, 5A) was designed to fit the entire electronic parts needed for the development of the proposed FDM machine. RAMPS can also run at 24V with various precautions however, it was recommended to run the RAMPS at 15V maximum. The RAMPS modular design includes the following features which influenced the choice of selection: (i) It has provisions for the cartesian FDM machine and extruder; (ii) It has three mosfets for heater / fan outputs and three thermistor circuits; (iii) It has a heated bed control with additional 11A fuse; (iv) It has servo-connector ports to connect the endstop switches, motors, heated bed and extruder; and (v) It has a 5A fuse for additional safety and component protection.

### 3.4.3 Stepper motor type selection

Bipolar stepper motor was considered for the design since they are the most popular for all types and brands for 3D printer. For this reason, stepper motors suitable for bipolar drive, which have 4 or 8 wires were used in the development of the FDM machine. It was not possible to use motors with 5 wires, because those were intended to be driven in unipolar mode only hence were not suitable for the developed FDM machine.

Stepper motor rated current and inductance were also considered. Stepper motors rated current is the maximum current that can pass through both windings of the motor at the same time. The inductance of the motor affects how fast the stepper motor controller can drive the motor before the torque drops off. Those two parameters are usually indicated on the stepper motors. NEMA 17 (40 mm, 1.2 A, 0.4 Nm) and NEMA 17 (60 mm, 1.5 A, 0.65 Nm) stepper motors were considered for selection. However, NEMA 17 (40 mm, 1.2 A, 0.4 Nm) stepper motor was selected for the development of the FDM machine because of its step angle of 1.8° fine resolution This step angle is suited for the machine and can be driven by the machine power supply of 12V.

### 3.4.4 Determination of stepper motor voltage rating

Stepper motors are classified in terms of voltage rating per phase, current per phase, resistance per phase and. Amps per phase is the maximum current that the motor windings can handle without overheating. Resistance per phase is the resistance for each phase. The voltage hooked up with a stepper motor is very critical because excess voltage gets the motors very hot and can cause permanent damage of the motor. For the stepper motors used in the developed FDM machine, the rated supplied voltage is 2.81 V which was obtained from Ohms law as stated in Equation 1.

$$V=IR \quad (1)$$

where,  $I$  is the rated current of the stepper motor (specified as 1.68 A),  $R$  is the rated resistance of the stepper motor (specified as 1.67  $\Omega$ )

The calculated voltage indicates the minimum voltage required by the stepper motors to run effectively. However, it should be noted that stepper motors can run at a higher voltage than the rated value but this must be done with stepper motor driver to avoid motor coil burnt out.

### 3.4.5 Determination of the motor step angle

Stepper motors have a step angle. A full 360° circle divided by the step angle gives the number of steps per revolution. For example, 1.8° per full step is a common step size rating, equivalent to 200 steps per revolution as obtained using Equation 2. It is sometimes possible to use motors with larger step angles, however for printing accuracy, the resolution of the stepper motor to achieve the motion need to be smaller i.e. angle moved per step reduced.

$$S = \frac{360}{n} \quad (2)$$

where,  $s$  is the steps per revolution and  $n$  is the step angle (in degree) of the stepper motors.

There are two common step angles:  $0.9^\circ$  and  $1.8^\circ$  per full step, corresponding to 400 and 200 steps/revolution. Most 3D printers use  $1.8^\circ$  per step motors. Also, in this study, 12 V, stepper motors with  $1.8^\circ$  per step was preferred to those with  $0.9^\circ$  per step as the latter have lower holding torque and must be driven using 24 V supply to achieve a high speed.

#### 3.4.6 Determination of machine maximum volumetric speed

The volumetric speed refers to the speed at which the filament is extruded and deposited by the machine every second during printing. This is calculated in cubic millimetre per second ( $\text{mm}^3$ ). For complicated prints, lesser volumetric speed is required to give a higher quality print however for simple prints, very high volumetric speed can be used. For the designed FDM machine, the maximum volumetric speed,  $V_s$ , was determined as  $8 \text{ mm}^3/\text{s}$  using Equation 3.

$$V_s = S \times N_d \times L_h \quad (3)$$

where,  $S$  is the default auto speed set by the slice3r software (specified as  $100 \text{ mm/s}$ ),  $N_d$  is the nozzle diameter of the extruder/hotend ( $0.4 \text{ mm}$ ); and  $L_h$  is the layer printing height ( $0.2 \text{ mm}$ ). The equation indicated that using bigger nozzles for printing can increase the volumetric speed of the FDM machine.

