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FEASIBILITY STUDY OF ULTRASONIC FREQUENCY APPLICATION ON FDM TO IMPROVE PARTS SURFACE FINISH

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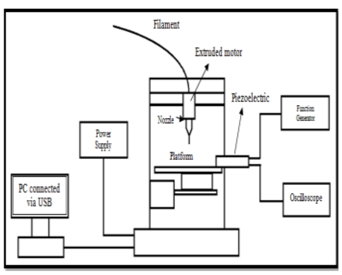
Graphical abstract



Abstract

Fuse Deposition Modeling (FDM) offer several advantages such as less expensive material, lack of expensive lasers and allows complex geometry to be built. However, FDM have limitations such as seam lines appear between layers and excess material residue, leading to surface roughness and poor finish. Ultrasound has been applied in various conventional machining process and shows good machined surface finish. However, from the literature review, it was found there is no investigation made on the application of ultrasound for Additive Manufacturing (AM) especially for FDM. This paper presents an adaptive approach to improve surface finish of FDM sample by applying ultrasonic vibration. The papers discuss the result of the surface finish of test piece printed via a desktop FDM system whereby an ultrasound device that was securely mounted onto the platform during printing process. Frequency that was used in the experiment is 11, 16 and 21 kHz with acrylonitrile butadiene styrene (ABS) material. Optical microscope with the aid of pro VIS software version 2.90 was used to measure the surface roughness of the four samples printed with a vibration in the above specified frequency. It was found that a 21 kHz frequency applied to the FDM process achieved the best surface finish due to less surface defects found and thickness had finer layers being produced. The results from this study could potentially be applied to other AM system such as the selective laser sintering, electron beam machining and stereolithography. The new data on effects of ultrasonic FDM technique and machining parameter for achieving improved surface finish has potential benefit to be used in various industries such as automotive, consumer, medical, sports, etc to produce prototypes or customized end used product or part. The data will benefit in term of product design and development elimination of manual post processing. Further study that could be done is to use different types of material such as polyactic acid (PLA) or composite material.

Keywords: Additive manufacturing, fuse deposition modeling, ultrasonic frequency

Abstrak

Pemendapan Pemodenan Terlakur (FDM) mempunyai beberapa kelebihan seperti bahan lebih murah, laser yang murah dan boleh membina bahagian yang kompleks. Walau bagaimanapun, FDM mempunyai kelemahan seperti kelihatan garis pada lapisan dan sisa bahan berlebihan, permukaan yang kasar dan kemasan yang kurang baik. Ultrabunyi telah digunakan pada pelbagai proses pemesinan konvensional dan menghasilkan kemasan permukaan yang baik. Walau bagaimanapun dari kajian literatur, didapati bahawa tiada penyiasatan dibuat pada aplikasi ultrabunyi untuk Pembuatan Tambahan (AM) terutamanya FDM. Kajian ini membentangkan tentang pendekatan untuk meningkatkan kemasan permukaan sample FDM dengan menggunakan getaran ultrasonic dan membincangkan hasil kemasan permukaan bahagian ujikaji yang dicetak melalui sistem FDM dimana alat ultrabunyi dipasang dengan selamat pada bahan kerja semasa proses percetakan. Frekuensi yang digunakan dalam eksperimen ini ialah 11, 16, dan 21 kHz dengan bahan acrylonitrile butadiene styrene (ABS). Mikroskop optik pro VIS dengan bantuan perisisan versi 2.90 telah digunakan untuk mengukur permukaan kasar sampel-sampel yang dicetak dengan 4 frekuensi yang dinyatakan di atas. Didapati frekuensi 21kHz menghasilkan kemasan permukaan sampel yang terbaik kerana kurang kecacatan dan lapisan lebih baik. Hasil daripada kajian ini ia perpotensi untuk digunakan pada sistem AM yang lain seperti pensinteran laser selektif, pemesinan elektron rasuk dan stereolithography. Kesan data baru pada teknik FDM dan parameter pemesinan untuk mencapai pembaikan kemasan permukaan mempunyai potensi faedah yang digunakan dalam pelbagai industri seperti automatif, pengguna, perubatan, sukan, dan lain lain unutk menghasilkan prototaip atau produk khas akhir pengguna. Data yang diperolehi akan member faedah dari segi reka bentuk produk dan menghapusan proses manual. Kajian lanjut yang boleh dilakukan adalah dengan menggunakan bahan yang berlainan seperti polyactic acid (PLA) atau bahan komposit.

