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Methods to Improve Surface Finish of Parts Produced by Fused Deposition Modeling

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Abstract Fused deposition modeling (FDM) is one of the rapid prototyping technologies that can use plastic material, which can be effectively used for making patterns for investment casting. The surface finish of the investment casting depends upon the surface finish of the pattern. But the surface finish of the parts produced by using FDM is not very good as compared to wax patterns, which are conventionally used in investment casting. Therefore to use plastic patterns instead of wax, a technique is required to improve the surface finish of the FDM parts. It has been found that there are various methods to improve surface finish of plastic patterns made by FDM. These methods have been reviewed in this paper.

Keywords Fused Deposition Modeling, Surface Finish, Rapid Prototyping, Investment Casting

1. Introduction

Rapid prototyping (RP) systems were emerged in 1987 with the introduction of stereolithography technology, a process that solidifies layers of ultraviolet light-sensitive liquid polymer using laser technology. In subsequent years, various other rapid prototyping technologies were introduced, such as: Fused Deposition Modeling (FDM), Selective Laser Sintering and Laminated Object Manufacturing, Solid Ground Curing, Poly jet etc. The industry's very first 3D rapid prototyping system based on FDM Technology was introduced in April, 1992, by Stratasys [1]. The RP technologies can convert a three dimensional CAD model into a physical model directly without any tool or die.

The Fused Deposition Modeling (FDM) is an RP technique in which a plastic or wax material is extruded through a nozzle that traces the part's cross sectional geometry layer by layer. The FDM machine uses two materials i) build material ii) support material. In this process, a gantry robot controlled extruder head moves in two principle directions over a table. The table can be raised or lowered as needed. Extruder head follows a predetermined path (controlled by the software) and makes a thin layer of build or support material. After first layer the table is lowered and subsequent layers are formed. Each new layer makes bond with the previous layer. The support material is used to build the support structures that are automatically generated for overhanging geometries and are later removed by breaking them away or by ultrasonic cleaning. The build material is thermo plastic or wax usually supplied in filament form which is extruded through the small orifice of heated nozzle. The thermoplastic is cooled rapidly since the platform is maintained at a lower temperature [2]. A schematic diagram for an FDM machine is shown in Figure 1.

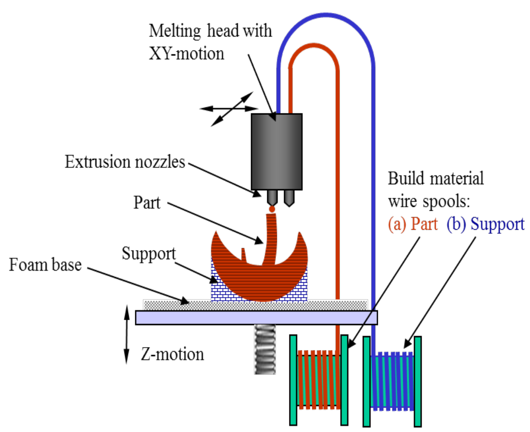

Figure 1. Schematic diagram of FDM [1]

The most common non-wax material used in FDM is Acrylonitrile Butadiene Styrene (ABS). Like wax, this material can be used for making investment casting patterns. This material has some advantages over the wax [3] and this material is proven to be suitable for burn out from the ceramic shell with minimal modification to the standard foundry processes. Therefore, the FDM machine can be used for making complex casting patterns to be used in investment casting [4]. In investment casting with ABS, either wax gates or vents are attached to the ABS pattern by the foundry or these are made as integral part of pattern during pattern making by FDM. The ceramic slurry is then invested on the pattern to make ceramic shell similar to traditional investment casting process. Then the pattern is burned in a furnace to get a mould. Molten metal is poured in this mould to get the required casting.