#### 3.4.7 Filament selection

There are a handful of plastics that are compatible with FDM-based printers. Each has their pros and cons. For the developed FDM machine, PLA (Polylactic acid or Polylactide) is preferred for use as filament because of its low toxicity and general environmental friendliness. However, it should be noted that the most important factor in choosing a printing filament lies in the capability of the hotend/extruder. This is with respect to its ability to withstand the melting temperature of the selected filament material. The selected PLA filament for the designed FDM machine is extruded at temperature of  $160^\circ\text{C}$  and  $220^\circ\text{C}$ . The selected hotend/extruder material is however, capable of withstanding a maximum temperature of  $260^\circ\text{C}$ . This indicates that the hotend/extruder is capable of melting the PLA filament at  $220^\circ\text{C}$  hence, the adoption of the filament type. The selected PLA filament tends to be stiffer than ABS (Acrylonitrile Butadiene Styrene). PLA filament can be used for printing without a heated bed. However, this can cause the material to warp during cooling.

#### 3.4.8 Determination of total power requirements

The power requirement for the FDM machine was determined by the summation of the wattage required to power each sub-unit coupled together. The power of the Arduino board is  $1.2 \text{ W}$  ( $100 \text{ mA}$ ,  $12 \text{ V}$ ), heated bed heater is  $120 \text{ W}$  ( $12\text{V}/10\text{A}/1.2\Omega$ ), hot-end heater is  $40 \text{ W}$  ( $12 \text{ V}$ ,  $3.33 \text{ A}$ ), stepper motor is  $24 \text{ W}$  ( $1.2 \text{ A}$ ,  $4 \text{ V}$ ), losses due to emf is  $24 \text{ W}$ , LCD is  $5 \text{ W}$  ( $12 \text{ V}$ ,  $416 \text{ mA}$ ), cooling fan is  $1.8 \text{ W}$  ( $12 \text{ V}$ ,  $150 \text{ mA}$ ) and the total power requirement is  $220\text{W}$ . Hence, a  $240 \text{ W}$  ( $12 \text{ V}$ ,  $20 \text{ A}$ ) power pack is sufficient to energize the developed FDM machine.

#### 3.4.9 Design factor of safety

The factor of safety was used to determine the structural integrity of the machine design, which can be obtained using Equation (4). This value is expected to be greater than 1 to assure of the machine static stability.

$$FoS = \frac{YS}{WS} \quad (4)$$

where,  $FoS$  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.

#### 3.4.10 Software configuration and manipulation of the FDM machine

The Slic3r software is being used to convert STL files into G-codes. This software has been described as one of the open source that allows modifications and is compatible with the developed FDM machine firmware for direct uploading capabilities. Also, Slic3r can be customized to fit the 3D dimensions and a specific bed size. Using the Slic3r 3D printing

software, the 3D models of various file types are converted into the code for the developed FDM machine with user defined settings that are readily available on the software. The slicer is what turns a STL file into a series of commands, typically G-codes, that tells the printer where to move the print head and when to extrude the plastic filament. Slicing is a critical phase of the printing process. It is a careful balance between quality, speed, and amount of material used.

### 3.4.11 Finite element analysis of the machine frame

Static stress analysis of the FDM machine frame was carried out to determine the Von Mises stress distribution and furthermore the material displacement caused by the stress. The analysis of the static stress was done using Autodesk Inventor software package. After analysis was completed using the software, the results obtained was used to determine whether the machine structure is statically stable and fit for development.