Kata kunci: Pembuatan tambahan. pemodelan pemendapan terlakur, frekuensi ultrasonik

1.0 INTRODUCTION

Additive Manufacturing (AM) process has come through an evolution of rapid prototyping (RP) technologies over the past 30 years. There are various terminologies used at present that could be seen as alternatives to the internationally recognised term of AM such as 3D printing, additive fabrication, layered manufacturing, additive layered manufacturing, layered free-forming, part growing, freeform fabrication, layer-based manufacturing and rapid manufacturing. These variations of terminology have resulted due to various perspectives that appears from the industry and academic that utilise the systems. In the US, solid freeform fabrication is the preferred term for AM. In broad terms AM can be summarised as a technology for producing end use parts by adding, or building up material to form an object from 3D CAD data[1].

However, with all the conflict in the definition that exists, it cannot be denied that at present RP machines are being used to make AM products. In general, AM eliminates the need for tooling and shortens the overall time to manufacture. AM also differs from conventional manufacturing technology in that the concept of manufacture is not subtractive or formative (such as machining away material or moulding and casting to from product), but rather the "workpiece" is built by adding material in layers until a complete finish product is produced. AM requires a number of generic steps to produce a part or a product as follows:

(a) Create an STL file from the CAD model of the part and feed it to the machine's computer.
(b) Determine the orientation in which the part will be created.
(c) Generate virtual slices of the part with preset slice thickness.
(d) Create the first slice on the part platform.
(e) Move the part platform down by a distance equal to the slice thickness and repeat the process till the entire part is built.
(f) Post process the part including removal of support structures, curing, finishing, etc.

AM has seen a rapid uptake over the last decade in the industry. As it becomes more widely available, FDM systems that use a wide range of materials in a filament form has shown to be increasingly popular due to its availability and cost effectiveness [2]. AM also referred to as 3D printing, is a method of making 3D objects directly get from original CAD data by using layer by layer process which each layer on part derived is a thin layer of cross-section and have a finite thickness. The output can be different from the original by means of each layer must be thinner due to thickness layer affects the accuracy of the models.

FDM is an AM process which produces parts from thermoplastic filaments. The build and support materials are a continuous filament held on a spool that is fed through heated extrusion nozzles. The material is heated to a semi-liquid state and extruded via a heated nozzle by form each layer to generated sections of parts, which is controlled by a x-y motion control [3]. The nozzle extrudes material as it follows the contours in the x-y plane based on the program generated by the CAD model. Once a layer is complete the build table moves in the z direction one layer thickness for the next layer to begin. This process is repeated for each layer until the final build height is reached. Various applications can be produced through the use of FDM such as design verification, functional testing, and design studies [4].

Despite its ability to build functional parts with complex geometrical shapes, due to it's staircase effect during the parts' printing process that resulted in poor surface finish, the final result of FDM parts usually requires some form of post-processing such barrel finishing, chemical treatment or hand finishing. Whereas, traditional machining processes have trouble forming internal voids or other geometries beyond the physical reach of the standard tools, AM processes have the freedom of geometry part due to the layer-based build method.

The purpose of this research is to investigate the novel use of an ultrasonic-assisted technique to improve the surface quality of parts built by FDM. According to Yang et al. [5], ultrasound is a proven technology that has been extensively used for machining and it has been claimed to improve surface quality of work pieces. The ultrasonic vibration with piezoelectric components that vibrate in a vertical direction have been used to assist laser machining and it has produced a high degree of surface finish [6]. The ultrasonic assisted machining process is non-thermal, non-chemical and does not require the work piece to be electrically conducted. As a result, there are no adverse integrity effects; yet increased fatigue strength. Taking a step further, this research proposes the use of ultrasound by converting low frequency electrical energy (60 Hz) to a high-frequency electrical signal (approximately 20 kHz) that is fed to a transducer.

Nad [7] found that, ultrasound has been increasingly used in many industrial applications, and it is a proven technology being able to improve the quality of machined surface finish. In ultrasonic machining, the tool vibrates at a high frequency usually higher than 20 kHz, and abrasive slurry is pumped between the work piece and the tool [8]. This process does not cause a chemical reaction and is therefore regarded to be safe and does not chemically corrode the work piece. Ultrasonic vibration is an effective method to release the local energy concentration because a high frequency repetitive motion has an effect normalizing the spatially concentrated energy uniformly.

