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# Optimization of Truss Collinear Lattice Fabricated using Fused Deposition Modeling Technique

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***Abstract:** manufacturing (AM) enables the production of lattice structure architecture due to its capability to produce complex geometries. Lattice structure is a design that contains a space-filling unit cell that can be tessellated among any axis. It is an analytic design to reduce mass and weight of the object. However, many challenges arise in the AM- printed lattice such as warping, shrinkage, elephant foot, first layer problem, surface finishing and mechanical properties especially when fabricated using fused deposition modeling (FDM) technique. Hence, this study aims to optimize the influence of process parameters of collinear lattice FDM printed part using Taguchi. Meanwhile, S/N ratio was used to find the optimal process parameters in improving the printing quality. Other than that, the analysis of variance (ANOVA) was used to provide the significance ranking of various factors analyzed. From the results, it was found that the layer thickness is the most significant factors that affect the maximum force (N) of collinear lattice structures. In addition, this study was conducted to assist the fabrication of printed part for the structural applications.*

***Keywords:** AM, Fused Deposition Modeling, Collinear Lattice, Layer Thickness, Nozzle Temperatures, Travel Speed*

## I. INTRODUCTION

Fused deposition modeling (FDM) is an additive manufacturing (AM) process that involves the extrusion of plastic material in layer-by-layer process. The process extruded plastic onto a build platform to build the complete parts according to 3D CAD model and processed using STL file. It has been widely used for its reliability and affordability.

Common materials used in this process are acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), nylon, polycarbonate (PC) and several composite materials such as carbon fiber reinforced polymer (CFRP) and metal powder reinforced polymer.

This technique has an enormous impact on certain applications. For example, the aerospace industry employs this technology because of the capabilities to manufacture light weight parts with lattice structures [1]. Lattice structures defined as a continuously repeating unit cell that connects to each other in three dimensions which typically created using a truss design [2-3]. Truss design is a structure that contains a core that is fully opened in all directions and it was classified into three groups; pyramidal structures, tetrahedral structures and collinear structures [4] as shown in Figure 1. In general, lattice structures are referred as a cellular solid which can be categorized into stochastic structures (foam) and non-stochastic structures [5]. Lattice structure is also suitable to be used as ultralight structures, conformal cooling, low thermal expansion structures and energy absorber [6-9] in automotive industry. It is widely used in a biomedical application such as tissue engineering and orthopedic implant [10-11].

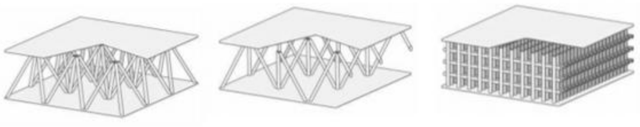
(a)pyramidal (b)tetrahedral (c)collinear

**Fig 1: Types of truss lattice structure**

Previously, the lattice structures were manufactured using a variety of traditional manufacturing process such as deformation forming, wire bonding, sheet metal and investment casting [12]. Therefore, only a simple macro scale lattice structure was capable to be manufactured. These often require multiple post-treatment techniques to finish production and also require specific apparatus with precise process control and assembly to produce the whole lattice. Recently, the usage of lattice structures has been in high demand for the industries.

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AM or 3D printing provides an alternative to produce these complex design of lattice structures in microscales without a requirement of additional tooling and costs [13]. Thus, the functional flexibilities of lattice produce from AM are very attractive to many applications. However, many challenges still arise in AM part's quality such as warping, shrinkage, elephant foot, low dimensional accuracy, low mechanical properties and surface roughness especially for the FDM technique [14]. FDM involves a technique that can produce lattice structures using layer by layer movement of the heated nozzle and work plate. Before the extrusion of the semi-liquid material happened, suitable printing process parameters were selected such as layer thickness, diameter of the extruder, and printing speed. From this point of view, it can be found that the manufacturing quality of the FDM printed part was affected by many factors. Therefore, the optimization process and quality control of the FDM process is necessary. Many scholars have studied the optimization process parameters in FDM. For example, the layer thickness, temperature, printing speed and other process parameters have a great impact on the printing quality [15-19]. Rao et al. [20] studied on the monitoring concept using multi-sensor to monitor the manufacturing process and investigated the effects of the material extrusion speed, temperature of the extruder and layer thickness on the surface roughness of the printed parts. Meanwhile, some researchers studied the method to reduce the model error by modifying the layer thickness and optimizing the STL model [21-23]. However, these studies were conducted using a simple geometry rather than the complex structures. It is compelling for a structure to be optimized because it contains a very small features and overhangs. In the lattice design, the overhang was found in a horizontal struts and incline struts which challenge the manufacturability in the AM process [24]. Due to the lack of research on the effects of process parameters on complex structures, there are no guidelines provided to obtain the optimal process parameters for FDM fabrication on the lattice structures. Therefore, it is essential to explore the relationship among the process parameters of FDM and the quality of lattice structures produced from this technology. It is the motivation of this study to analyze the truss collinear lattice structures. The structure was produce using FDM, and the optimization process was conducted using Taguchi analysis to obtain the better quality of maximum force (N) in terms of its design and fabrication process. This lattice type was chosen because the design contains open-celled topologies that can provide a good load support in either compression or tension and the mechanical performance of such lattice truss is therefore superior to the other stochastic foams structures. Further explanation of the lattice design was described in the methodology section.