### 3.4.12 Thermal stress analysis of the heated bed and hotend

The temperature distribution in a part can cause thermal stress effects, hence the temperature analyses of the heated bed and hotend/extruder were assessed using COMSOL Multiphysics Simulation Software. The process of the analysis involved performing a steady-state heat transfer analysis to obtain the temperature distribution on the two component parts. The objective of this analysis is to predict the temperature response of the heated bed and hotend/extruder. In order to accurately conduct the thermal stress analysis of the heated bed and hotend/extruder. The suitability of the selected heated bed and hotend/extruder for the development of the FDM machine was determined by the results of this analysis.

## 4. RESULTS AND DISCUSSION

### 4.1 Design evaluation

To determine the suitability of the design of FDM machine for development, the CAD model of the machine was subjected to stress analysis. The displacement, factor of safety and stress variation analysis on the structural frame members of the machine were investigated using FE simulation tool in Autodesk inventor application software. The CAD model of the heated bed and hotend/extruder was also subjected to thermal stress analysis to evaluate the components suitability for use in the FDM machine. The thermal stress analysis on the parts which are considered as critical parts of the FDM machine was done using COMSOL Multiphysics CAD application software. The simulations for both analyses, i.e. stress variation on the machine frame members and thermal stress effects on the heated bed and hotend/extruder, were run.

### 4.2 Machine frame assembly

In the Autodesk Inventor FE domain, the solid mesh of the FDM machine frame was generated by discretizing the frame model into 154640 elements with 300057 nodes. The simulation was run and the results was obtained. The total forces acting on the machine frame amounted to a total load of 301.29 N, as indicated in Figure 2a. The mechanical properties of the aluminium alloy (6061-T6 anodized aluminium) and the ABS selected for the machine frame and stand members are presented in Table 2.

Table 2: Mechanical properties of the aluminium alloy and ABS plastic selected for the machine frame

Properties	Mass density, $\text{kg.m}^{-3}$	Tensile strength, $\text{N.m}^{-2}$	Elastic modulus, $\text{N.m}^{-2}$	Poisson ratio	Shear modulus, $\text{N.m}^{-2}$	Yield strength, $\text{N.m}^{-2}$	Y. strength (ABS), $\text{N.m}^{-2}$
Aluminum	2700	$2.90 \times 10^8$	$69 \times 10^9$	0.33	$2.60 \times 10^{10}$	$2.40 \times 10^8$	$4.60 \times 10^7$

The simulation analysis of the stress distribution in the FDM machine frame member is shown in Figure 2a. The FE analysis simulation result showed that the maximum stress of 3.67 MPa, is experienced by one of the machine stands through which the entire assembly is mounted. However, this maximum stress value obtained is lesser than the yield strength of the ABS plastic selected as material for the machine stand as shown in Table 2.

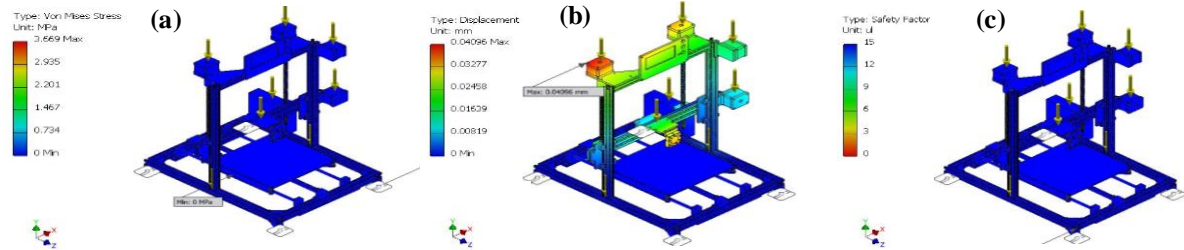


Figure 2: FE analysis of the distribution of stress (a), resultant displacement (b); and factor of safety (c) acting on the machine frame members

Figure 2b shows the distribution of the resultant displacement of the machine frame members under the action of the total load. A maximum resultant displacement of 0.04 mm was noted on one of the stepper motors at the top of the machine frame. The results further showed that deformation decreased with distance away from the top level of the frame (Figure 2b). Regions with high displacement exceeding 0.03 mm were localised around the stepper motors of the FDM machine. The influence of the maximum resultant displacement on the stability of the machine frame may be considered negligible, this is as a result of lower maximum stress observed that is far below the yield strength of the aluminium alloy earmarked for the manufacture of the machine frame.

