Study on Surface Roughness Quality of FDM and MJM Additive Manufacturing Model for Implementation as Investment Casting Sacrificial Pattern

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ABSTRACT

Additive Manufacturing (AM) technology is relatively new and has developed with diverse research activity to implement AM in every possible manufacturing process. Its implementation in the Investment Casting (IC) is one of development in AM technology. Traditionally, the wax IC pattern was prepared using an injection molding process. Compared to the traditional method, AM could shorten the process by a considerable margin. This study is made to identify the capability of Multi-Jet Modeling (MJM) and Fused Deposition Modeling (FDM) techniques to produce an IC pattern within the desired surface quality. The AM part is fabricated with varying process, internal structure pattern, and part build orientation, and the fabricate part is tested using a surface roughness tester to get the average surface roughness value. The results show that part built with 90º built orientation

ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2017-05-05
Accepted for publication: 2017-05-23
Published: 2018-05-15

produced a better result compared to part built with 0º built orientation. Also, parts with hatch internal support structure would produce better surface quality compared to the others. Generally, AM techniques are capable to produce a good surface quality for sacrificial IC pattern.

Keywords: *Additive Manufacturing, Investment Casting, Fused Deposition Modeling, Multi Jet Modeling, Surface Roughness*.

Introduction

Additive Manufacturing (AM) technology has proven its capability to produce complex parts with shorter lead time. This advantage could benefit tremendously in application such as the Investment Casting (IC) process. IC is an industrial process which employs a disposable pattern that is used to produce a mold in which parts can be cast [1]. Implementations of AM technology into the IC process could come in two approaches of whether direct or indirect technique. The difference is that the direct technique will produce IC mold directly from AM that were ready for metal pouring while indirect technique will use AM to build the wax pattern for mold making.

According to reports from previous researchers on process optimization, part quality improvement, new materials applications, process invention, and functional part developments such as medical parts, mostly studying on applying AM technologies through indirect technologies that involved wax preparations for IC [2, 3, 4, 5, 6]. Among them, very few have attempted to study the direct AM method of producing patterns of ceramic mold that can be employed directly for a single metal casting. The potential through this alternative idea is that it could eliminate the rapid tooling technology in conjunction with an AM fabricated sacrificial pattern which would result in a more cost effective [5].

Early attempts of direct AM IC sacrificial patterns was reported in 1989 with the use of block molds. Several foundries have utilized various AM techniques to produce IC patterns [7]. For instance, Shellcast Foundries Inc. (Montreal. Quebec) developed a process called Solid Model Casting (SMC) that allows direct conversion of AM models to prototype casting. Cercast Group (Quebec, Canada) has identified the most important variables in designing AM models for IC applications. Nuclear metals Inc. (Concord, MA) have done a comparison of AM techniques for casting a Beralcast family of alloys [7, 8, 9].

The IC pattern is conventionally made by injecting wax or plastic into a pattern die which has been manufactured by machining processes [5, 10]. The pattern produced in the pattern die is melted or burned out of the mold in which parts are later cast. The mold is built up around the pattern by a well-known process the details of which differ depending upon the type of metal to be cast in the mold. This wax pattern is dipped in refractory slurry, which coats the wax pattern and forms a skin [11].

The advantage of AM implementation for IC is the expandable pattern and ready-to-pour mold could be easily manufactured to cast complex shaped object by direct or indirect casting method. It is most suitable to use a material with high strength and low diffusion temperature for making an IC pattern. However, the implementations of AM technique for IC also have its limitations. The build layer thickness has been critical since by decreasing the layer thickness might improve the surface finish but it would increase the build time.

The study will evaluate the surface roughness of AM parts with hollow and quasi hollow internal AM pattern structure that was fabricated using MJM and FDM techniques. It was found that reports on there were numerous inner built design strategies for SLA process pattern and simple hollow design are employed to decrease the stress and improve pattern drainage [2, 6, 10, 12]. However, research on the different inner patterns for MJM acrylic based materials and FDM Polylactic Acid (PLA) material were still lacking and previous studies which mostly related to SLA QuickCast process.