## II. METHODOLOGY

During the experiment, the material polylactic acid (PLA) was used on FDM 3D printer. Then, the lattice structure was fabricated using open source 3D printer machine. Three process parameters were selected as a potential factor to influence the maximum force (N) in the compression testing of the lattice part. The detail descriptions of the experiment were discussed in the following sub-sections.

### A. Design method for truss collinear lattice

As mention, a lattice structure is generated by a unit cell's repetition following a spatial pattern. Therefore, a production of lattice structure is included in the pattern design and a unit cell. In this study, the truss collinear lattice structure was chosen. There are two types of collinear lattice designs; (a) collinear in diamond (b) collinear in square [25]. However, collinear in square was designed and discussed further in this paper. In addition, there are three component parts in a collinear lattice structure. It consists of a node, a cell and a beam as shown in Figure 2.

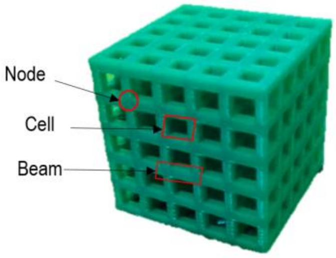


**Fig 2: A component in collinear lattice structure**

From Figure 2, node is a component that was attached together between the unit cells, meanwhile the cell is a representative as a single unit cell that is hollow and open celled [26]. Lastly, a beam connects all the nodes and unit cell together. This beam is commonly referred as overhang parts or a bridge which challenge the manufacturability in the FDM process. The lattice structures were then developed using direct patterning in which the unit cells are collinearly repeated. The dimensioning of the 3D CAD model of the designed lattice structure is shown in Figure 3.

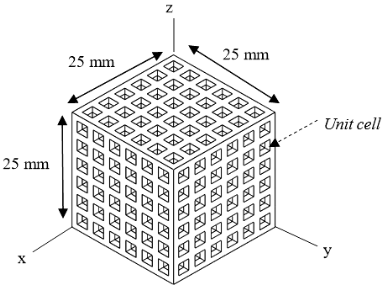


**Fig 3: Dimensioning of the 3D CAD model of truss collinear lattice in square**

The cube specimen in Figure 3 was designed using SOLIDWORKS software with a measurement of 25mm x 25 mm x 25 mm. It contains a unit cell size of 3mm$^3$ for x, y and z directions. After the design is completed, it was simplified into the STL file and later g-code was generated.

### B. Experimental setup

An FDM open source 3D printer was used for the experiments. The build volume of this machine is 250 x 250 x 180 mm. The porosity percentage of this lattice is constant for all of the specimens which is 40%. The porosity is expressed either in a fraction varying between 0 and 1 or a percentage between 0% and 100%. The porosity, *p*, is calculated using the relationship as in equation 1 as follows,

$$P = \frac{V_P}{V_T} \times 100 \qquad (1)$$

where;
$V_P$ = total volume of a pore
$V_T$ = total volume of a solid part

### C. Parameter selection and orthogonal array L9 Taguchi analysis

In this study, Taguchi analysis was conducted which involved nine samples of lattice structure being fabricated. The design parameters for the Taguchi analysis involved three levels of parameters which are lower rank, medium rank and a higher rank. Three parameters were selected as factors for the experiment and serve as an entry parameter to calculate the orthogonal arrays. The parameter descriptions were elaborated in Table I. Meanwhile, Table II describes the selected optimized parameter and their levels respectively.