The integrity of the FDM machine frame assembly was investigated by running the finite element simulation for factor of safety of the assembly. Figure 2c presents the distribution of the factor of safety acting within the machine frame members. 12.54 was observed as minimum factor of safety acting within the distribution, which was discovered on one of the machine stands. The effect of FE simulation runs on the designed machine frame was validated by employing Equation (4) to determine the factor of safety. Having arrived at **maximum stress of  $3.67 \times 10^6 \text{ N.m}^{-2}$** , yield strength of  **$4.60 \times 10^7 \text{ N.m}^{-2}$  (Table 2) and**, the estimated factor of safety is 12.54, which is in line with the value of factor of safety obtained from the finite element simulation run in Figure 2c. Hence, the structural integrity of the FDM machine design for development is guaranteed and acceptable.

### 4.3 Heated bed assembly

The CAD model of the heated bed was discretised into a solid mesh of 826 elements. The ends of the heated bed were constrained during the thermal analysis. It was expected that the heated bed will be subjected to a maximum temperature of 110 °C (383 K) during printing operation. The behaviour of the heated bed at the maximum temperature of 110 °C is simulated in COMSOL Multi-physics software application. A temperature of 110 °C was applied through the side of the heated bed. The effect of thermal stress (stresses caused by thermal expansion or contraction of the material) experienced by the heated bed is expected to result from the thermal loads applied to the heated bed. The mechanical properties of the aluminium alloy selected for the heated bed assembly are stated in Table 2. The output result of the Finite Element analysis displaying the temperature distribution on the heated bed assembly part is shown in Figure 3a. The result showed that a high temperature of 350 – 385 K is distributed very close to the edges of the heated bed, and a lower temperature of 310 – 330 K is concentrated and distributed in the middle of the heated bed.



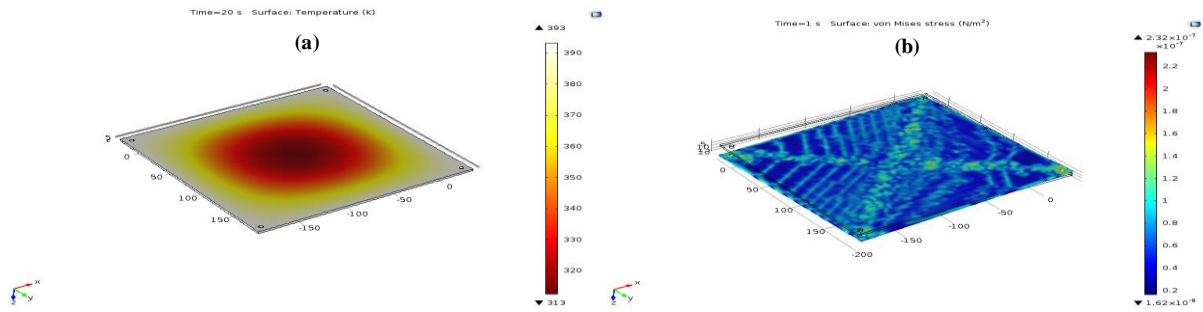


Figure 3: Distribution of temperature (a) and thermal stress (b) of the heated bed

The Figure 3b shows the effect of simulation on thermal analysis of the stress distribution in the heated bed. According to simulation result, maximum stress of about  $1.5 \times 10^{-7} \text{ N.m}^{-2}$  is concentrated and distributed along the diagonals of the heated bed component. However, the result of maximum stress value obtained is lesser than the yield strength of the aluminium alloy selected as material for the heated bed as seen in Table 2. The result indicates that the selected material is suitable for use as heated bed in the development of the FDM machine.