In recent years, several researchers have investigated the effect of ultrasonic vibration in machining in order to improve the quality of machined surface. Most of the ultrasonic research in were in the field of subtractive manufacturing and there is lack of information of its application in AM especially FDM. Kang et al. [9] have investigated the effect of ultrasonic vibration in nanosecond laser machining on work surface finish. Tabatabei et al. [10] have reported ultrasonic assisted machining is an advanced processing technology that has a capability to improving the machining process, especially for hard material. Friel and Harris [11] studied the ultrasonic additive manufacturing in a hybrid production process and found that, the processes are suited to high tech metal matrix composites with high temperatures and pressure. Nik et al. [12] studied the effect of ultrasonic on grinding of Ti6A14v alloy. As a result by using ultrasonic frequency range 20 kHz applied to on workpiece has shown a reduction of grinding forces and improvement of surface roughness. Kim et al. [13] have experimentally demonstrated to overcome the micro sized holes on the surface of fabrication that do not have a high aspect ratio or a good surface finish. The author used a piezoelectric transducer with 23.56 kHz frequency to get a better surface fabrication. Lian et al. [14] have concluded that the ultrasonic assisted micro-milling frequency is not the bigger the better because high frequency vibration, will affect the cutter teeth tool life. Therefore, the quality of the processed depends on ultrasonic frequency.

In this study, two important process parameters of FDM were considered: (a) experimental concepts for the ultrasonic-assisted FDM and (b) frequency of ultrasonic vibration. The measured surface roughness at the end of the printing process was recorder using an optical microscope with the transducer clamped on the side of work piece. Comparatively analysis of sample produced with and without the applications of ultrasonic frequency was done.

1.1 Problem Statement

The main disadvantage of the FDM process (Figure 1) is that seam lines appear between layers and excess material may sometimes be produced as a residue, leading to surface roughness and poor finish [15]. Researchers have proposed that better surface finish for AM parts could be achieved by having an (i) optimal build orientation (ii) slicing strategy (iii) optimising the built parameters, and (iv) post-processing. According to Phatak et. al [16], using genetic algorithm technique to find the optimum orientation of the CAD part model by minimize build time, staircase error and material used to improve in productivity, part quality and economy during the part manufacture. However, there are too many procedur and required high skills. More specifically for the FDM process, good surface can be obtained by considering on few primary control factors such as layer thickness, depositon direction of filament roads, road (or raster), width, gap sized between filamnets and stacking sequence of the vertically stacked layers of bonded fibers (roads) [17]. The use of chemical treatment for FDM parts has shown potential but at the expense of a negligible change in the volume and may also affect the structural integrity of the prototype [15]. In addition, this technique requires time, set up and costly.

Figure 1 Example of poor finish product

2.0 EXPERIMENT SET-UP AND METHODOLOGY

Prior to the lab experiment, a simulation analysis of applying frequency on a FDM desktop was conducted to ensure the suitability and safety of experiment equipment. The dimensions of the FDM nozzle were measured and a 3D CAD model was created with a CAD software. Figure 2 shows the exploded view of the FDM nozzle and Figure 3 shows the assembly view of FDM Nozzle. Table 1 shows the detail about each parts of the FDM Nozzle including the parts name, the quantity, the volume(mm^3), the types of material and its density. There are 7 parts with 2 types of materials which are stainless steels and magnesium alloy. Each part has a different volume.