The surface finish is vital in moulding. The mould duplicates whatever kind of surface condition the master pattern presents. Therefore, to produce castings with good surface finish, the master pattern made by FDM must have good surface finish. But, in FDM process the surface finish of the parts produced is found to be inferior as compared to wax and some other RP technologies. This is due to the resolution of the process which is dictated by the filament thickness [5]. In FDM, the different layers remain visible on the surface of the pattern produced by FDM as shown in Figure 2.

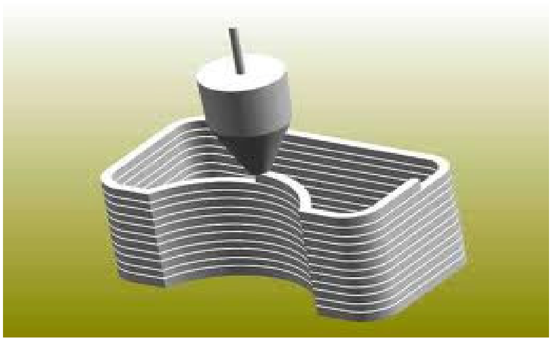

Figure 2. Layers visible on FDM part [2]

In order to achieve good surface finish, many researchers have conducted various studies to make FDM parts suitable for investment casting purpose. Literature suggests that there is not a single method to improve surface finish. A number of different methods have been reported and each have their own advantages and limitations. There is a need to categorize and review these methods. These methods have been reviewed in this paper.

2. Methods to Improve Surface Finish

All the methods for improving surface finish can be divided into four categories, namely:

1. Optimization of build orientation
2. Slicing strategy (layer thickness).
3. Fabrication parameters optimization
4. Post-treatment.

In first three methods are used before making the FDM parts but the fourth method is used after making the part.

2.1. Optimization of Build Orientation

The orientation at which the part is built, can have a significant effect on the surface finish of the part. Different methods have been developed by various researchers to find the optimal orientation for the fabrication of part on RP machine.

Vijay et al. [6] determined the optimal surface finish of model built by varying build orientation, layer thickness and keeping other parameters constant of FDM process using experimental design technique. Experiments were conducted using a fractional factorial design with two levels for layer thickness and three levels for orientation factor. The authors concluded that for 20 and 45 degrees built orientation the roughness value is directly proportional to the layer thickness but for 70 degree built orientation roughness value is decreased as the layer thickness is increased.

Allen & Dutta [7] and Sreeram et al. [8] developed a method for automatically computing the support structure for the part in layer manufacturing and then deciding the best orientation from a candidate list of orientations The authors developed a method to determine the optimal orientation based on variable slicing thickness in layered manufacturing for a polyhedral object.

Lan et al. [9] determined deposition orientation for stereolithography parts based on the considerations of surface quality, build time and complexity of the support structures. Surface quality was evaluated either by maximizing the area of non-stepped surfaces or by minimizing the area of worst quality surfaces. Build time was indirectly assessed by using the height of the part in the deposition direction. Support structure was minimized by minimizing number of supported points. The author discussed the orientation problem from geometric and algorithmic points of view, and established decision criteria for the determination of good fabrication orientation.

In a study, Frank and Fadel [10] proposed an expert system tool that considers the various parameters that affect the production of the prototype and recommends the best direction of building the part based on both the user's input and a decision matrix implemented within the expert system.

A proper orientation may lead to reduction in cost also in addition to the better surface finish. Alexander et al. [11] determined part deposition orientation for accuracy and cost. Surface accuracy was maximized by minimizing average weighted cusp height. Cost models were presented for stereolithography and FDM in such a way that the cost of the component can be estimated for different orientations. A suitable orientation for one of the objectives is determined from the list of pre-selected candidate base planes. Pham et al. [12] developed a system to orient CAD models for part deposition in stereo-lithography to obtain the best trade-off among build time, cost and accuracy. Their tool is a feature-based system that considers cost, build time, problematic features, optimally oriented features, over hanging areas and support volume for recommending a build direction.

