Finite Element Analysis on Vacuum Chamber for Fused Deposition Modeling Applications

S.Maidin, J.H.U.Wong, A.S. Mohamed, W.F.A.Romlee, S.Sivarao

ABSTRACT: In general, fused deposition modeling (FDM) process is operated either in enclosed or open space to produce physical polymer parts. Hence, environmental factors such as air quality, temperature and humidity cannot be well-controlled. Consequently, these factors will indirectly affect the quality build of FDM printed parts. Vacuum technology has been used in a wide variety of applications to create space devoid of matter. Despite numerous studies on vacuum chamber, there is no investigation on FDM operated in a vacuum chamber. This paper presents an approach to the design and analysis of vacuum chamber to sustain medium vacuum pressure for FDM monitoring and applications. The inner vacuum chamber required to be 1.325 kPa (medium vacuum) which will lead to external compressive forces of 100 kPa. Thus, to sustain the sufficient amount of pressure, design specifications such as design, size, shape, material, safety factor, displacement and stress value will be considered in the design stage. The finite element analysis (FEA) from the simulation result shows that the rectangular vacuum chamber using Polymethyl methacrylate (PMMA) material is able to sustain the 100 kPa with 1.7 safety factor and maximum displacement of 7.02 mm. In future, this study can be used to aid performance study on the mechanical strength of FDM printed parts.

KEYWORDS: Fused Deposition Modeling, Vacuum Chamber and Finite Element Analysis.

1. INTRODUCTION

Additive manufacturing (AM) is one of the layer based additive technology where a parts are manufactured using a layer by layer addition of material from a 3D-CAD model. AM is able to create visualisation models for products in short production time and capable of producing parts with complex geometry compared to other manufacturing processes [1].

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Fused deposition modeling (FDM) is one of the popularly used additive manufacturing processes to produce polymer parts [2]. FDM basically works by preparing a 3D CAD model and converts into a STL file. The file will be sliced into tiny horizontal sections. FDM machine will then reads the horizontal sections and extrudes thin molten filament based on the 2D contours in which, when stacked upon each other will create 3D model [3]. As AM technology is continuing growing, it has found a new utility in production, to manufacture end-use parts rather than just prototypes to save tremendous cost and time. However, insufficient mechanical properties of the parts are still an issue need to be solved in order to be used as a functional product [2].

Conversely, vacuum technology has been used to assist in major applications such as die casting [4], resin infusion moulding [5] and drying process [6] due to the fact that the vacuum is capable of changing the environment of the study or applications in a lower atmospheric state. The suitability of using vacuum is not only due to its pressure of molecular impacts on bounding surface, but rarefaction of gas which a number of gas molecules in a void volume can flow without getting weakened [7].

As an interest to investigate the use of vacuum chamber for FDM, this study will focus on designing a suitable vacuum chamber for FDM use. This paper aims to aid FDM to operate under medium vacuum stage (3,000 to 0.01 Pa) by developing a chamber design capable of sustaining stress due to the difference in pressure. The vacuum level required is 1.325 kPa which is less than atmospheric pressure, 101.325 kPa and leads to a compressive force, 100 kPa acting upon the chamber from the vacuum pump. Finite element analysis will be conducted by linear stress analysis to the vacuum chamber for expected stress of 100 kPa after deducting 1 atm by 1,325 Pa (vacuum). The chamber also required to be transparent for monitoring purposes. The factor of safety is expected to be in a range of 3 to 5 for reliability. For future references, this study shall be used to create more consistent and comprehensive design for FDM vacuum chamber to improve mechanical properties.

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2. BACKGROUND STUDY

Subsection Headings, Tables and Figures

Fused deposition modeling is one of the additive processes to produce polymer parts. Easily drawn 3D-CAD data set is sliced into layers and converted to a STL file. The file will be transferred to the FDM machine for support structure calculations and tool path generation. The FDM machine will heats up and deposits a molten polymer filament to create each layer on the designated tool path. The thermal fusion will allow the layered filaments in between to bond together and solidify [8]. FDM allows faster development process, especially handling complex geometries in a few steps, unlike other manufacturing processes which involve numerous stages [9]. FDM eliminates expensive tooling, part modifications and customisation freedom as well as minimal wastes produced. For a smaller batch production run, FDM has cost and time advantages over conventional manufacturing [10]. FDM however, possesses poor mechanical strength [11]. Studies showed that mechanical properties of the parts are affected by the bonding achieved between the filaments. The extruded filaments are unable to hold the temperature long enough for complete bonding between the filaments. Thus, mechanical properties of the printed parts and polymer filament material are not the same [12-13]. The low-pressure vacuum could minimise heat loss by reducing conduction and convection transfer of energy [14].