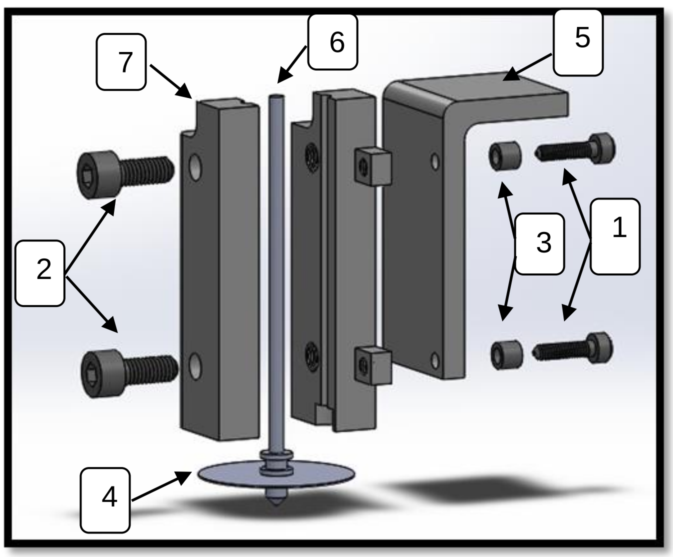


Figure 2 Exploded view of FDM Nozzle

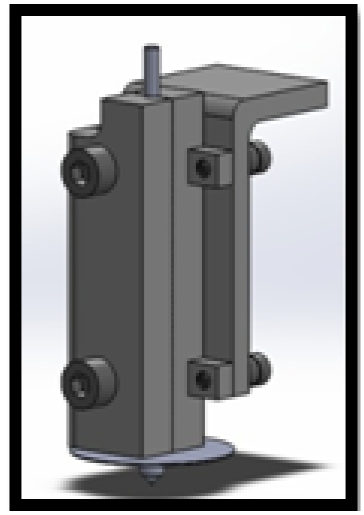


Figure 3 Assembly View of FDM Nozzle

Table 1 Parts of the FDM Nozzle

No	Part	Quantity	Volume (mm^3)	Material	Density (kg/m^3)
1	Cap screw M3	2	120.54	Stainless Steel	7750
2	Cap screw M5	2	413.72		
3	Bushing	1	50.27	Magnesium Alloy	1800
4	Extrusion nozzle	1	444.87		
5	Guider	1	8134.91		
6	Back clamper	1	8728.59		
7	Front clamper	1	8373.06		

ANSYS is a CAE software was used to run the simulation and analysis. The CAD file was saved in an IGES format to allow ANSYS to read the file. Static structural analysis was carried out to analyze the nozzle reaction to a force applied and to avoid any damage prior to the actual experiment on the FDM machine later. Total deformation of the FDM nozzle, virtual stress tests and the Factor of Safety (FoS) were obtained in the analysis.

The CAD data model used to analyze the reaction of the nozzle when subjected to the vibration from the ultrasonic transducer. The total deformation of the FDM nozzle and equivalent stress with frequency 20 kHz - 30 kHz and 30 kHz - 40 kHz were studied in this analysis.

Figure 4 shows the equivalent stress of FDM nozzle for frequency 20 kHz to 30 kHz. The highest value is 11.721 MPa and the lowest value is 21.324 MPa. The Factor of safety (FoS) for this model was obtained by using this result. The calculations showed that the factor of safety of the model was 20.56, referring to the fact that the nozzle can withstand a frequency range of between 20 kHz to 30 kHz that will be transmitted from the ultrasound transducer. Even though the FoS is high, we observed that bending still took place on the nozzle due to the fact that the part has a thin thickness profile. Our assessment also showed that no loose screws were found on the part after being subject to vibrations.

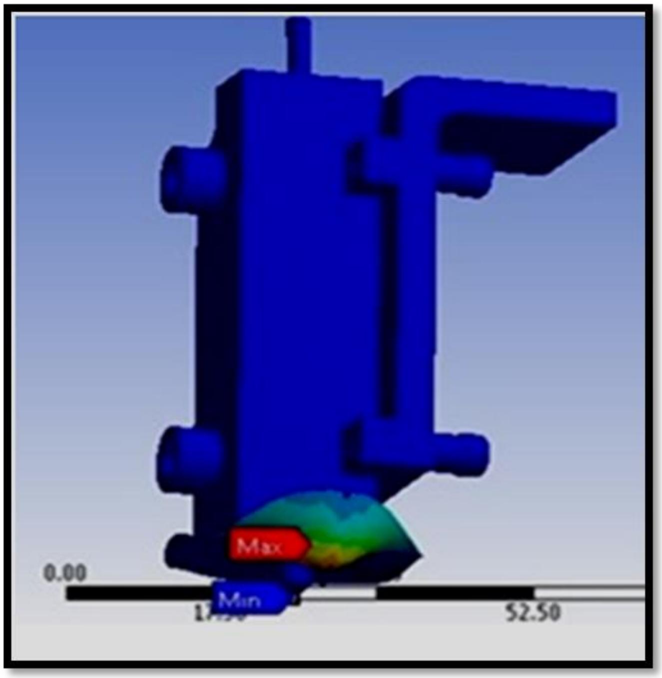


Figure 4 Equivalent stress of FDM nozzle using frequency 20 kHz to 30 kHz

$$\text{FoS} = \frac{\text{Ultimate tensile strength}}{\text{Maximum stress}}$$

$$= \frac{241\text{MPa}}{11.721\text{MPa}}$$

$$= 20.56$$

The highest value of maximum stress was 12.753 MPa and the lowest value is 6.464 MPa. The FoS for this model was found to be 18.8975, referring to the fact that the nozzle could potentially withstand frequencies between 30 kHz to 40 kHz from the ultrasonic transducer. The FoS was higher than 20 kHz to 30 kHz because the ultimate tensile strength also higher. The ultimate tensile strength was higher because the frequency was increased. The supposition is that having a higher frequency will result in a lower FoS for FDM nozzle. From the results of the analysis, we found that the FDM extrusion nozzle could potentially withstand frequencies up to 40 kHz. The lowest FoS that was obtained was 18.8975 (Figure 5).