Hur and Lee. [13] developed an algorithm to calculate the staircase area, quantifying the process errors by the volume supposed to be removed or added to the part, and the optimum layer thickness for the stereolithography system. They determined the optimum orientation based on the user's selection of primary criteria and the optimal thickness of the layers. Thrimurthulu et al. [14] presented an approach that determines the optimal part deposition orientation for FDM process. Two contradicting objectives, namely build time and average part surface roughness, were minimized by minimizing their weighted sum. The adaptive slicing was simultaneously used in the determination of optimum part deposition orientation. The predictions of the developed system were validated using the results published earlier.

2.2. Slicing Strategy

In general, a thinner slice layer produces better surface finish but it will increase the build time. Many researchers have found that the layer thickness significantly influences the surface finish.

Vasudevarao et al. [15] investigated the effect of parameters such as build orientation, layer thickness, road width, air gap and model temperature on surface finish. The experiments were conducted using fractional factorial design with two levels for each factor to be proposed for optimum settings. The authors concluded that layer thickness and part orientation were substantiating to be significant factors in determining the surface quality of the part. The best surface finish is obtained with .007" layer thickness and part orientation of 70 degree.

Anitha et al. [16] used Taguchi method to determine the effect of layer thickness, road width and deposition speed each at three levels on the surface roughness of component produced using FDM process. The results indicate that layer thickness is the most influencing process parameter affecting surface roughness followed by road width and deposition speed.

In a study by Azanizawati [17] better surface finish has been produced with low layer thickness. Ahn et al. [18] proved that layer thickness is the most influencing parameter for the surface finish of layer manufacturing processes. The author presented that the values of surface roughness depend on different angles of the parts.

Khan et al. [19] found the effect of slice layer and support structures thickness on the surface roughness of model made by FDM technique. Measurement of roughness was done on the both side of the specimen in perpendicular to the direction of build layer. The authors concluded that lower setting of slice thickness gives higher surface quality. Moreover the part surface which is adjacent to the top layer of the support has smoother structure as compared to the other surfaces.

Bakar et al. [20] analyzed the effect of three process parameters such as layer thickness, contour width and internal raster. The optimum condition was proposed for FDM process. Experiments were conducted on a test model that contained a variety of geometrical shapes and sizes such as slots, cylinders, cube and ring that are commonly available on plastic parts. The authors concluded that the best dimension to be built with FDM in x, y directions is 2 mm and above. Moreover the authors have recommended to use appropriate values of contour width and internal raster besides applying thin layer and fine visible surface finish while making small parts The study showed that both of these parameters can aid in the bonding quality between layers and lead to better surface finish.

2.3. Fabrication Parameters Optimization

The surface finish also depends upon a number of process parameters of the FDM machine. With proper adjustment of the build parameters, quality can be significantly improved without incurring additional expenses.

In a study, Zhou et al. [21] pointed out that the fabrication speed and the prototype precision are the basic functional requirements for RP equipment. However, these requirements are affected by user-selected processing parameters. Factors affecting the precision of RP parts include STL file format, material properties, RP machine parameters, and post-processing. The authors revealed that although users can only adjust parameters on processing machines, these small adjustments are very valuable for product precision improvement.

Lee et al. [22] used Taguchi method find the optimal process parameters for (FDM) rapid prototyping machine that was used to produce ABS prototype. In this study, the authors obtained the optimal process parameters for FDM process and the main process parameters that affect the performance of the prototype. Experiments were carried out to confirm the effectiveness of this approach. From the results, it is found that FDM parameters, i.e. layer thickness, raster angle and air gap significantly affect the elastic performance of the compliant ABS prototype. The optimum levels of parameters at different angle of displacement are also presented. Zhang and Chou [23] developed a 3-D finite element model to evaluate the effects of deposition parameters on residual stresses and part distortions. According to authors the scan speed is the most significant factor affecting part distortions.

