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Post-processing techniques for enhancing the surface finish of goods produced using additive manufacturing technologies: An Overview

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Abstract: Direct prototyping from computer-aided design (CAD) is now a real possibility thanks to additive manufacturing (AM) techniques. These models serve as test subjects prior to finalisation and, in certain cases, as the finished product itself. Compared to the conventional method of product creation, additive manufacturing offers several benefits, such as facilitating early consumer participation in product development, enabling complicated form generation, and saving time and money. The unique difficulties of additive manufacturing, such as low surface quality, unpredictable physical properties, and the need for specialised raw materials, are often well worth the effort required to overcome them. There have been several efforts to enhance the surface quality of additively manufactured components by manipulating process parameters and using various post-processing methods. This study primarily aims to record the results of a comprehensive literature research of additive manufacturing's post processing procedures.

Keywords The method of post-processing in additive manufacturing · Laser surface finishing may be used for the surface.

Introduction

A technique for quick prototyping, additive manufacturing involves building things up layer by layer by successively combining different materials. It enables designers to create precise physical prototypes in a matter of hours straight from 3D-CAD models.
Processes work best with generally complicated items that have a small number of flat surfaces and a lot of freeform curves and features. The "Stair Casing Effect," seen in Fig. 1d [1], causes a poor surface quality, which is a big concern for commercial usage.
Figure 1 provides an overview of the stages involved in AM production. Below is a list of the steps:
1. Any commercially available CAD program may be used to generate a 3D model (Fig. 1a).
2. Creating 2D layers from a 3D CAD model (Fig. 1b).
3. The sequential stacking of these 2D layers to generate the physical output (Fig. 1c).
The resulting model has a rough surface finish as a result of the "Stair Casing Effect," as seen in Figure 1d, which occurs when 2D layers are stacked.
Extensive research has been conducted on various additive manufacturing process parameters, including part orientation, layer thickness, and orientation of material deposition, in an effort to minimise the stair casing effect. Additionally, numerous post-processing techniques have been developed to achieve optimal results.
Depending on the application and the material of the model, several post-processing procedures are used to enhance the surface quality.

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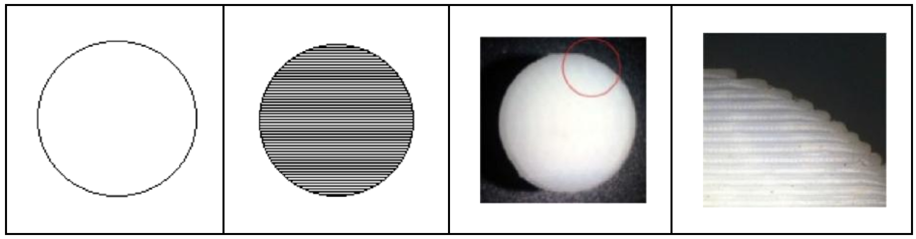

Fig. 1 An illustration of the layer-based additive manufacturing processes and related stair-stepping effect. a CAD Model, b Slicing c Actual output by AM d Stair casing effect

Table 1 Classification based on raw material used

Raw material used	Additive manufacturing process
Polymer	Stereolithography (SLA)
	Fused Deposition Modeling (FDM) Three-dimensional Printing (3DP) Selective Laser Sintering (SLS) Laminated-Object Manufacturing (LOM)
Metal	FDM
	3DP SLS
	Direct Metal Laser Sintering (DMLS)
Ceramic	3DP
	SLS

Additive Manufacturing Methods

Advantages, disadvantages, and potential uses of the many additive manufacturing processes are as varied as the processes themselves. There are a number of ways to categorise the existing additive manufacturing techniques, depending on factors such the raw material type, shape, and principle [1].
The categorisation is provided in Tables 1 and 2 according to the raw materials used.