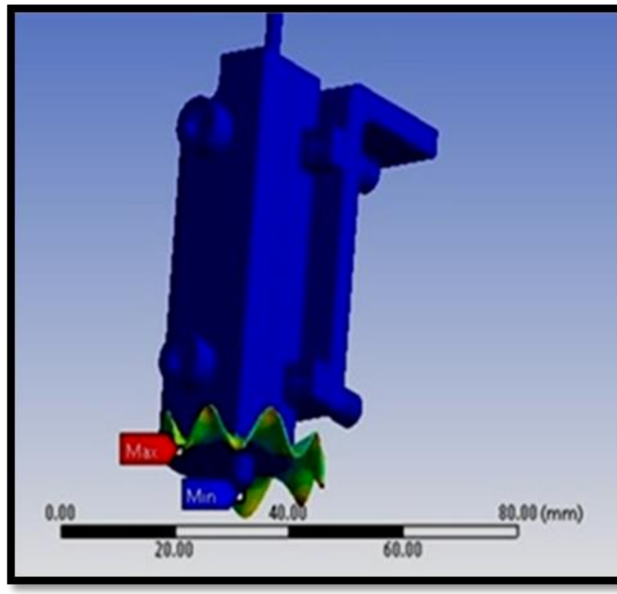


Figure 5 Equivalent stress of FDM nozzle using frequency 30 kHz to 40 kHz

$$\text{FoS} = \frac{\text{Ultimate tensile strength}}{\text{Maximum stress}}$$

$$= \frac{241\text{MPa}}{12.753\text{MPa}}$$

$$= 18.8975$$

The findings show that the nozzle is structurally and mechanically strong enough to withstand the high frequencies transmitted from the ultrasonic system. High deformations had occurred on the extrusion nozzle, but not to the cap screws. Our assessment also found that the joints of the cap screws remained secure throughout the process even after being subjected to a frequency of 40 kHz.

From this simulation, it was found that the nozzle of FDM system can tolerate a maximum frequency of 40 kHz frequency with a factor of safety (FoS) of 18.8975 [18]. The previous study also ascertained that the screws that hold the extrusion nozzle tips did not become loose when the vibration was applied due to the high frequency vibration being subjected to the nozzle. For this research, three experimental setups were developed to explain how the ultrasonic vibration device was connected to the FDM desktop system. Table 2 shows the three novel experimental concepts for the ultrasonic-assisted FDM. The product design specification consists of how easy was the installation, how safe the printer and ultrasonic piezoelectric transducer during printing and reliability of the transducer that was mounted to the 3D printer.

2.1 Conceptual Design

Figure 6 shows an FDM UP Plus 2 3D printer which has build size of 140mm X 140mm X 135mm and a 0.4mm nozzle diameter was used due to print the sample due to its ability to achieve fine build parameters through its thin layer thickness and road width, as well as being compatible with the ultrasonic-assisted system. The printer was chosen due to its popularity among users, as well as it availability. The material that was used in this research is ABS plastic which is the most common material for FDM systems. To aid the investigation, a standard piezoelectric ultrasonic transducer operating in a horizontal vibration mode was designed, fabricated and securely mounted onto the platform of FDM machine. The piezoelectric transducer was affixed to the whole surface so that the vibration will be transmitted equally thoroughly. The key challenge of this set up was the position of piezoelectric have to be mounted properly without touching others 3D printer component while calibration and printing process.