Methodology

In this research, the AM part is constructed with 0º and 90º build orientation as shown in Figure 1. The different orientations have different error factors and the number of layer requirements [13]. The orientation of the part also affects other factors such as the build time, the complexity of the support structure, shrinkage, curling, trapped volume, and material flow in AM processes [14]. The layer resolution setting is fixed at 0.00158 inches (MJM) while 0.0118 inches for FDM. A study by Vasudevarao et al. (2000) and Azanizawati (2003) indicated that layer thickness and part orientation have a significant effect on the roughness of part fabricated [15, 16].

The AM model is a staircase shape containing hollow and quasi-hollow (cross, hatch and square) internal support structure designed using SolidWorks software before being fabricated using ProJet™ SD3000 3-D Printer machine (MJM) and MakerBot® Replicator™ 2 Desktop 3D Printer (FDM). The idea is to build a webbed epoxy specimen that would collapses inwards due to flexion and potential fracture under the influence of heat rather than expanding outwards and damaging the IC mold.

MJM and FDM are categorized under the solid material forming of AM. The MJM and FDM model have the potential to be used as a physical model in the stage of discussing design ideas, checking with a spatial insight design model for appearance assessment, and as the master model or pattern for lost wax casting technique. The MJM model is fabricated using VisiJet®

SR200 build material and VisiJet® S100 support material while the FDM model uses PLA build material and does not require any support material.

The Visijet® materials have the ability to address a wide range of applications. Producing an accurate, high-definition parts is also possible as the Visijet® material is able to provide such fine feature detail. The parts fabricated would has a smooth surface whether it is the interior or the exterior surface. The PLA build material filament is a biodegradable plastic that was derived from corn and commonly used in many types of packaging [17]. PLA material could be considered as a more 'earth friendly' plastics compared to petroleum based acrylonitrile butadine styrene (ABS).

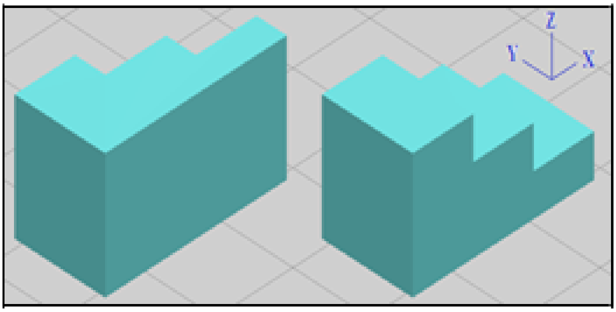

Figure 1: AM part orientation construction.

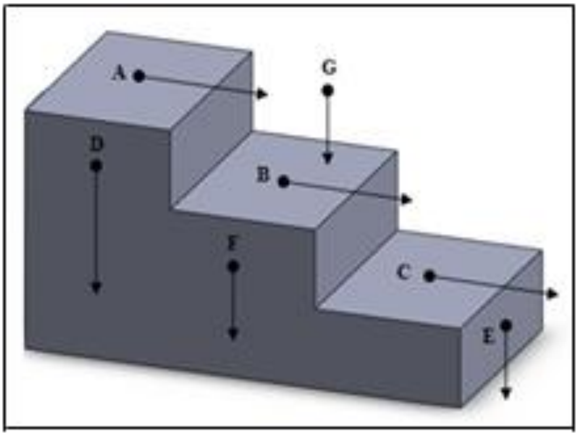

Figure 2: Surface roughness measurement.

Surface roughness testers used to measure the surface is from Mitutoyo model SJ-40. The device is set as a condition according JIS B0601:1994 standard. Using R profile and GAUSS filter, the evaluation length is set at 0.75 mm and the number of sampling length setup is set, N at 3. The Changes cutoff length, λc and λs are set at 0.25 mm and 2.5

respectively. It is important to have the machine calibrated before every usage and the surface roughness tester has been calibrated by using a PGN 3 geometric standard. The measurement positions are taken according to the reference, illustrated in Figure 2. These steps were done to the entire specimen that total of forty-eight pieces, from three specimens for four internal pattern structure design, comparing between two build orientations of 0º and 90º.