Classification Based on Principle Used

In 2010, the American Society for Testing and Materials (ASTM) group ‘‘ASTM F42—Additive Manufacturing’’ formulated a set of standards that classify the range of Additive Manufacturing processes into seven categories (Standard Terminology for Additive Manufacturing Tech-nologies, 2012) [2]

1. VAT Photopolymerisation
2. Material Jetting
3. Binder Jetting
4. Material Extrusion
5. Powder Bed Fusion
6. Sheet Lamination
7. Directed Energy Deposition.

Table 3 shows various principles used for different types of Additive manufacturing processes. These methods are having some capabilities such as,

- Unbounded geometric freedom,
- To control the local geometric (micro-structure)
- Avoid the use of tooling
- Lowered inventory requirements
- Waste-less fabrication
- Unattended operation (allowed fully automated operation)
- Customer-driven design.

As there are many advantages of AM, however there are some disadvantages also such as,

- Demand for better materials.
- Existing CAD systems.
- Data management (Size of STL file)
- Low-volume production
- Financial overheads
- Surface Quality of Products

The surface quality is inferior compared to other traditional AM methods due to the stair casing effect and layer-by-layer manufacturing. Consequently, AM suffers from an important problem: pieces with an unsatisfactory surface quality. In relation to the thickness of their layers, the surface roughness outcomes produced by the various AM methods have varied. Surface roughness values of components produced by various AM methods have been studied by the researchers [3]. The roughness values for several AM methods are shown in Table 4 below. Compared to other methods, FDM produces a surface polish band that isn't very good (9-40 lm). A variety of post-processing operations, including machining (including turning, milling, and CNC machining), chemical machining, abrasive machining, laser surface finishing operations, and abrasive flow machining, have been sought after in an effort to achieve the necessary surface finish. Optimisation of process parameters, such as, requires a lot of effort.

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Table 2 Classification based on form of raw material used

Supply phase	Additive manufacturing process	Materials
Liquid	SLA	Photopolymers (acrylates, epoxies, colorable resins, filled resins)
	FDM	Polymers (ABS, polyacrylate, etc.), wax, metals and ceramics with binder
Powder	3DP	
	DMLS	
Ceramic, polymer and metal powders with binder		
Solid	SLS	Polymers, metals with binder, metals, ceramics and sand with binder
	LOM	Paper, polymers

Table 3 Classification based on principle used

Principle used	Additive manufacturing process
VAT photopolymerisation	–
Material jetting	Drop on Demand (DOD)
Binder jetting	–
Material extrusion	FDM
Powder bed fusion	DMLS
	Electron Beam Melting (EBM) Selective Heat Sintering (SHS) Selective Laser Melting (SLM) SLS 3DP
Sheet lamination	LOM
Directed energy deposition	–

Table 4 Surface roughness of AM technique [3]

Sl. no.	Name of process	Minimum layer thickness, mm	Surface roughness (Ra), 1m
1	SLA	0.10	2–40
2	SLS	0.125	5–35
3	FDM	0.254	9–40
4	3D printing (3DP)	0.175	12–27
5	LOM	0.114	6–27
6	Poly jetting process	0.10	3–30

managing the orientation of the part during the initial stage using various combinations in relation to the STL file in order to achieve the desired output. Managing the layer thickness and the built-in orientation of machined components. An issue that has already been mentioned is the "Stair Casing Effect," which cannot be resolved via optimising the parameters. A post-processing technique is required to reduce it to a minimum.

Approaches to Post-Processing

Starting with the component's fundamental design and working up to the finished product is made easier using the additive manufacturing technology. time spent developing a product through iterative processes. The staircase effect, surface quality, and dimensional accuracy are three of AM's biggest downsides, despite the technology's many benefits compared to other manufacturing methods. To get over these problems, most of the studies focused on post-processing methods. The two automated finishing approaches that have been studied by certain researchers are ultrasonic abrasion finishing and vibratory bowl abrasion finishing [4]. Components manufactured from Ciba-Geigy XB5081-1 (durable resin) and XB 5143 (general purpose resin) are subjected to these procedures in an effort to achieve a satisfactory surface roughness. The model surfaces might be improved using either surface topography studies or Scanning Electron Microscopy (SEM), according on the experimental findings. The Vibratory Bowl abrasion finishing process outperforms Ultrasonic abrasion finishing in terms of surface quality and processing time, improving upon the latter by approximately 74% (from an initial Ra value of 5.71 lm to 1.68 lm).