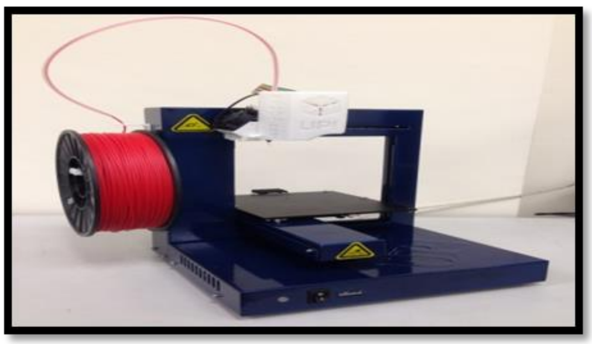


Figure 6 UP Plus 2 3D printer

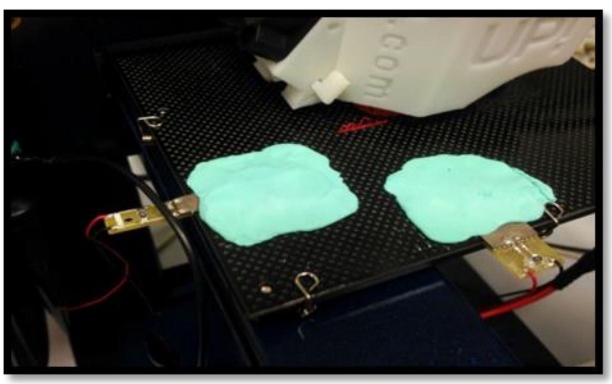


Figure 7 The platform of FDM

A function generator with a maximum power of 20V having an adjustable frequency was used to power the device. In this experiment, the frequency was set at 11, 16 and 21 kHz respectively was chosen randomly from a range of frequency of 11 to 27 kHz to study the effect of ultrasonic application on the sample with regards to the surface finish. There were 4 models printed using the FDM UP Plus 2 3D printer including the model printed without the ultrasonic vibration, following which the generated oscillation by the transducer is then transferred, focused to the platform of the FDM as shown in Figure 7 and a 3D CAD model was created (Figure 8). Figure 9 shows experiment set up for the experiment.

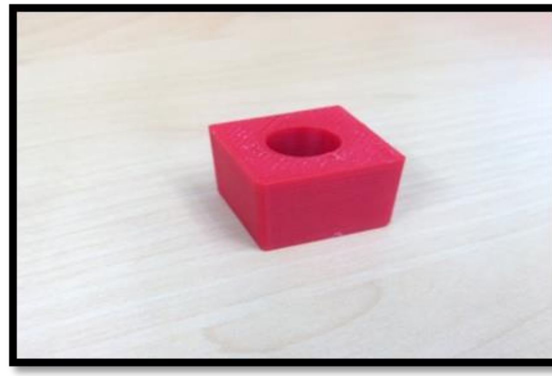


Figure 8 Sample printed

For this research, three experimental setups were developed to explain how the ultrasonic vibration device could be connected to the FDM desktop system. Table 2 shows the three experimental set up possible for the ultrasonic-assisted FDM. The product design specification consists of how easy was the installation, how safe the printer and ultrasonic piezoelectric transducer during printing and reliability of the transducer that was mounted to the 3D printer.

This research has extended our knowledge by using ultrasound technology to improve the surface finish of parts produced from a desktop FDM system. A comparative study was made and an analysis has been summarized in Table 1. Concept 1 has the most radical feature whereby the ultrasonic transducer is integrated with the heating block and the nozzle. Although this would avoid disturbing the process of melting the filament directly into nozzle, the main concern was that the heated block has a high temperature and could caused the transducer performance drop. Concept 2 is a variation of the first concept where the transducer was kept separate from the heater block and nozzle using a welded or screen sheet metal. Concept 3 showed the work piece being clamped onto the surface of the ultrasonic transducer being without exposed to high temperature and had direct transmission of vibration to the sample it is seen as the safest approach and the most feasible among all three concepts due to safety and the reliability of the transducer.

