A STUDY ON SURFACE ROUGHNESS DURING FUSED DEPOSITION MODELLING: A REVIEW

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ABSTRACT: Rapid Prototyping (RP) is technology used to produce a physical model or prototype directly from three-dimensional Computer-Aided-Design (3D CAD) data in a very short time. Fused Deposition Modelling (FDM) is a process for developing RP objects from plastic material by laying tracks of semi molten plastic filament on to a platform in precise layers from bottom to top. RP has been extensively used by manufacturers from different backgrounds to accelerate their product development and cycle time without neglecting product quality. In the RP process, surface finish is an important criterion as it can influence the part precision, post-handling expenses and functionality of the part. This paper presents a review of current studies on surface roughness using FDM. This paper also highlights design of experiments (DOE) and its association with surface finish.

KEYWORDS: *Rapid Prototyping; Additive Manufacturing; Fused Deposition Modelling; Design of Experiment*

1.0 INTRODUCTION

Manufacturing is a process of converting raw materials into finished products to be used for certain purposes [1]. The requirement for the rapid production of complex shapes has provided a new challenge for manufacturers. Product cycles are becoming shorter, and new product designs must be promptly available to suit current demand in order to win the market share. Aware of the growing demand for new designs, manufacturers must accelerate their product development and cycle time to meet market demand without neglecting product quality. Therefore, manufacturers must respond to market demand faster than their competitors.

RP is now used extensively, replacing traditional approaches to fabricating initial prototype models. Mostly, RP has been used in crucial industries such as automotive, consumer products, business machinery, medical and aerospace to accelerate their product to the market. Figure 1 shows the estimated breakdown of worldwide 3D printing use in 2014 [2]. Taking advantage of flexibility, cost and time saving, RP is used extensively by manufacturers from different industries. The potential of the technique is seen to be widespread, as it helps to optimize the product development process, time to market and the creation of complex parts with precise dimensions.

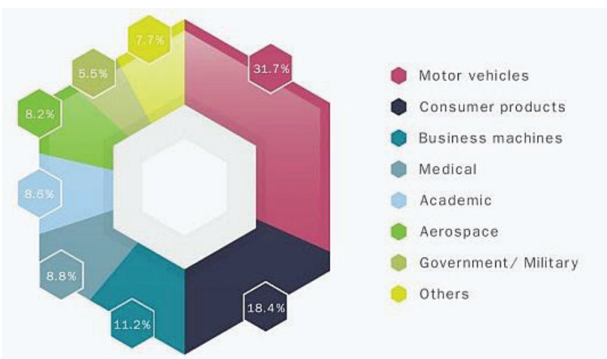

Figure 1: Estimated breakdown of worldwide 3D printing use in 2014 [2]

Generally, RP techniques can be categorized into three segments: solid based, liquid based and powder based. There are six major RP techniques currently practiced, namely Selective Laser Sintering (SLS), Stereo Lithography (SLA), Laminated Object Manufacturing

(LOM), Solid Ground Curing (SGC), 3D Ink Jet Printing and Fused Deposition Modelling (FDM) [2]. It is evident that FDM is considered to be the most popular process compared to other RP techniques because of simplicity of operation, economical hardware and sturdiness of fabricated parts [3-4].

FDM was introduced by Stratasys in 1988, and was developed by Scott Crump [4]. FDM is a process of extrusion of plastic filament material via temperature controlled heat. The heated nozzle deposits semi molten thermoplastic onto a platform surface in layers of ultrathin filament to form a 3D model [5]. Then, the heated melted material cools and hardens immediately once it reaches room temperature. The process of forming desired parts requires support to hold the product in place, especially when dealing with complex design. This support material is removed once finished by manually breaking it away, or by utilizing ultrasonic cleaning. The most common build materials used in FDM are Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA) and Polycarbonate (PC) [6]. Since these materials have different melting temperatures, the selection of material may vary according to the machine's heating element capability. Details of the operating temperatures are shown in Table 1.