To remove surface imperfections from SLS components, the researchers have [5] experimented with vibratory grinding. Using this technique, we were able to find the optimal ceramic bodies and calculate the processing timeframes. Researchers showed that parts without complicated structures can be easily ground using vibratory tools (with a removal of less than 0.1 mm) and that the surface's Ra value can be changed from 11 to 2 lm using optical variance analysis. Attempts to improve surface quality utilising FDM-built components and HCM (Hot Cutter Machining) procedures have been carried out by several researchers [6]. The surface roughness is observed to be on the order of 0.3 lm with a confidence level of 87%, thanks to the layer-by-layer machining that this process provides. However, this approach is limited to surfaces that are flat.

The effects of a chemical post-processing treatment on FDM models made of Acrylonitrile Butadiene Styrene (ABS) plastic have been investigated by the researchers [7, 8]. Dimethylketone (acetone), ester, and chloride solvents are used in the experiment, which is conducted in a chemical bath. The cheap cost, very low toxicity, and high diffusion rate of dimethylketone led to its selection. During the experiment, the model is submerged in a water-and-dimethylketone mixture for three hundred seconds.

In order to improve the surface quality of AM-generated components, the researchers have developed a simple post-processing technique [10]. To enhance the surface quality of the fused FDM model, this case study used an aluminum-filled epoxy resin as a filler. Wax patterns may have their average surface roughness lowered from 17.10 lm to 2.76 lm. It is possible to enhance the surface roughness by as much as 83.85%.

Using CO2 and Nd:YAG lasers, some researchers have conducted experiments on SLS-built components to enhance surface finish [11]. Experimental evidence suggests that surface partial-melting increases with Ra levels and decreases with over-melting. After using CO2 and Nd: YAG laser polishing, the obtained findings show that the Ra roughness of 420 stainless steel—bronze infiltrated SLS parts has been reduced. For the best results, try these settings: (1) 220 W and 2.2 mm/s for a Ra reduction of 2.1 to 1.6 lm; (2) 320 W and 1.19 mm/s for a Ra reduction of 2.38 to 1.65 lm; and (3) 420 W and 4.5 mm/s for a Ra reduction of 2.38 to 0.8 lm. At 220 W and 1.7 mm/s, the most effective Nd: YAG laser polishing results in a Ra reduction of 9.0 to 2.40 lm.

When it comes to lines, flat surfaces, and slanted planes, the researchers have already conducted testing using laser polishing [12]. Components having an initial roughness of 7.5-7.8 lm Ra, as produced by the SLS method, were subjected to the experimental testing. Results from the experiments show a final surface roughness lower than 1.49 lm Ra, an 80.1% decrease in mean roughness.

It has also been shown that post processing procedures may increase the surface quality. Table 5 below lists a number of post-processing methods organised according to conventional and non-conventional viewpoints.

Table 6 also organises the same procedures according to the additive manufacturing raw materials.

Based on the data in Table 6, laser micromachining is a popular method for treating materials such as ceramics, metals, and polymers. The emphasis here is on laser surface finishing as a result.

Finishing Surfaces with a Laser

A combination of LASER's quality features with contact-less machining's great degree of flexibility and the

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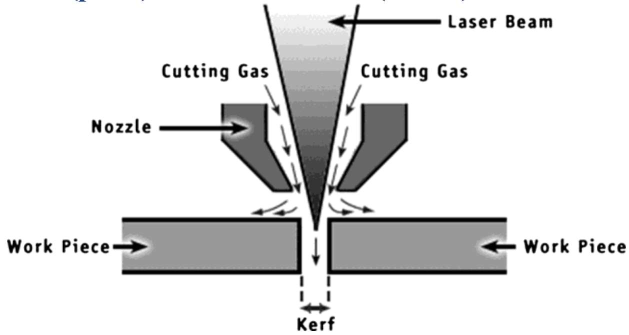