2.1 Vacuum Technology

Vacuum is an empty space of matter and occurs in relation to the atmosphere. In short, the vacuum is defined as a region or space with a gaseous pressure lower than the atmospheric pressure [14]. Depending on the applications and reasons, the amount of gas removed is different. Atmospheric pressure (101,325Pa) contains molecules that constantly hitting the surfaces. To elaborate, in an atomic level, the rate of collisions of individual particles with each other and the walls will depend on the amount of pressure. Therefore, when exposed under lower pressure environment, low amount of molecules can travel in a direction with a low chance of collisions [15]. This situation can be useful for various effects such as neglecting heat losses by convection through the air [16]. In order to perform a low-pressure applications and tests, the vacuum system is required. The vacuum system is to obtain, measure, and contain vacuum pressure in a chamber or vessel. It usually consists of pumps, gauges, valves and pipes [17]. Vacuum chamber operates by ensuring firm enclosures in every side by allowing removal of gases with the aid of vacuum pump. The vacuum chamber is used by researchers and industries for numerous test and applications.

2.2 Engineering Design Process

The engineering design process will divide the design stage of the vacuum chamber into three main phases which are conceptualisation, preliminary design and detailed design. The three phases will ensure optimised and correct final design of the vacuum chamber. The conceptual design phase is used to plan the proposed project by generating ideas such as developing work structures, brainstorming, ideation and creativity [18]. As mentioned, specifications are required to achieve the objectives. In this research study, the design requirements set for designing the vacuum chamber are to withstand 100,000 Pa external pressure and with optical properties. The vacuum chamber is assumed to be sealed perfectly from every attachment. Based on the requirements, information regarding the size and shape of the chamber, material used, safety factor, and stress have to be gathered. The result and analysis will determine the suitable design to be selected. The von Mises yield criterion (Refer Equation 1) is used to predict the yielding of materials under any load before failure. When the energy of distortion reaches the same energy from simple uniaxial tension, failure of the material will occur. Thus, to prevent the material yielding, the von Mises yield stress must be lower than the yield stress of the material chosen.

$$\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2} \geq \sigma_y \qquad (1)$$

$$\left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{1/2} \geq \sigma_v$$

The denoted as von Mises stress. When the stress, exceeds material yield strength, failure will occurs. The failure condition of the material can be summarized as,

$$\sigma_v \geq \sigma_y$$

The factor of safety, therefore, will be,

$$FOS = \frac{\sigma_y}{\sigma_v} \qquad (2)$$

Preliminary phase is the gap in between concept design and detailed design phase. This phase

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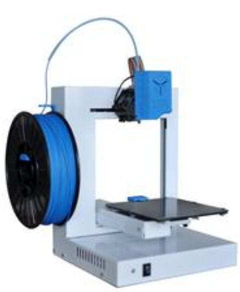
focuses on creating a general framework to create the vacuum chamber [19]. The design of vacuum chamber comes in all shapes and sizes depending on its purpose. For example, commonly used shapes are a sphere, ellipsoid, pyramid, cone, diamond, cylindrical (domed or flat ends) and box (rectangular or square) [20]. The shape of the vacuum chamber affects the volume and surface area of the chamber itself. Reducing the surface area increases the efficiency of the pumping time to remove the air particles. In comparison with cylindrical shape with other shapes, the cylindrical shape is able to sustain higher pressure with identical wall thickness and size [19], [20], [21]. Other than the shape and size design, material selection plays an important role to withstand high pressure to avoid failure due to yield. Pressure exerted on the shell uniformly in which properties of the material must be analysed.

2.3 Finite Element Analysis

Finite element analysis (FEA) is crucial to address problems and the key to effective design. For example, static analysis is performed to determine the stress, strain, displacement, fatigue and factor of safety on the design model. The analysis will be able to give the insights on the design model and chances to refine it and re-analyse. Commercial softwares such as ANSYS, Abaqus, SolidWorks, Adina and many more offers simulation studies in wide applications. The study has been done to evaluate the stress concentration factors and the notch stress intensity factors using sharp and coarse linear elastic finite element model which was validated with experimental results shown satisfying results [22]. In another study, one-dimensional finite elements derived through a Unified Formation calculates a thermal stress analysis on beam and the results are accurate after validated by the software ANSYS [23]. Researchers are constantly improving finite element analysis's accuracy and efficiency so that it will be more reliable and close to the actual applications [24-25].

3. MODELLING

In this study, a 3D CAD model for vacuum chamber was generated based on the background study. UP Plus 2 wasselected as the FDM machine shown in Figure 1.