Table 1: Common FDM material, extrusion and bed temperature [8-9]

Material	Extrusion temperature (^{0}C)	Bed temperature (^{0}C)
ABS	230-240	80-100
PLA	215-235	60-80
PC	250-320	120-130
Nylon	240-280	60-70

In FDM machines, the main component consists of a table which is equipped with foam base material. This table moves in x-y direction. The other major component is a nozzle to extrude the material. This nozzle merely moves in z direction. The extruded material is supplied via filament spool as shown in Figure 2. The major process parameters during FDM processes are extrusion temperature, layer thickness, build orientation and deposition speed. The shape of the designed part is developed through the motion of the table in X and Y direction. Once a layer is completed, the nozzle moves in the Z direction. Then, the next layer will be constructed on top of the other until the final layer of a model is fabricated.

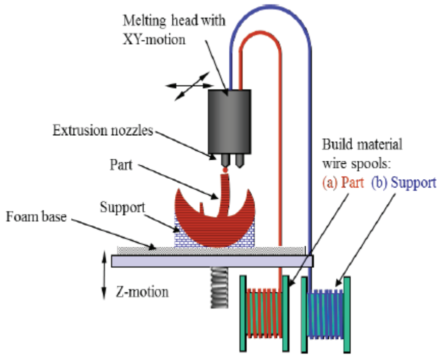

Figure 2: Schematic diagram of fused deposition modelling [8]

2.0 PRODUCT QUALITY

In today's manufacturing industry, product qualities such as surface roughness are given special attention, as the manufacturer needs to accelerate their product cycle and time to market. The demand for better quality products has forced manufacturing companies to continuously improve their quality control and machining technology. The quality of machine surface is characterized by the dimensional accuracy and surface finish during production. Hence, measuring and describing the surface quality can be considered as the indicator of machining performance [9]. Initially, physical prototypes produced by using FDM are used as a three-dimensional visualization of product designs that can be used for testing or as a master pattern. They are not created to be used in production, but to ensure that customers have a clear understanding of a new concept. Prototypes with the characteristics of the final product allow detailed evaluation and can be used for design verification, functional testing and design studies [10].

Nowadays, RP application has begun to make its way into the aeronautical industry, where it is set to have profound implications [11]. The aerospace industry has implemented RP throughout all processes and functions, from prototypes to the end product [12]. RP is being used in the aerospace industry to optimize the product development process and time to market. However, the potential of RP in the aerospace industry is disturbed due to FDM weaknesses, such as seam lines appear between layers and excess material produced as a residue leading to poor surface finish [13]. In the aerospace industry, it is a requirement to manufacture precise parts with critical dimensions of surface roughness ≤ 0.8 μm [14]. Other common surface defects which may exist in FDM include the staircase effect, chordal effect, support structure burrs and errors due to the starting and ending of deposition [15]. Figure 3 shows an example of surface defects which exist in FDM.

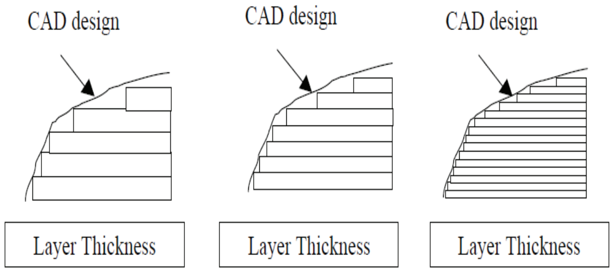

Figure 3 : Staircase effect [15]

Staircase effect is a common defect which occurs in most RP methods. The cause of staircase effect might be restricted by diminishing the layer thickness of each layer during operation. Meanwhile, chordal effect originates from Standard Triangulation Language (STL). The STL is fundamentally the same as meshing in Finite Element Analysis (FEA), where every single curved surface in the CAD are approximated as a series of triangles. Therefore, in order to have a highly curved surface, many triangles are required to be employed. Chordal effect can be lessened by specifying binary mode and smallest chord length when exporting CAD files to STL [16].

3.0 DESIGN OF EXPERIMENTS (DOE)

Design of experiments (DOE) is a planned approach for determining cause and effect relationships [17]. Before DOE was introduced, most studies were based on trial and error to achieve the desired results. However, this method is less effective, more time consuming, and uses lots of energy and resources [18]. DOE is widely used by researchers in many fields. It uses specific data and analyses statistical correlation between variable output and input [19]. DOE was introduced initially for agricultural purposes. However, it became a statistical tool during Second World War. DOE has been applied in process industries such as chemicals, food and pharmaceuticals. It is accepted to be a simple technique for specialists to control the input factors in an operation, such as, time, temperature, weight and flow rate, with a specific end goal to distinguish the optimum input [17].