**Table I: Summary of printing parameters and its descriptions**

| Parameter | Descriptions | Recommendations |
|---|---|---|
| **Layer thickness** | Lower height, greater quality | It is between 0.1 mm to 0.3 mm. The layer thickness should not be greater than 80% of the nozzle diameter |
| **Travel speed** | The speed of extruder when travelling from one point to another | The default is between 80 to 150 mm/s depends on the type of printer. However, it is recommended to print with a moderate speed of 130 mm/s. |
| **Temperature** | The temperature in 3D printer is variance depending on the type of thermoplastic material that is used. The composite material however having a higher temperature compared to the thermoplastic polymer | It is recommend to use the lower temperature because higher temperature lead to the degradation of polymer material and affected the part's quality especially strength |

**Table II: Factors and levels**

| Symbol | Printing parameters | Unit | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|---|
| **A** | Layer thickness | mm | 0.15 | 0.25 | 0.35 |
| **B** | Nozzle temperature | ˚C | 190 | 200 | 215 |
| **C** | Travel speed | mm/s | 40 | 60 | 80 |

These experiments were produced using a solid density to maximize the strength of the parts in order to achieve the maximum forces of the printed specimens. The lattice structure also contains hollow parts and these factors help to reduce the usage of materials and also optimize the built time. Taguchi analysis was conducted to obtain the optimal combination of process parameters. It measures the maximum force (N) of lattice structure using compressive testing. The lattice specimens were then fabricated according to the sample sequences described in Table III.

Based on three influence factors and three levels of parameters, orthogonal array L9 was selected to minimize the specimens. According to the orthogonal test array, nine sets of comparative test were conducted.

**Table III: Control log of experiment for collinear lattice fabrications**

| Specimen number | Layer thickness (mm) | Temperature (Celsius) | Printing speed (mm/s) |
|---|---|---|---|
| 1 | 0.15 | 200 | 40 |
| 2 | 0.15 | 215 | 60 |
| 3 | 0.15 | 220 | 80 |
| 4 | 0.25 | 200 | 60 |
| 5 | 0.25 | 215 | 80 |
| 6 | 0.25 | 220 | 40 |
| 7 | 0.35 | 200 | 80 |
| 8 | 0.35 | 215 | 40 |
| 9 | 0.35 | 220 | 60 |

## III. RESULTS AND DISCUSSION

In this section, results and discussion were discussed based on two parts; (A) analysis of S/N ratio and (B) Analysis of variance (ANOVA). The results from experiments express the maximum force (N) for lattice structure when the force was applied through the compression testing.

### A. Analysis of S/N ratio for compressive strength

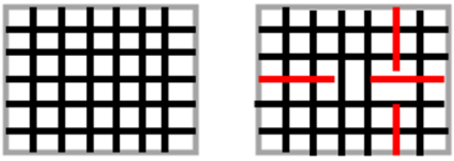
S/N ratio measures the variation of the compressive strength data in experiment. The best value for this analysis is to have the maximum force (N). Therefore, the S/N ratio is calculated using the objective function "larger-the-better". The S/N ratio for this function was expressed as;

$$SN_{LB} = -10\log\left[MSD_{LB}\right] = -10\log\left[\frac{\sum_{i=1}^{n}\left(1/y_i\right)^2}{n}\right] \tag{2}$$

where;
$y$ = responses for the given factor level combinations
$n$ = number of responses in the factor level combinations

In the experiment, nine test samples were fabricated and inspected to determine the quality of the lattice printed part. In Figure 4, the schematic diagram to compare the successfully printed lattice and the broken lattice was presented. The printed lattice was evaluated as a successful fabrication when all the elements of the whole lattice such as unit cell, nodes and beams were fully fabricated. If one of the element is broken, the printed lattice was categorized as a failure printed part. The results of the part quality from the inspection were tabulated in Table IV.

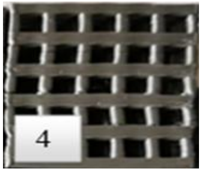
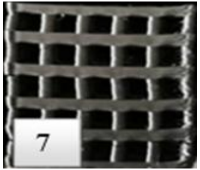
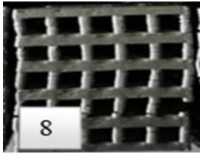
The broken part developed when the three elements in collinear lattice was not fully connected to each other when the fabrication occurs. Some parts of the unit cell were broken as shown in Test 9 in Table IV. This was happened when the material is not properly extruded due to the uncontrolled printing temperature.