Printing Material	ABS or PLA
Printer Weight	5 KG
Printer Size	245 x 260 x 350 mm

Figure 1: Up Plus 2 FDM machine

A rectangular shaped chamber will be selected due to the nature of the FDM shape. This will reduce the surface area of the chamber to increase the efficiency of air removal rate. In order to ensure unobstructed operation of UP Plus 2 FDM machine, the chamber has to be larger than the FDM machine itself. The extruder, filament tube, filament spool and platform will be the major components that deviate from original FDM size. Polymethyl methacrylate(PMMA) material will be chosen as modelled material and its properties are shown in Table 1.

Table 1: Material properties of PMMA

Property	Value
Elastic Modulus	3.0e9 N/m^2
Poisson's Ratio	0.35
Mass Density	1200 kg/m^3
Yield Strength	4.5e7 N/m^2

It inhibits excellent optical properties, good abrasion resistance, hardness and stiffness compared to other materials. The inner dimensions are 350 x 390 x 400 mm with 12 mm wall thickness shown in Figure 2. With the density of the material and volume of the chamber, the estimated mass is 13.66 kg.

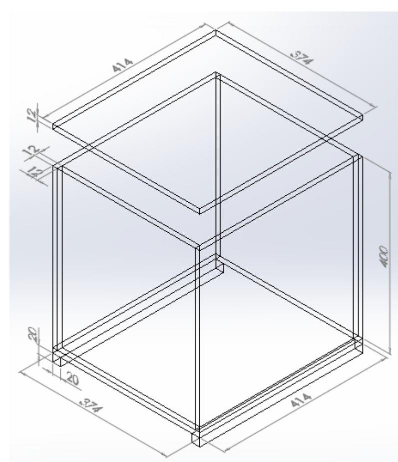


Figure 2:Dimensions of vacuum chamber (mm)

4. METHODOLOGY

CAD-embedded simulation allows the user to carry out a structural analysis of models with finite element analysis. A linear stress analysis was applied to ensure the geometry remains in linear elastic range. In preparations to conduct finite

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element analysis, a 3D vacuum chamber model was generated. The simulated environment was set to 24^{o}C and the assembly parts were assumed to be perfectly sealed to test the strength of the vacuum chamber. The sealing type was adhesives bonding and applied to all parts which are thin and does not allow shear. The contact sets was globally bonded as well. Structural analysis simulation was used to run the analysis. The static analysis study was selected to carry out on the vacuum chamber. Next, the model was selected and applied with PMMA material only. In interactions step shown in Figure 3, a fixture as the fixed geometry was placed on both support stands (20 x 20 x 214 mm) at the bottom, all parts are bonded –adhesives and 100,000 Pa pressure were exerted uniformly on all surface of the vacuum chamber wall. Every object has a 6 degree of freedom. Conversely, both of the support stands are fixed in geometry (restraint) which there will be no translation and no rotation. The pressure of outside air exerts on the chamber is applied in all directions. This means there will be no motion along the restricted DOF and the number of DOF of the chamber is reduced to 1. Even if the chamber is loaded, only displacements due to its deformation raise. Since the model is a flat cube shape with no curvature surface, the standard mesh will be used. The standard mesh uses the Voronoi-Delaunay triangulation splitting the geometry into triangles or tetrahedrons. The model meshed in highest mesh quality. The total numbers of the element are 35,994 with the size of 14.22 mm and tolerance of 0.71 mm. Lastly, the simulation was run to define the von Mises Stress, displacement and factor of safety. The strength of the vacuum chamber can be identified by reporting component stress and deformations. Hence, this study will be able to test the suitability of design structure and specifications on the vacuum chamber.

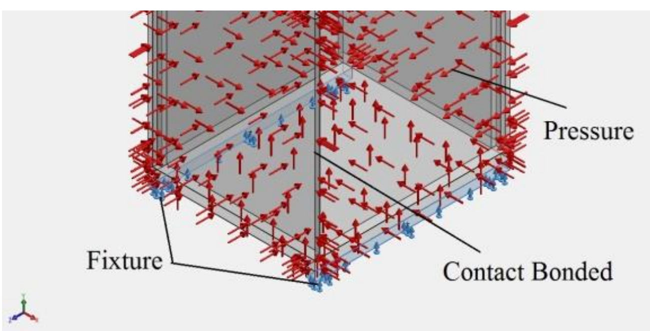
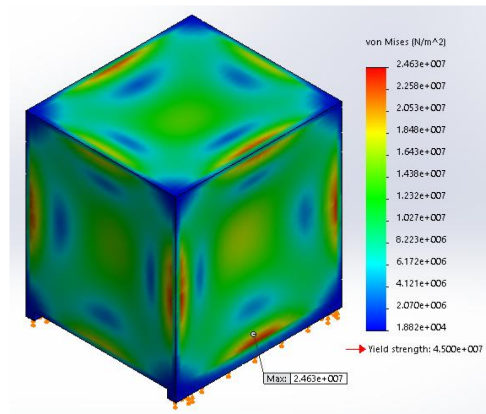