There are several techniques that can be used for DOE. The most dominant techniques are Taguchi technique, full factorial, and response surface methodology (RSM). RSM has been preferred to other techniques due to it being considered the most promising method for optimization, as it gives fewer standard errors than experimental verification [20]. Besides, the effect of two or more factors on quality criteria also can be investigated and the optimum values can be obtained [21].

3.1 Process Optimization

Process optimization is the process of meeting multiple objectives while at the same time adopting the parameters of the selected range. High product quality, low cost and a rapid production process are examples of objectives that need to be achieved. To meet one or more objectives, the best set of parameters will be selected [22]. Process optimization could trade off the other parameters in order to obtain the desired result.

Taguchi technique is widely used in engineering analysis for performance optimization through sets of parameters. This technique is simple and systematic to optimization. It can cater to many design factors at one time. Taguchi technique uses two major tools in robust design, which are signal to noise ratio and orthogonal array [23]. It involves a combination of mathematical and statistical methods used in empirical research. This method is widely used because it is more economical with a lower number of experiments, and is able to analyze complex processes. The advantages of the Taguchi technique are that it is more robust, and qualitative factors are considered in the matrix experiments.

Anitha et al. [24] have used Taguchi technique to study the effect of process variables on the surface roughness of the parts produced by the FDM process. The controlled process parameters investigated were layer thickness of 0.178 - 0.356 mm, road width of 0.537 - 0.706

mm and deposition speed of 100 – 200 mm/min. The results showed that the layer thickness was found to be the most significant, followed by road width and deposition speed by 0.356 mm, 0.537 mm and 200 mm/min respectively. Nancharaiah et al. [25] have studied the effect of process parameters such as layer thickness, road width, raster angle and air gap on the surface quality of FDM parts by using the Taguchi technique. It was observed that surface roughness on FDM-built parts can be improved by using lower values of layer thickness and air gap, because they reduce voids between layers.

Meanwhile, experiments using factorial design allow for examining the effects of various independent variables simultaneously, and the degree of interaction between inputs. Generally, each factor has two levels, namely as 2^K experimental design, where K is the number of factors while the 2 is the level of each factor. For the 2 factors with 2 levels, -1 and + 1 would make four experimental conditions [26]. Like the Taguchi method, factorial experiments also allow the use of qualitative rather than quantitative in the design of experiments. The disadvantage of this technique is that it requires a larger number of experiments compared to the Taguchi techniques [22].

Vasudevarao et al. [19] in their study of determining the optimal surface finish of FDM part build, have used this technique with two levels for layer thickness and three levels for build orientation factor. The results show that layer thickness and part build orientation have a significant effect on FDM-built parts. Akande et al. [27] have also performed desirability function analysis on producing parts with good surface finish and dimensional accuracy by using factorial design. Three types of process parameters have been used in this experiment, namely layer thickness, speed of deposition and fill density. It was observed that the optimal sets of dimensional accuracy and surface roughness are low layer thickness, low speed of deposition and high fill density.

Response surface methodology (RSM) is a collection of statistical and mathematical techniques which are useful to quantify relationships among the input factor and output. RSM also has to be used to improve and optimize processes [19]. Raol et al. [7] have studied the effect of process parameters on surface roughness of FDM-built parts.

The influence of three process parameters with three levels such as layer thickness of 0.178-0.330 mm, part build orientation of 0-30^0 and raster angle of 0-60^0 on FDM-built parts have been studied by using RSM. The result shows that part build orientation has the most significant effect on surface roughness, followed by layer thickness. However, raster angle does not have a significant effect on the surface roughness. Krishna et al. [28] have also investigated the effect of process parameters, layer thickness, part built orientation, raster width, raster angle and raster gap to the surface roughness of FDM built parts via the RSM method. Genetic algorithm method has been used to determine the optimum process parameters. The result shows that the method is able to produce parts with overall improvement in accuracy of dimensions with optimum values of surface roughness of 3.046 μm. By using optimization and proper selection of process input, the good quality of part can be improved [29].

4.0 CONCLUSION

This paper presents literature related to FDM quality products. It is also noted that the DOE was used extensively in order to obtain optimized parameters. Most of the effect on the surface roughness of FDM parts was influenced by layer thickness, build orientation, road width, deposition speed, extrusion temperature and raster angle. Generally, it can be concluded that the combination of these optimized parameters can produce a good surface product.

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