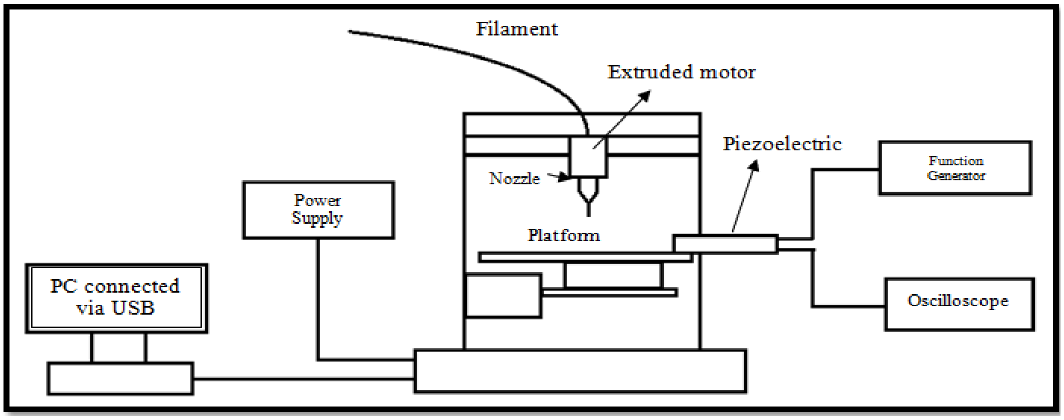
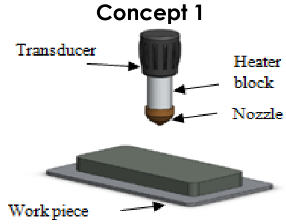
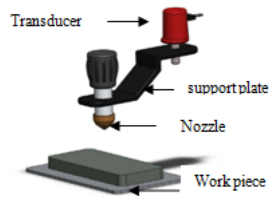
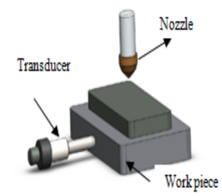


Figure 9 Schematic diagram of ultrasonic transducer

Table 2 Ultrasonic-Assisted FDM System Experimental Setup Concept

Conceptual Design / PDS	**Concept 1** 	**Concept 2** 	**Concept 3** 
Description of experiment setup	In this first concept, the transducer could be attached to the body of nozzle.	The second concept uses a sheet metal as a support on the transducer placed on the exterior of nozzle.	The third concept suggests that the work piece is clamped on the surface of ultrasonic transducer.
Installation	The transducer could be attached parallel on the top of heater block. The transducer vibration could be transmitted from the top of heater block to the nozzle.	Sheet metal is used to hold the transducer that is pivoted on the nozzle being welded or screwed	The transducer is clamped on the side of work piece. Only the work piece will be vibrated by the transducer.
Safety	The transducer should be monitored regularly and be in a safe operating temperature as the heater block has a high temperatures could block the nozzle during the material deposition and could cause transducer performance drop.	The selection of material for sheet metal need to be considered because of transducer's temperature could be too high and exterior transducer become easier to monitor.	The work piece will need to be properly aligned to the origin due to increased weight and for it to move up and down on the build platform smoothly.
Reliability	The transducer mounted on the top surface of the heater box without disturbing the process of material deposition.	Identical to concept 1 but the transducer is not directly connected to nozzle.	Fear of instability on the model produced due to the vibration of work piece.

2.2 Evaluation Parameter

Table 3 shows the FDM deposition parameters. For this research, the layer thickness, frequency and fill of surface were chosen as factors that would identify the quality of the surface roughness. The layer thickness and fill of surface parameters was set up base on the UP Plus 2 3D printer software and the frequency value setting by function generator. Layer thickness can be between 0.2 mm per layer to 0.4mm per layer. The finer layer thickness produced better quality, stronger the printed part and longer it takes to print. There are four types of honeycomb fill that could be selected from the 3D printer setting. However, only one type was choose namely semi-solid honeycomb (level 1) due to time consideration, quality and better surface of model produced. In this research, the ultrasonic actuator will be vibrated by ultrasonic power supply, with 11, 16 and 21 kHz and amplitude of 10μm which is the standard frequency.

Table 3 FDM deposition parameter

Parameter	Value
Layer thickness, t	0.2mm
Frequency, f	11, 16 and 21kHz
Fill of surface	Level 1
Amplitude, A	10µm

After the sample (square shape in size of 2 x 2 cm) was created with CAD software, it was printed using the 3D printer with a piezoelectric transducer mounted onto the built platform. An optical microscope with the aid of the pro VIS software was used to measure the surface roughness of the four models printed with the vibration in the specified frequency (Figure 10).