The effects of extruding parameters on the quality characteristics for the FDM process has been discussed and examined by Chang and Huang [24]. The authors investigated the effects of extruding parameters, including contour width, contour depth, part raster width, and raster angle, on quality characteristics by Taguchi's method. A thin solid model based on a 2-D spiral was designed to demonstrate the proposed approach. Results of ANOVA and confirmation experiments showed that the parametric criteria found in this study could obtain satisfactory performances on profile error and extruding apertures in the FDM process. It is found that the contour width has the effect on both issues. The larger the width, the better the profile accuracy. On the other hand, a narrow width results in a dense and good appearance of the aperture area on the surface layer. The contour depth also has a great influence on profile error. Increase of contour depth improves forming stability and lessens profile error. Nevertheless, the influence on surface apertures is unclear. The part raster width and raster angle which relate to the inner tool path, have less effect on profile error.

2.4. Post Treatment

In spite of all the techniques like slicing strategy, optimal orientation and parametric optimization, still it may not be possible to achieve the required surface finish of FDM parts. Therefore, post treatments may be required before using them. Various studies related to post treatment of FDM parts in order to increase surface finish have been reviewed below.

Pandey et al. [25] examined the use of hot cutter machining to improve surface finish of FDM parts. Hot cutter machining was used to remove material of designed parts. Fractional factorial design was used with two levels and four process variables such as rake angle of cutter, cutting speed, direction of cut with respect to layers and build orientation. It was concluded that the proposed machining method is able to produce the surface finish of the order of 0.3 µm with 87% confidence level. It was found that hot cutter machining can be used for getting better surface finish of the FDM part [13].

Galantucci et al. [26] found the effect of FDM machining parameters on ABS surface finish and also used chemical treatment to decrease surface roughness. Square prisms were manufactured using different levels of input variables such as raster width, slice height and tip diameter. After that chemical treatment was applied using dimethyl ketone and water solution. The authors concluded that slice height and rater width are important input machining parameters. The chemical treatment is fast, cheap and easy to use which significantly improved surface finish. The authors continued his work and compared the tensile and bending properties as well as surface qualities of treated and untreated parts. The mechanical properties determined by designing and performing the central composite design of experiment and verified by testing as FDM marine turbine blade. The treatment improved surface finish but with minor reduction of tensile strength [27]. The flexural strength has improved due to compactness of material.

Percoco et al. [28] investigated the effect of chemical treatment on the compressive strength and surface roughness of FDM parts with a solution of 90% dimethyl ketone and 10% water. The study resulted in increase in compressive strength. The authors concluded that the proposed finishing treatments that can be used with immersion times up to 300 sec to reduce roughness up to 90%, improving mechanical properties in some cases better than those of non-treated parts.

Rao et al.[29] analyzed the various parameters of chemical treatment process such as concentration, time of exposure, time and initial roughness by design of experiment. Two different chemicals were used. The authors found optimal results of parameters significantly affecting the dimethyl ketone and methyl ethyl ketone. In case of acetone solution concentration and initial roughness were most significant parameters. But for methyl ethyl ketone concentration, concentration-temperature and concentration-time were significant parameters. The parts obtained have glossy look compared to plastic molded parts.

Besides the above discussed chemical treatments the surface finish of FDM parts can be improved by interacting the surface of the part with vapours of tetrahydrofuran. In this process the part to be smoothed is placed on a non-soluble support of some kind inside of a closed vessel with a non-air-tight lid. Heat is then applied to evaporate the tetrahydrofuran so it can interact with the object's surface to make it smooth [30].

3. Conclusions

In this paper the literature related to various surface finish techniques has been reviewed. It has been found that there are various methods to improve surface finish of FDM parts. The surface finish can be improved by choosing suitable build orientation of the part. It can also be increased by reducing the layer thickness of build material. However, it will increase the build time. Some authors has reported that proper setting of FDM machine parameters may lead to better surface finish. It has been found that the surface finish can also be improved by using some post processing techniques. Out of post processing techniques, chemical treatment has been used successfully by some researchers to produce a very good surface finish.

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