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Study on the Effect of Fused Deposition Modeling (FDM) Process Parameters on the Printed Part Quality

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ABSTRACT
3D printing known as additive manufacturing (AM) has been applied for applications in different fields such as aerospace, automotive, biomedical, and energy industries. It is the fact that 3D printing has gained a very wide acceptance over the last decade. However, several significant hurdles prevent its wider adoption. One of the most important barriers is the quality of the printed parts. Currently, many manufacturers and end users have difficulty stating with certainty that parts or products produced via 3D printing will be of consistent quality, strength, and reliability. Without this guarantee, many manufacturers will remain leery of AM technology. For getting the good quality of the printed part, influence factors must be considered such as material properties, machine specifications, printing conditions and process parameters. Among the large number of 3D printing methods, fused deposition modeling (FDM) method is used widely for printing the plastic products. The paper presents the analysis of the influence factors during FDM process reported in the literature as well as technology handbook to drive out the appropriate values of the printing process parameters. Experimental results were carried out with the optimal values of printing process in the 3D-FDM printer.

Keywords – 3D printing, Additive manufacturing, FDM, Printing quality, Surface roughness

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I. INTRODUCTION

3D printing is an advanced prototyping technology. Currently, with the rapid growth of AM technology, there are a large number of 3D printing methods in the market. Materials used for printing are classified into groups such as polymers, metals, ceramics, and cermets. In each group, materials are classified into types such as powder, solid, and liquid. For applications with plastic materials such as ABS, PLA in filament form, FDM is a suitable 3D printing method. Resent researches focus on evaluation of the quality of the FDM and applications of FDM for medical field [1]. For developing and refining the FDM technique, many vendors not only supply different AM systems to the market but also support the open source for users to develop the control system for specific applications [2]. In consideration of the printed part's quality with FDM technique, evaluation of open source as well as material properties have been carried out [3,4]. One of important applications of the FDM technique is for education field with graphic design and rapid prototyping courses [5].

Figure 1 shows the principle of FDM printing with two different color printing materials. Using the method of extrusion of thermoplastic materials based on the principle of melting plastic fibers is deposited through a thermal nozzle on a surface. The nozzle movement is controlled according to the 3D data supplied to the printer. Each layer after settling will solidify and bond to the previously printed layer [6-8].

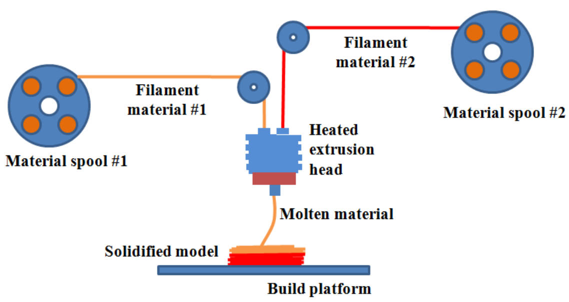

Fig. 1 Mechanism of fused deposition modeling

II. CORE FACTORS AFFECTING TO THE PRINTED PART

Nowadays, the additive manufacturing processes including FDM process are required to deliver the consistent quality, high productivity rate, safety, low manufacturing cost, and short lead time. In order to meet these requirements, the FDM process parameters must be established for each application [9]. The quality of the final part is decided by powder properties, process parameters and FDM machine characteristics as shown in Fig.2.

For getting the best quality of the printed part, influence factors must be considered such as material properties, machine specifications, printing conditions and process parameters.