#### 4.4 Hotend/Extruder assembly

The CAD model of the hotend/extruder assembly was discretised into a solid mesh of 1051 elements as shown in Figure 10. The pointed end of the hotend/extruder was constrained during the thermal analysis. It was expected that the hotend/extruder will be subjected to a maximum temperature of  $260 \text{ }^\circ\text{C}$  ( $533 \text{ K}$ ) during printing operation. The behaviour of the hotend/extruder at the maximum temperature of  $260 \text{ }^\circ\text{C}$  ( $533 \text{ K}$ ) was analysed in the finite element domain of COMSOL Multi-physics software application. A temperature of  $260 \text{ }^\circ\text{C}$  ( $533 \text{ K}$ ) was applied through the pointed end of the hotend/extruder. The thermal stress effects (stresses caused by thermal expansion or contraction of the material) experienced by the hotend is expected to result from the thermal loads applied to the hotend. The mechanical properties of the aluminium alloy selected for the hotend/extruder are listed in Table 2. Temperature distribution result on the hotend/extruder component is presented in Figure 4a. The result showed that a maximum temperature of  $510 - 530 \text{ K}$  is experienced and distributed at the pointed end of the hotend/extruder. Furthermore it showed that temperature decreases towards the other end of the hotend/extruder.

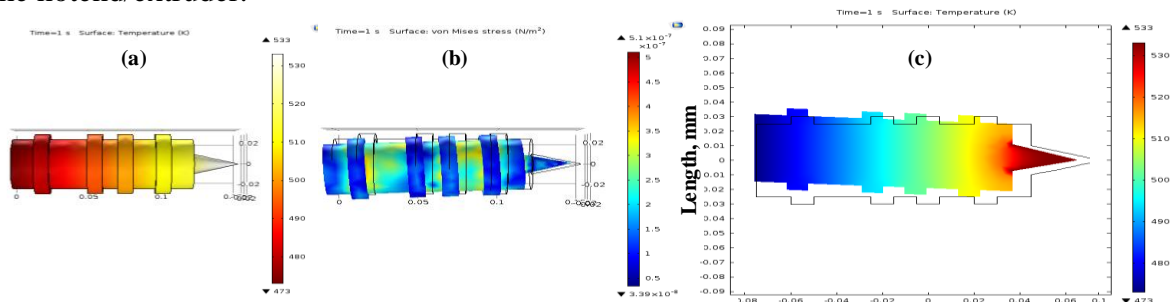


Figure 5: Distribution of temperature (a); thermal stress (b); and resultant displacement (c) for the Hotend/Extruder model

The simulation of stress distribution on thermal analysis of hotend/extruder component is shown in Figure 5. The simulation result occurring on the maximum stress of the component is between  $2.5 \times 10^{-7} \text{ N.m}^{-2}$  and  $3.5 \times 10^{-7} \text{ N.m}^{-2}$ . The stresses are distributed along the length of the hotend/extruder component. However, this maximum stress value obtained is lower than the yield strength of the aluminium alloy selected as material for the hotend/extruder as seen in Table 2. The result indicates that the selected material is suitable for use as the hotend/extruder in the development of the FDM machine.

Furthermore, a thermal deflection of the hotend/extruder was observed during the analysis. The deflection occurred due to the action of the thermal stress on the component part. Figure 4c shows the distribution of the resultant deflection of the hotend/extruder under the action of thermal loads. A maximum resultant deflection of 0.01 mm was observed on the entire component part. The effect of the maximum resultant deflection may be considered negligible since the maximum stress observed on the part is below the yield strength of the aluminium alloy selected as material for the component.

#### 4.5 The developed FDM machine

Figure 5a shows the developed FDM machine which was locally fabricated using some locally sourced and bought-out parts. The developed FDM machine was able to perform the intention of its development as plastic -based prototypes of car logos were fabricated using the machine as shown in Figure 5b.