Figure 3: Model interactions

5. RESULTS AND DISCUSSION

Finite element analysis was carried out to study the static stress acting on the vacuum chamber due to external compressive force. Von Mises Stress states that failure will occur when the energy of distortion reaches the same energy from uniaxial tension [26]. The results shown in Figure 4, the maximum Von Mises stress estimated from the FEA is 2.403e7 Pa which is lower than the compressive yield strength 4.5e7 Pa. Hence, the vacuum chamber is safe from this criterion. The maximum stress is located in between both walls [27]. This is due to the pressure applied perpendicularly on each side of the walls causes the joint to experience stress due to compression from both sides of the walls [28].



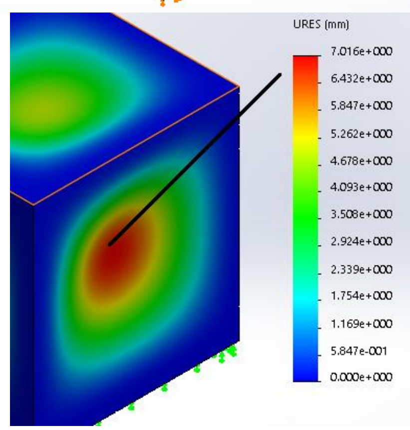


Figure 4: Maximum Von Mises Stress Figure 5: Maximum static displacement

Displacement study was carried out to ensure allowable deflection of the chamber wall from its original place. This will prevent the wall from affecting FDM operations during the vacuum stage. From Figure 5, the maximum displacement is 7.02 mm occurred in the middle of 414 x 400 mm side chamber. One of the reasons behind this gap is because the chamber walls are perfectly bonded with each other in the simulation and not considering the type of contact joints. The factor of safety is performed to prevent the structural model to fail when beyond the capacity of expected loads. In order to achieve more than 1 safety factor, the ultimate stress has to be higher than von Mises stress. Referring to Max von Mises stress criterion, the factor of safety (refer Equation 2) can be calculated by dividing material yield strength with von Mises stress. In Figure 6, the minimum factor of safety is 1.7 which is in the desired range of 1.5 to 3. Hence, the structure will fail at 1.7 times the design load. The lowest factor of safety is located in between the joint on the walls due to the stress experienced by both sides of the walls.

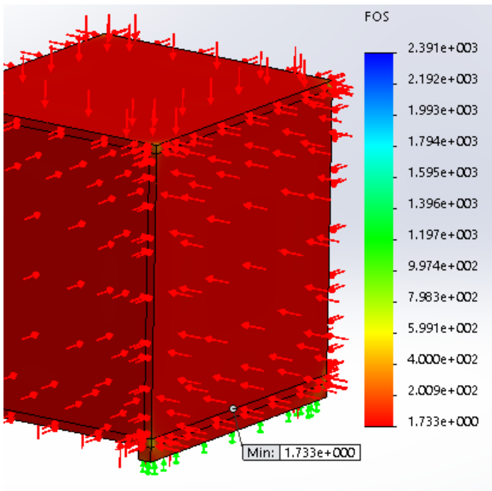


Figure 6: Factor of safety for vacuum chamber

6. CONCLUSION

A preliminary design of vacuum chamber was achieved for this study. By adapting engineering design process, a 3D model of vacuum chamber was created. The internal rectangular vacuum chamber size was 350 x 390 x 400 mm with 12 mm wall thickness. It weighed 13.66 kg and has excellent transparency due to material optical properties. From the finite element analysis, the vacuum chamber was able to withstand design pressure of 100 kPa with a safety factor of 1.7. The appropriate design and size of the chamber, as well as strong PMMA material properties, allows UP Plus 2 FDM machine to operate inside the vacuum chamber up to medium vacuum of 1.325 kPa. Moreover, the maximum displacement experienced by the chamber at 7.02 mm is in an acceptable range and will not obstruct the FDM operations. The actual chamber and simulated chamber may have differences in quality and geometric tolerances, the simulations results only can serve as design guidance. Therefore, reinforcement frame may be required. In future, other considerations such as O-ring and groove design to study air leakage will be explored to improve the reliability of the vacuum chamber for FDM use to maintain certain vacuum pressure.

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