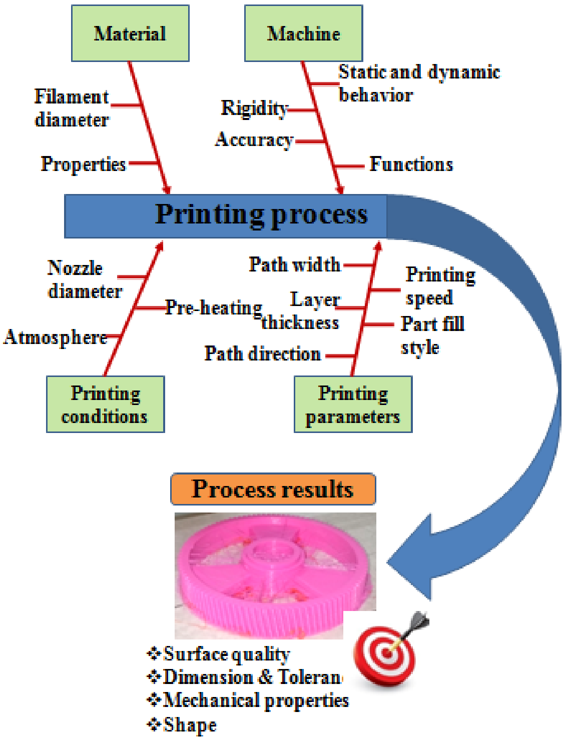

Fig. 2 Influence factors affecting the part quality

Currently, the default setting of printing process parameters provided by the manufacturer is used by user. However, in some cases, these default values do not guarantee quality (dimension error and strength) of the printed part, since there are several process parameters that need to be considered [10]. The key success of the FDM process depends upon the selection of optimal process parameters. Determination of the optimal parameters for printing process plays an important role to ensure quality of products, improve dimensional precision, avoid unacceptable wastes and large amount of scraps, enhance productivity rates and reduce production time and cost [9]. In the literature, the several optimization techniques have been successfully used for optimizing FDM process.

2.1. The heated extrusion head

Figure 3 shows the printing components including the printing head, heating material, and the cooling unit to ensure the printing head temperature. The printing unit is mounted on the rack and slide on the guide shaft to perform X-axis motion for printing.

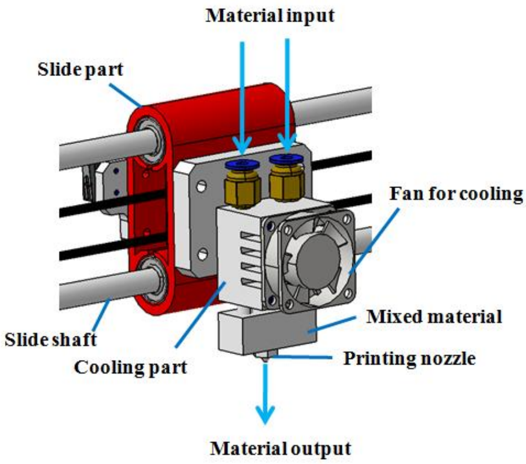

Fig. 3 The printing system

Hofstaetter et al. studied on the temperature distribution in the printing system with the E3D HotEnd Extruder which is manufactured diameters of 200÷400 µm in the nozzle tip [11]. The temperature distribution ensures that the suitable printing temperature for ABS material is 230 °C as shown in Fig. 4.

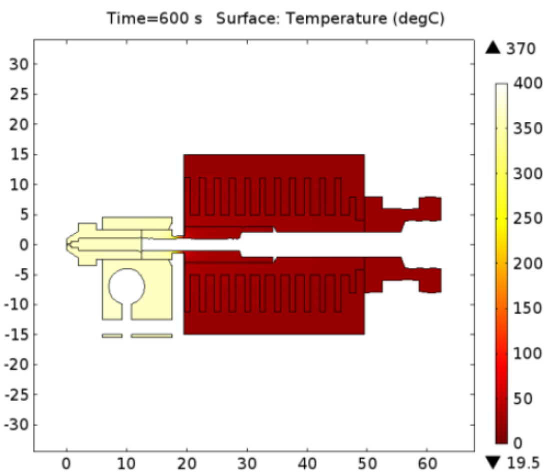

Fig. 4 Temperature distribution in the printing system [11]

2.2. Nozzle diameter

Choosing the optimum nozzle diameter is very important, not only in terms of accuracy but also in terms of the extrusion time [12]. The nozzle diameter is in the range from 0.2 mm to 0.4 mm [13]. The 0.3 mm diameter nozzle has been suggested as the optimum value for extruding PLA material in consideration of the extrusion time. This effect is shown in the formula for calculating the extrusion time as follows [12]:

$$\text{Extrusion time} = \frac{V}{d \times f \times l}$$

In which *V* is the volume of the printed part (mm^3), *d* is the nozzle diameter (mm), f refers to the filament feed rate (mm/s) and l is the total layer thickness (mm).