Result and Discussion

The result from surface roughness testing often provides a good indicator as to predict the performance of a mechanical component. Although often undesirable, it is quite difficult to control, while decreasing the surface roughness would increase the manufacturing cost, which is a pretty common trade-off.

The parts built with 90º build orientation were measured at x and y direction, while parts with 0º build orientation were measured at direction x and z. For each surface, the measurement was taken three times to get the average value. The recorded data were the arithmetic to mean surface roughness (Ra) which is the mean of the sums of all profile values.

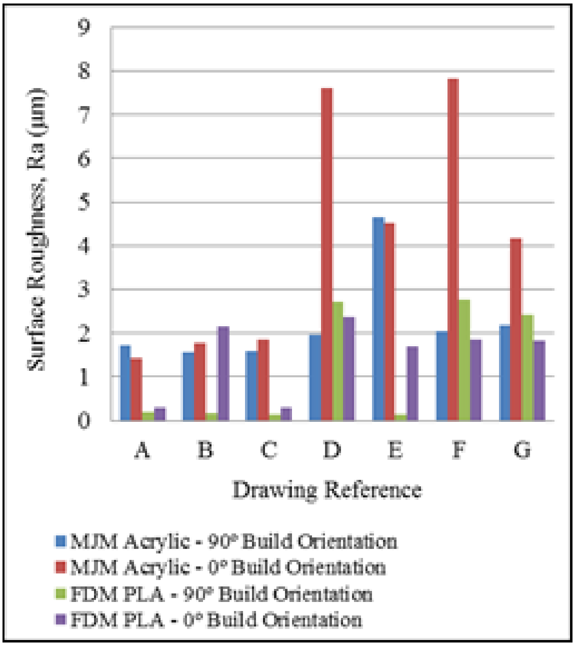

Figure 3: Comparison of surface roughness measurement between 90º and 0º build orientation at different planes.

Figure 3 shows the Ra measurement between 90º and 0º built orientation for MJM and FDM techniques. It could be seen that at 0º parts built orientation, the Ra at plane D, E, F, and G were quite high for MJM Acrylic parts. The plane F reads at about 7.83 µm which was the highest. The measurement was taken from the z-axis, which is the direction of layers increment. For the 90º parts built orientation, the reading at plane E shows the highest value at 4.66 µm. The lowest value was 0.15 µm at plane E of FDM PLA part with 90º build orientation. The values show the part smoothness was within a desirable range for x and y-axis compared to the z-axis.

The results reveal that built orientation has affected the part surface since the frictional force resulting from the direct contact of writing head and the upper scanned surface, which its deteriorates the repeatability of the foam accuracy of the part in the vertical direction [18]. The part surface could be improved with post processing as stated in previous studies. The application of sealants or infiltrations, followed by light polishing would smoothens the surface and prevent the slurry to penetrate during the mold production and dewaxing process [19, 20].

In the Table 1, it shows the average surface roughness for the parts with different internal pattern structure on 90º and 0º build orientation. The average was taken from three part samples for each cross, hatch, hollow, and square internal pattern. The values were illustrated in Figure 4. The lower number represents the better smoothness which is the desirable quality.

Table 1: The average value of surface roughness among all internal structure patterns.

IPS	Surface Roughness, Ra_{avg} (µm)			
	MJM Acrylic		FDM PLA	
	PO = 90º	PO = 0º	PO = 90º	PO = 0º
Cross	2.35	4.45	1.00	1.41
Hatch	2.15	3.71	1.22	1.49
Hollow	2.19	4.13	1.64	1.58
Square	2.22	4.40	1.34	1.53

Legend: IPS; Internal Pattern Structure
PO; Part Orientation

Figure 4 shows a surface roughness comparison between different internal pattern structures (cross, hatch, hollow and square) for 90º and 0º built orientation using MJM and FDM techniques. From the graph, Cross MJM Acrylic - 90º built orientation produces the coarse surface with the average values of 4.45 µm. Part with smoothest surface were the on Cross

FDM PLA - 90º orientation with the average values of 1.00 µm. It could be seen that FDM technique with PLA material produced better part surface roughness compared to the MJM technique with Visijet® SR200 acrylic material.