(a) Successful part (b) Broken part

**Fig 4: Schematic diagram of (a) successful printed lattice and (b) broken printed lattice structures**

**Table IV: Printed part and its quality evaluation**

| Sample no | Printed part | Inspection |
|---|---|---|
| **1** |  | Successfully fabricated |
| **2** |  | Successfully fabricated |
| **3** |  | Successfully fabricated |
| **4** |  | Successfully fabricated |
| **5** |  | Fabricated |
| **6** |  | Fabricated |
| **7** |  | Slightly broken part |
| **8** |  | Broken node |
| **9** |  | Broken unit |

According to Table IV, all of the samples were fabricated. However, some of the compartments in the lattice such as unit cell, nodes and beam were broken and considered as failure to be fabricated as shown in Test 7, 8 and 9. It was already expected that these three samples number having a lower mechanical strength compared to the other samples. Figure 5 presented the S/N ratio graph of the maximum force (N) based on the Instron compression testing. From the graph, it can be seen that the layer thickness gave the significant factors that contribute to the maximum force of lattice structure followed by the printing speed and nozzle temperature.

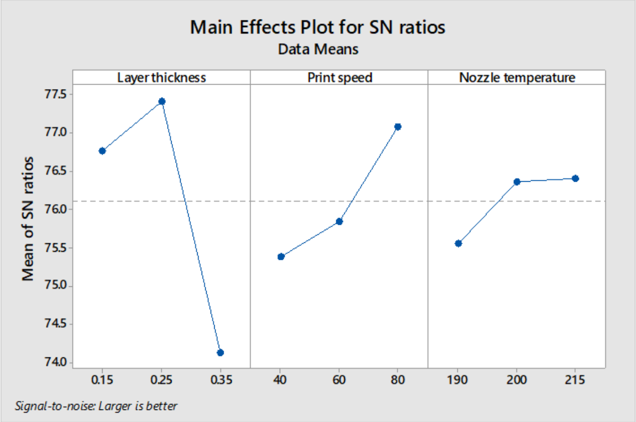


**Fig 5: Main effect graph between the layer thickness, travel speed and nozzle temperature of the maximum force (N)**

Meanwhile, in Table V, the travel speed (mm/s) gave less significant effect to the findings. According to FDM theory and practical, the printing process happened when the material is deposited in layer-by-layer manner. Thus, in order to produce a strong printed layer, the material needs to be properly adhered to the respective layer. Therefore, slow printing process is recommended to improve the layer adhesion and the quality [27]. However, in this study, fast printing was recommended to build the lattice structure because the parts contain a repeating beam (overhang/ bridges) in every unit cell. Thus, in order to fabricate the successful overhang parts, printing with fast speed is necessary to prevent the material extrusion from falling out, and produces unwanted sagging underneath the constructive layers.

**Table V: Response table and ranking factors**

| Level | Layer thickness (mm) | Travel speed (mm/s) | Nozzle temperature (°C) |
|---|---|---|---|
| 1 | 76.77 | 75.38 | 75.55 |
| 2 | 77.43 | 75.84 | 76.36 |
| 3 | 74.12 | 77.09 | 76.41 |
| Delta | 3.31 | 1.71 | 0.86 |
| Rank | 1 | 2 | 3 |

### B. ANOVA analysis

Analysis of variance (ANOVA) was conducted to determine the higher maximum force of lattice in compression testing. According to Table VI, the layer thickness shows a significant effect with p = 0.113, meanwhile for print speed p = 0.294 and nozzle temperature contributes by p = 0.719.