2.3. Printing process parameters

The printing process parameters such as the layer thickness, path width, printing speed, and path direction as shown in Fig .5 play an important role on the printed part quality. In the literature, many researchers have reported the relationship of the printing parameters with the quality as surface roughness. The estimation of surface roughness for FDM systems was carried out by Nourghassemi [14].

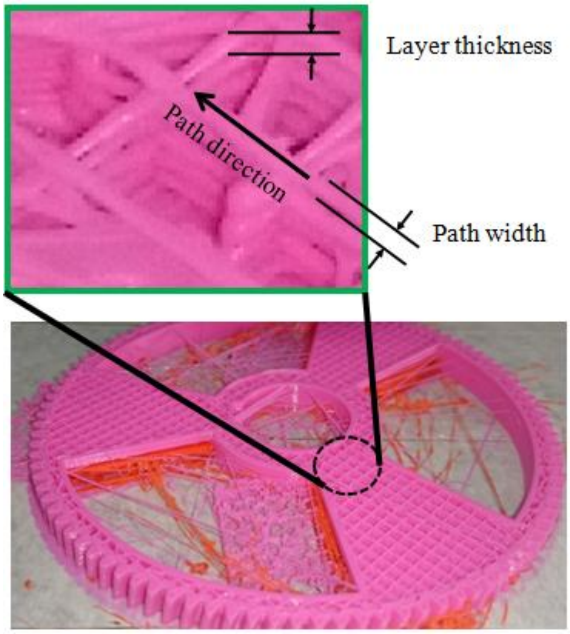

Fig. 5 Printing process parameters

The factor having the most important influence on the surface roughness is the layer thickness compared to path width and printing speed. It was also revealed that there was inverse relation between layer thickness and surface roughness [9].

2.4. Slicing and machine path generation

There is no standard machine path code for rapid prototyping (RP) because of the differences in the nature of rapid prototyping processes. Each RP process, based on its characteristics and requirements, uses the standard CAD file format to extract the required data for the process. The CAPP system needs a specialized machine path generator to create an appropriate machine path file. Machine path such as boundary path and hatch path should produce the printing pattern that enables the machine user to easily remove the fabricated part from the surrounding material. The machine path generator provides the ability to process CAD models of any size and complexity, the ability for machine path verification before sending the file to the machine, and the ability to fix the possible STL files disconnection errors.

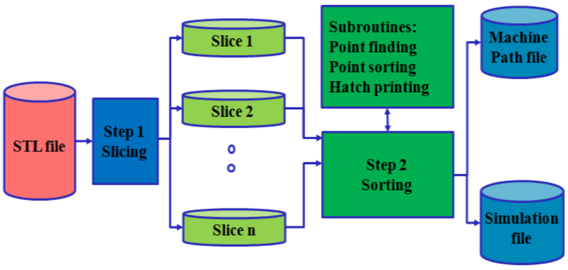

Fig. 6 Steps of slicing and machine path generation [15]

The CAPP system uses STL files with the ASCII format as input and works in two steps (Fig. 6). The first step generates slices at each increment of Z by intersecting the XY plane with the facets within the part. The second step uses all individual unsorted intersection lines in each Z increment to form the contour. This step includes sorting the intersection lines, recognizing the closed loops and disconnections (STL file error), and generating the machine path such as boundary path and hatch path, and simulation files.