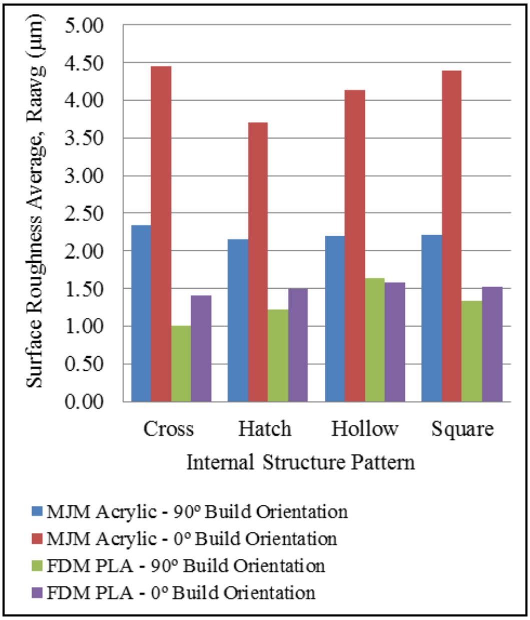

Figure 4: Comparison of surface roughness measurement between 90º and 0º build orientation between different internal pattern structures.

Both of the technique builds the parts by layering, thus its exhibit 'stair-step' or 'staircase' effect as shown in Figure 5 [21]. So it may cause an uneven surface of the fabricated part, though it is not significant in this study since the lack of sloping surface.

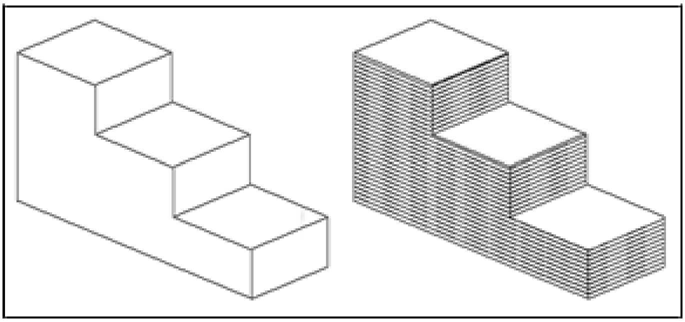

Figure 5: Staircase effect on Additive Manufacturing parts [22, 23].

The surface roughness of a part are mainly affected by building technique, build orientation build material, scanning accuracy, and the layer build thickness [22], with thinner slice layer may reduce the surface roughness value [24]. According to Grimm (2002), the appearance and feel of a supported surface will be different than the unsupported areas [25]. The supported area tends to have a matte finish with a slight texture, while the other surface will have smooth, glossy appearance. Furthermore, the way the material is being bonded together also contributes a factor in producing a good surface finish. The time to cool down the previous layer depends on many heat consumption factors, and the waiting time for the each subsequent layer would affect the surface roughness. If the waiting time is not enough, the temperature of the build wall will gradually increase, thus the newly deposited layer could not freeze or cure quickly resulting uneven line width [20].

Conclusion

In general, all the AM techniques produced relatively good surface quality. It was found that different internal structures of AM patterns have an effect on the surface roughness of AM parts. It is important when it comes to implementing the AM pattern as the sacrificial pattern for IC process, as the quality features of the end product of investment casting depends on the quality feature of its pattern. It shows that parts of FDM PLA – 90º build orientation, produced better surface quality with an average value of 1.30 µm. When comparing among the different internal pattern, part with cross internal patterns produced the best surface roughness. Meanwhile, for part of FDM PLA - 0º build orientation, the average value is 1.50 µm, part of MJM Acrylic - 90º build orientation produces the average value of 2.23 µm and part of MJM Acrylic - 0º build orientation produces the average value of 4.17 µm. It seems that the FDM AM part were generally capable to be a good sacrificial pattern for investment casting application.

Acknowledgment

The authors would like to thank Universiti Tun Hussein Onn Malaysia (UTHM) for their financial support and facilitating in the research programme.

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