**Table VI: ANOVA for a maximum force of lattice produce**

| Source | DF | Adj SS | p-value | C% | Yes/No |
|---|---|---|---|---|---|
| Layer thickness | 2 | 9304392 | 0.113 | 67 | Yes |
| Travel speed | 2 | 2849871 | 0.294 | 13 | No |
| Nozzle temperature | 2 | 463937 | 0.719 | 3.3 | No |
| Error | 2 | 1185027 | | | |
| Total | 8 | 13803227 | | | |

From Table VI, 67% of the maximum force of lattice was affected by the layer thickness. At layer thickness 0.25 mm, the sample has the highest maximum force of the lattice. Meanwhile, for the lattice produced using the layer thickness of 0.35 mm, lower mechanical strength and forces were produced. The samples produced using low thickness are closely staked together, thus creating a better interlayer bonding between the layer and stronger compared to those with larger layer thickness values. In the hypothesis statement, it was expected that the sample produces for Test 1, Test 2 and Test 3 having a higher maximum force, however, the findings in this study is slightly different from the expected results and the main reasons was discussed further.After thoroughly examined on the lattice printed parts, the load was applied at the center of the lattice structure, thus, the center part must be stronger to extend the maximum load applied. Figure 6 describes the schematic diagram on the load applied to the lattice parts.

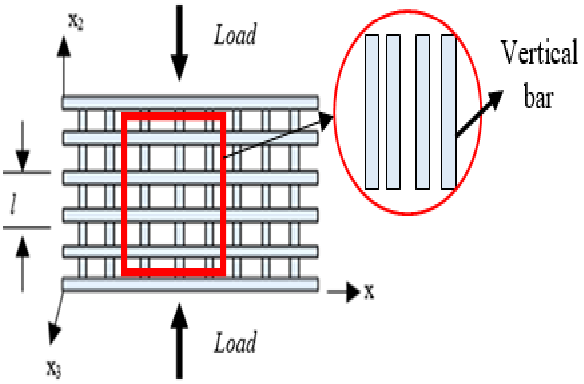
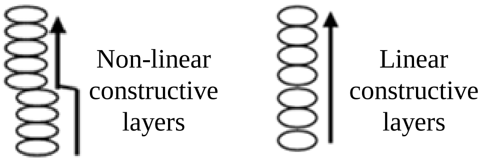


**Fig 6: Schematic diagram of applied load at the center of the lattice part**

According to Figure 6, the center of the lattice part is very important and it is necessary to be stronger compared to the other areas. Whilst printing the center of this collinear lattice, it was examined that the vertical bar produced on the lattice using layer thickness of 0.25 mm was constructed with a linear (straight line) layer compared to the layer thickness of 0.15 mm as described in the schematic diagram in Figure 7. Even though the parts produced using 0.15 mm layer is compact, the line is so small and closed to each respective layer, and however, the vertical bar produced is not in a linear shape. The distribution of the inconsistent force produces on the area, thus, the part is easily broken when the load was applied.



**(a) layer thickness 0.15 mm (b) layer thickness 0.25 mm**

**Fig 7: Schematic diagram on the comparison of the constructive layer on the vertical bar at the center of the lattice parts**

From the experiments, the nozzle temperature does not give any significant effects in the findings. In contrast with the other studies, the nozzle temperature does contribute on the mechanical properties. For example, the study conducted by Behzadnasab and Yousefi (2016) found that the melt viscosity of PLA is strongly dependent to the temperature. Hence, with the increasing of nozzle temperature while printing process occur; the melt viscosity of PLA decreased which resulted in a better diffusion of newly extruded PLA molecules in underlaying layer which produced a stronger interlayer adhesion [28]. However, in the studies made by [29], higher temperature increased the possibilities of the material degradations that lead to the lower mechanical properties of the printed part.

## IV. CONCLUSION

In this paper, the process parameter of FDM has been optimized for the truss collinear lattice structures. The lattice structure was designed using CAD software with consisted of a repeating unit cells, beam and node. Taguchi method was conducted which involved orthogonal array of L9 and nine sample of printed parts were produced. Three parameter was observed which are layer thickness, travel speed and nozzle temperature. In the study, it was found that the layer thickness with a small layer height (0.25 mm) contributed a significant effect to the high mechanical properties of the lattice structure with contribution factor (C) of 67%. Meanwhile, travel speed showed less significant effect to the mechanical properties with a contribution factor (C) of 13%. Furthermore, compression testing was conducted to investigate on the mechanical properties of lattice structure fabricated by a different processing parameters. From the study, it was observed that the proposed methodological work can improve the mechanical performance of lattice structure based on the printed part quality. In future, this research can be expanded by investigating the other materials properties such as the composite fiber reinforced polymer to produce a stiffer printed part that is suitable for the high impact and structural applications