In the first step the STL file is read as input. Slice files are then generated by executing the slicing algorithm. Only the intersection of those facets that intersect current Z=z are calculated and saved. In this step, one facet is read at a time from the STL file. Then the intersection lines of this facet with all XY planes are calculated. The intersection lines are stored in the specified file for the associated z increment. This results in one intersection line on each XY plane. By repeating this process for all facets, a set of slices is generated.

The example shown in Fig. 7 illustrates the slicing algorithm. After the completion of the slicing process, a set of vectors becomes available in each z increment. These vectors are not connected and are not in sequence.

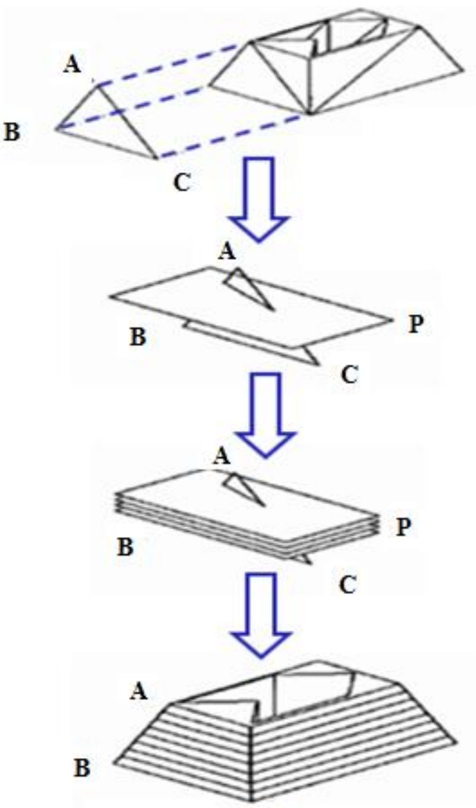

Fig. 7 Slicing algorithm [15]

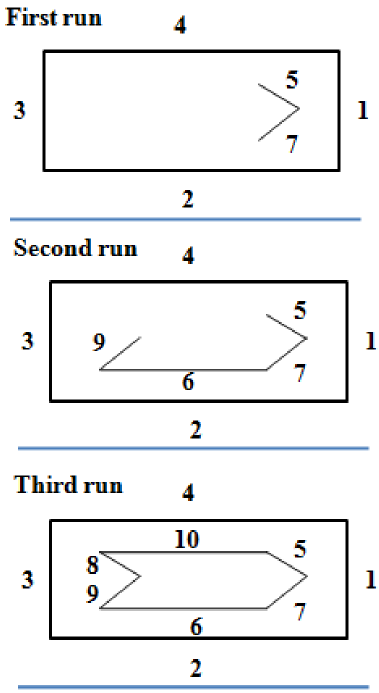

Fig. 8 Machine path generation [15]

In the machine path generation process as shown in Fig. 8, the software starts from one vector and tries to find the next connected vector to this vector. Then it does the same for the newly found vector until it reaches the start point of the first vector (in the closed loop cases) or finds a vector with no leading attachment (in faulty STL files containing disconnections). To sort the vectors, the algorithm reads one vector at a time from a slice file and writes it to another file. This file is either path file, when vector is connected to previous vector, or temp file, when the vector is not connected to the previous vector. Therefore, the sorting process does not need a large amount of memory to sort the data, and there is no limitation on the number of vectors in a slice and on input file size. This algorithm can generate a machine path even with disconnection errors in the STL file [15]. At disconnection instances the system sends a message to a log file and turns the printer off and starts from a new vector. In either case the printer is turned off and the system starts printing from another start point.

III. EXPERIMENTAL RESULTS

Figure 9 shows the structure of a 3D printer designed and manufactured. The Marlin software was chosen as the 3D printing driver software. Marlin is an Arduino-based program for 3D printing controllers using the Atmel's AVR microcontrollers. For each design of the 3D printers, it is necessary to set the following information: information of the control circuit; printer name; number of plastic extrusion; source type; temperature sensor; set up the extruder temperature stabilization; minimum allowable temperature; maximum allowable temperature; power supply for heat table; set up to prevent temperature problems for the printer; set the print area size; and set up the LCD controller.