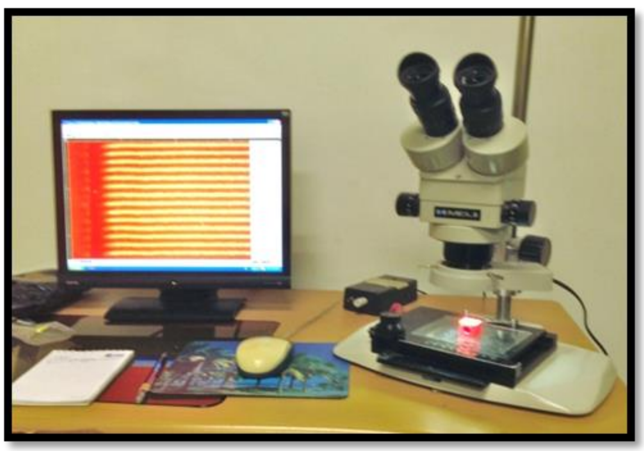
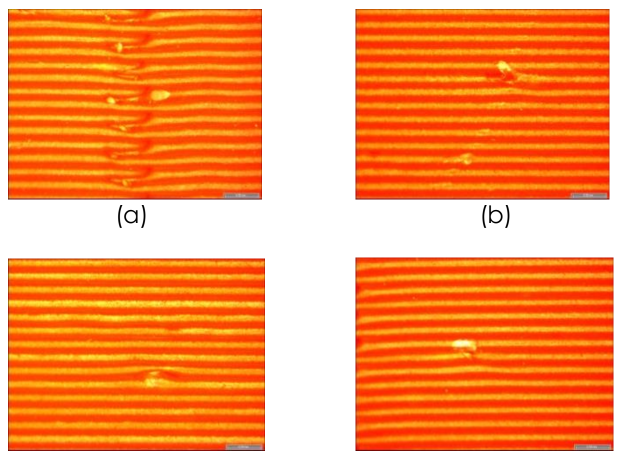


Figure 10 Optical microscope used to measure the surface roughness

3.0 RESULT AND DISCUSSION

Table 4 shows the results of frequency applied and the description of the surface roughness of each model. The experiment only focused on one critical surface whereby each model has 4 surfaces. The critical surface selected encompasses the high defect and rough surface that viewed through optical microscope (Figure 11).



(a) (b) (c) (d)

Figure 11 Surface roughness of sample (a) normal print, (b) 11 kHz, (c) 16 kHz and (d) 21 kHz.

Table 4 Result of surface roughness of each model

Frequency	Description
0 kHz (without vibration)	The surface roughness of the sample printed was poor. The result shows imperfections and discontinuity in the surface and the range of layer thickness was 0.17mm to 0.25mm.
11 kHz	When 11kHz frequency was applied the results shows the layer of surface was better than without vibration applied. Range of the layer thickness was between 0.07mm to 0.09mm.
16 kHz	When 16kHz frequency was applied the result shows that the defects were less compared to the 11kHz model. The thickness between the layers was consistent (from 0.08mm to 0.09mm).
21 kHz	When 21kHz frequency was applied the result was similar to that of 16 kHz. However, there were less surface defects found. The thickness between the layers was 0.07mm and 0.08mm thickness which had finer layers being produced. The defect layer thickness was reduced to 0.16mm. It was found that 21 kHz frequency shows the best surface roughness compared to 0 kHz to 16 kHz of frequency.

4.0 CONCLUSION

This research aims to present a new approach of ultrasonic-assisted FDM process to improve surface finish of FDM parts and considering the process parameter of layer thickness, road width and the speed of build. A comparative study was made and the analysis was summarised in Table 1. The research proved that the ultrasonic vibration to aid the reduction of the staircase effect during the printing process was able to make an improvement on the surface finish of the sample produced with the appropriate ultrasonic vibration frequency. The result shows that 21 kHz frequency applied to the FDM platform produced the best surface finish. By applying ultrasonic vibration during the FDM built process, the layer thickness was reduced from 0.09mm to 0.07mm. This shows that compression had occurred on the model surface while the vibration was transmitted. The defect thickness was reduced from 0.25mm to 0.16mm when frequency of 11 kHz to 21 kHz was applied. Future work to ascertain the technical advantages and disadvantages with process parameters such as layer thickness, build density and the speed of build will be varied and will be investigated, along with material removal rate, accuracy, and the quality of surface finish.

The results from this study have potential benefit to be used in various other AM process such as Selective Laser Sintering, Electron Beam Modeling and Stereolithography system. The data from this research will benefit in term of product design and development elimination of manual time consuming, hazardous and expensive post processing process. This could likely potential to benefit industries such as automotive, consumer, medical, sports, etc to produce prototypes or customised end used product or part.

For further study, it is recommended to print a complex part using geometries that have curved surface and with a different degrees of angles to study its consistency of surface finish produced. In addition, it is suggested to investigate the use of other material such as polyactic acid (PLA) or composite material and will print more than 1 sample for each frequency.

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