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## AUTHORS PROFILE

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**Aini Zuhra Abdul Kadir** is a fulltime senior lecturer at the School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM). She is currently a Post Doctoral Fellow at Universiti Tun Hussein Onn, Malaysia (UTHM). Dr. Aini Zuhra obtained her Bachelor of Engineering (CAD/CAM) and Master of Engineering (Manufacturing) from University of Malaya, Malaysia and her PhD (Mechanical Engineering) from University of Auckland, New Zealand. From 2013 until 2019, she has occupied the post of Postgraduate Coordinator for the Master of Science (Advanced Manufacturing Technology). She is a member of the American Society of Mechanical Engineers (ASME), the Board of Engineers (BEM) Malaysia and the Institute of Engineers (IEM) Malaysia. She has taught courses in product design, DynaMech industrial-academia teaching program, tooling for production (undergraduate and postgraduate), engineering economy, manufacturing process, automotive production, and work design. Her research interests include Additive Manufacturing, STEP/STEP-NC, CAD/CAM/CAPP, Virtual Manufacturing, Finite Element Analysis, impact/crash testing, sustainable materials and product design. Dr. Aini, has secured several government grants, is currently an active Project Leader and a Project Member of various community-based research organisations.

**Nor Hasrul Akhmal Ngadiman** received his Bachelor of Engineering in Mechanical Engineering (Industry) degree from Universiti Teknologi Malaysia (UTM) in 2012. Based on his excellent achievement in academic and extra-curricular activities, he was offered an opportunity to pursue his Doctor of Philosophy (PhD) degree directly after his first degree under the Fast Track Programme by UTM. He embraced the challenge and with diligence and perseverance, he obtained his PhD in Mechanical Engineering from UTM in 2016.

Currently, he serves as a Senior Lecturer in the Department of Materials, Manufacturing and Industrial Engineering, School of Mechanical Engineering, Faculty of Engineering (FE), UTM, Johor Bahru, Johor, Malaysia. Dr. Hasrul is involved (both as Project Leader and Project Member) in numerous research projects funded by the Ministry of Education, Industries as well as from UTM. He has also published numerous papers in various international and national journals, and also published and presented numerous papers at international and national conferences or seminars, obtained over 94 citations and H- index 6. Dr. Hasrul is also involved in several consultancy projects involving various local company and organizations. He has also conducted training on various topics during various training courses organized by the university and department.

**Yusri Yusof** is Professor in the Faculty of Mechanical and Manufacturing Engineering at the Universiti Tun Hussein Onn Malaysia (UTHM). He has a PhD in Manufacturing, which he obtained from the University of Loughborough, United Kingdom in the year 2007. He is currently holding the administrative post as Director Strategic Planning and Risk Management Office since 1st July 2017. He has been appointed as Dean, Faculty of Mechanical and Manufacturing Engineering for 2 terms at the Universiti Tun Hussein Onn Malaysia (UTHM) since 1st November 2011 till 30 Jun, 2015, then as Director, International Office 2 years later. He has served as Senate member since 2011 till now. Dr. Yusri has multidisciplinary research interests and his main areas of research are CAD/CAM and STEP-NC. He has published more than 50 international technical papers, mainly in CAD/CAM and advanced manufacturing. Dr. Yusri lead about 20 grant research project involved almost RM2 million under Sciencefund (MOSTI), Prototype Research Grant (PRGS), Fundamental Research Grant (FRGS) and Internal Research Fund under Intelligent Manufacture for STEP-NC Compliant Machining projects. He has served as the Editorial Board of the International Journals and currently involved in several international bodies such as, International Association of Engineers (IAENG), Senior member of the Science and Engineering Institute (SCIEI), The World Academy of Science, Engineering and Technology (WASET) Scientific and Technical Committees, editorial & reviewers boards on Natural and Applied Sciences and Senior member of the International Association of Engineering Technology (IAET).

**Md Saidin Wahab** is a Professor at the Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn, Malaysia (UTHM). He is also a principle researcher at the Centre for Advanced Manufacturing and Material. Dr. Saidin received his Bachelor's degree from Universiti Teknologi Malaysia, and Master's degree from University of South Australia in Advanced Manufacturing Technology and his Ph.D from the University of Leeds, UK in Additive Manufacturing technology. His work focuses on utilizing the Digital Manufacturing System for rapid product development and rapid tooling for various applications i.e. engineering component, medical devices and constrution industry.