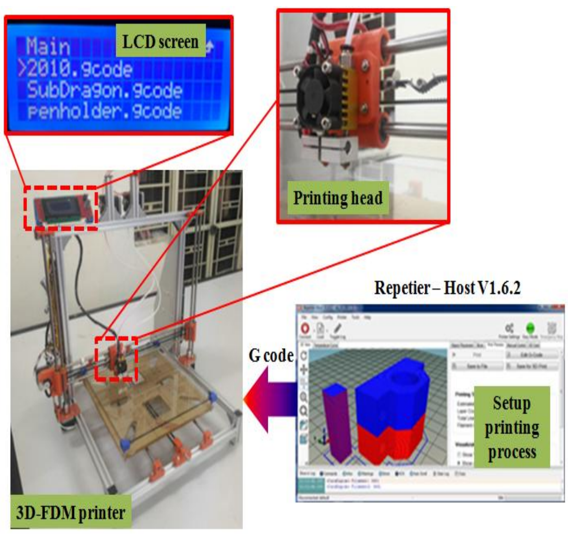

Fig. 9 Model of the manufactured 3D-FDM printer

Repetier-Host V1.6.2 software is used to create G-code for 3D printer. The parameters on the Repetier-Host software must be properly installed

with the 3D printer to be used.
The specifications of the 3D-FDM printer are as follows:
- 3D printer with FDM printing technology;
- Printing materials: ABS, PLA plastics;
- Maximum product size: 310x310x250mm;
- Printing thickness: 0.1 ÷ 0.5 mm.

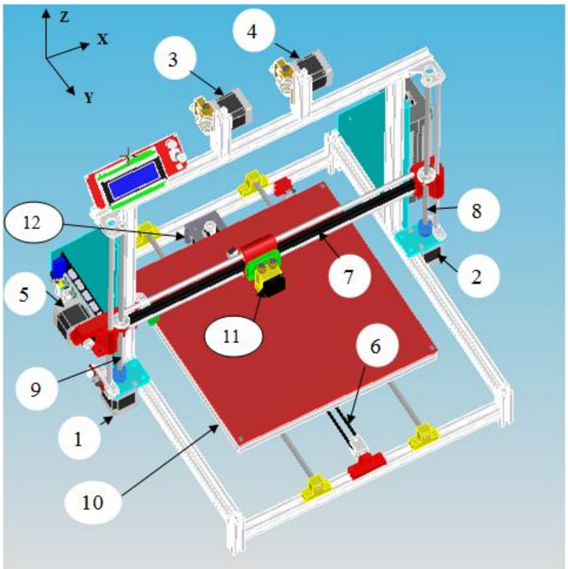

Fig. 10 Driver system for printing process

Figure 10 illustrates the 3D-FDM machine's driver system. The motors (described by 1 and 2) drive the printing head (described by 11) to translate up and down along the Z axis through screws and shafts (described by 8 and 9). The printing head is driven to translate along the X axis by the motor (described by 5) through the belt conveyor (described by 7). The build platform (described by 10) translates along the Y axis using the motor (described by 12) through the belt conveyor (described by 6). The motors (described by 1, 2, 3, 4, 5 and 12) are NEMA 17 42H42HM-0504A-18 motors. The motors (described by 3, 4) are used to drive the roll of plastic material for the printing head.

Printing the elements such as gears and shafts, then assembling these elements to a gear box as shown in Fig. 11 are a case study of this research. Systematic procedure for printing an element as the gear is described in Fig .12.