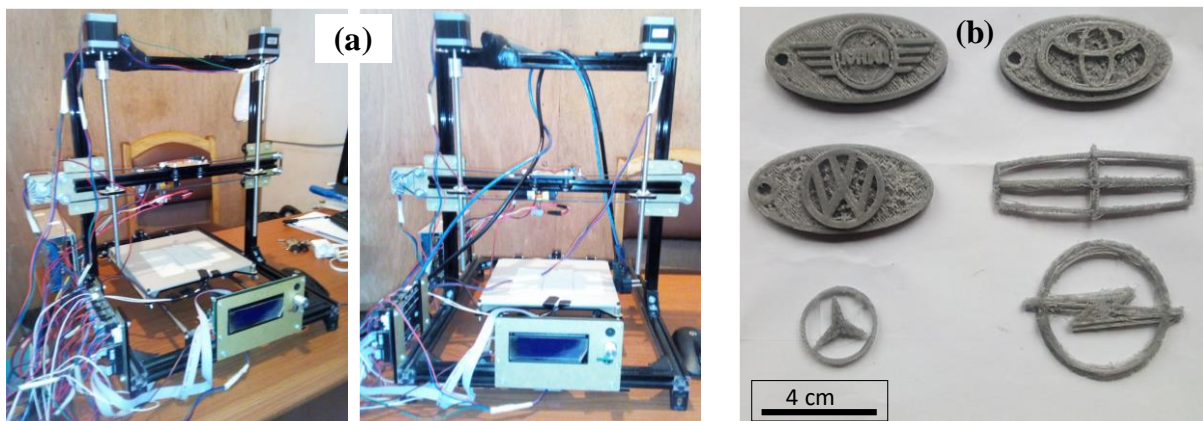


Figure 4: The developed FDM machine (a); and fabricated car logo prototypes using the machine

#### 4.6 Discussion

The results of FE simulation for the stress distribution and resultant displacement variation in the FDM machine frame members pinpoint the locations where maximum stress and displacement was subjected to. This is a location where structural failure may likely occur when developed machine is put to use. The simulation results also indicated that the material selected for the development of the machine were adequate and suitable for use. The yield strength of aluminium alloy for the development of the frame was far greater than the maximum stress value, which made the minimum factor of safety obtained to be high. The factor of safety is a good indicator to determine the structural integrity of the machine frame as it appears that the high value of factor of safety show the machine frame has been over-designed. However, it is important to note that this design choice is necessary in order to avoid any significant deflection of the machine beam as this will affect the quality of printed or produced prototypes from the FDM machine. This, however, is not to say that it is out of place to review the material selection for the frame in such a way that the factor of safety value is less increased. Selection of the material review can be carried out, provided there is low cost expenditure related with the newly selected material and it is available in the market.

Furthermore, the FE simulation on the heated bed and hotend/extruder to investigate temperature distribution, thermal stresses and deflections showed that the aluminium alloy chosen as the heated bed and hotend/extruder material was sufficient, as attained from the maximum stress on both component parts after the simulation which did not go beyond the material yield strength. Hence, the component parts are expected to be able to withstand the maximum temperature which they may likely be subjected to during printing operation.

## 5. CONCLUSIONS

In this work, the design of low cost FDM has been successfully achieved. The designed FDM machine is intended to be developed using locally sourced parts and some bought out component parts. The FDM machine was designed to have mechanical and electrical components. The design of machine frame members was analyzed and operational integrity of the designed FDM machine was assessed using Autodesk Inventor FE simulation tools. Having applied a combined load of 301.29 N on the frame structure, the result from Autodesk Inventor simulation depicted that a maximum stress of 3.669 MPa was achieved in one of the simulated machine frame members, which is lesser than yield strength of the material. The machine integrity of the designed frame was established by the minimum safety factor of 12.537 obtained from the simulation results.

The thermal analysis of the heated bed and the hotend/extruder was also carried out and the suitability of the component parts was determined using Finite Element modeling tool in CAD COMSOL Multi-physics application. Upon the subjection of the heated bed and hotend/extruder to a maximum temperature of 110°C (383 K) and 260°C (533 K) respectively, both component parts experienced a maximum stress of  $1.5 \times 10^{-7} \text{ N.m}^{-2}$  and  $3.5 \times 10^{-7} \text{ N.m}^{-2}$  that is below the material yield strength for both components. This indicates that the heated bed and the hotend/extruder design is appropriate. Hence, the design was considered suitable for use in the FDM machine based on the design analyses and evaluation. The FDM machine was developed and it was able to fulfill its intended purpose for fabrication of plastic-based parts.

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