Fig. 11 Printed gears and shafts in the gear box

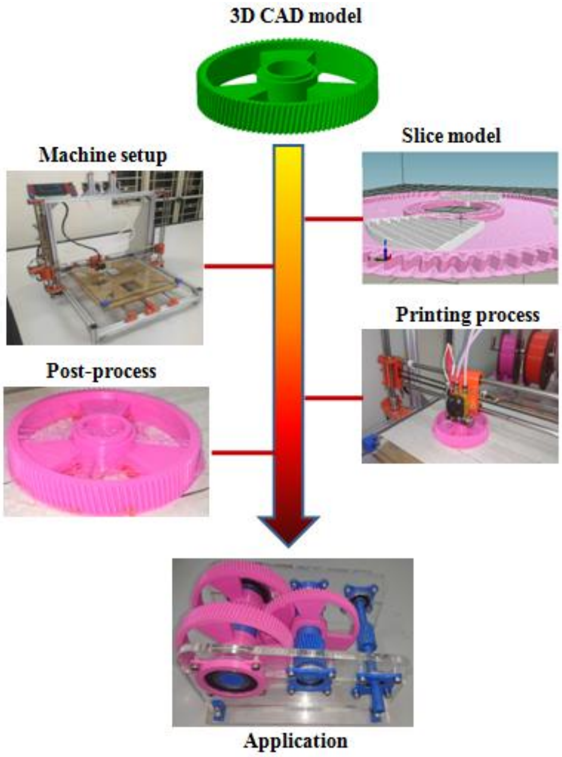

Fig. 12 Steps for printing the gear

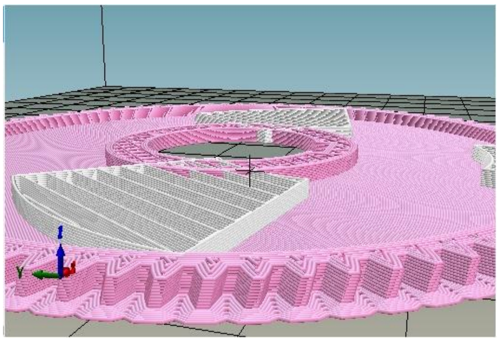
Fig. 13 Slicing model of the gear

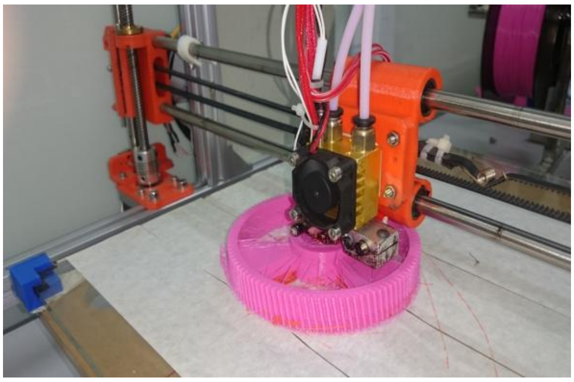

Fig. 14 Printing process

Slicing model of the gear and the printing process are shown in Fig. 13 and 14, respectively. Parameters for printing gears and shafts are as follows:

- Nozzle diameter: 0.3 mm;
- Layer thickness: 0.2 mm;
- Printing speed: 15÷20 mm/s;
- Filament diameter: 1.8 mm;
- Path style: Rectilinear;
- Materials: ABS, PLA;
- Printing temperature: 205 ^{0}C (PLA); 230 ^{0}C (ABS).

Gears and shafts were printed successfully on the 3D-FDM printer with the above mentioned printing parameters. The geometrical models of these parts are shown in Fig. 11. The dimensional accuracy of the printed parts is in the allowable limits. The deviation is recognized by comparing the CAD model with the scanned model of the printed part.

IV. CONCLUSION

3D printing with FDM method are applied widely for printing the plastic parts. For education field in universities, rapid prototyping from 3D printing enables to build 3D models for graphic design and rapid prototyping courses. On the basis of inheriting the available research for training in universities, the authors proposed the design and manufacture of 3D printer using FDM printing method (3D-FDM) [16]. This paper presents the results on analysis of influence factors to the part quality. Then, the optimal values of printing process are applied for printing the gears and shafts of the gear box with ABS and PLA materials. In those applications, for education in universities, 3D models for training are focused on.

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