Fig. 2 Laser cutting operation

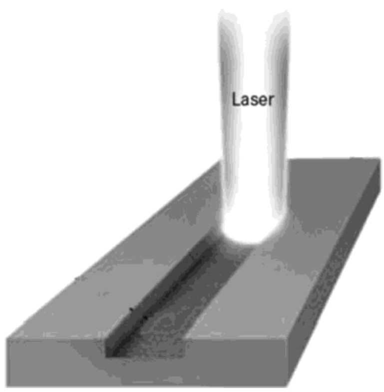

Fig. 3 Laser ablation process

This tool has the potential for high levels of automation and simple integration, which opens up a broad range of applications in macro machining operations on various materials, such as silicon, ceramics, metal, and polymer.

Laser micromachining, which the researchers have used in a variety of ways distinguished by feature geometry and surface material removal method, is one of these methods [13, 14]. A kerf that reaches all the way through to the other side of the substrate is left behind when a beam is utilised in laser micromachining. Typically, when laser cutting sheet metal, the majority of the material that is removed from the kerf is expelled out the other side. Laser cutting procedure is shown in Figure 2.

A procedure known as ablation is used when material is removed from a single side and then expelled from the same side that the laser was incident on. Figure 3 displays the process of laser ablation. In both circumstances, the material is mostly expelled via the kerf, which is sliced by the laser beam and follows its path as the tool moves along it. Depending on the substrate's reaction to the laser light, heat or chemical reactions may be used in the material removal process. If you want to do more than just heat the substrate at longer wavelengths, you'll need additional photon energy. At
when the laser is set to high enough intensities, the heat may be focused to the point where the substrate material melts in a localised zone before being vaporised in those spots. The substrate material then goes through a gas phase transition, but the laser radiation often ions the vaporised material afterwards, creating a plasma and plume that can block the incident beam. Convention calls for defining three areas surrounding the inci-dent beam:

1. The heat-affected zone or HAZ
2. The melt zone
3. The vaporization zone.

Some materials can pass directly from the solid phase to vapour phase by sublimation, and thus melt zone is absent. Both melting followed by vaporization or direct sublima-tion that is purely thermal ablation processes. At shorter wavelengths, the photon energy may reach the level of the chemical bond strength of the substrate. Laser radiation may then break those chemical bonds through direct pho-ton absorption, leading to volatilisation of the substrate into simpler compounds.

The investigators have [15] worked on short laser which are used for machining. In this process the photon energy is lost to chemical bond scission, the heating effects of the beam are greatly reduced, and this region is sometimes referred to as ''cold laser machining,'' or photochemical ablation. This greatly reduces the transient thermal stresses that occur as part of thermal ablation, and thus result shows less bowing, warping, and delamination of the substrate, as well as fewer edge melting effects which degrade feature accuracy. Since the peak temperature rise is greatly reduced, conductive heat flow away from the irradiation area is also reduced, and better dimensional control of the micro machined structure is obtained. There has been a general trend toward using shorter wavelength lasers for micromachining over the past two decades of development. Currently, UV lasers in the range of 350 to 250 nm which are used in industrial market because of cold laser machining.

Lasers for Post-processing (Laser Micromachining)

The market is filled with many kinds of lasers for treating materials. The carbon dioxide (CO2) gas laser is by far the most widely utilised laser for industrial processing, according to experts [16–18]. Its distinctive blend of high average power, great efficiency, and durable construction accounts for its appeal. CO2 lasers are widely used for drilling, cutting, marking, and engraving. Heat treatment, annealing, and welding a wide range of industrial materials. The extended wavelength results in a relatively wide spot diameter of *50–150 lm with a commensurate kerf width for micromachining applications. Neodymium-doped yttrium aluminum-garnet, or Nd:YAG, is the most widely used solid-state laser in the industry [19, 20]. There are four kinds of Nd used in micromachining:YAG

Conclusion

In this work, 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 parts manufactured by Additive manufacturing. The surface finish can be improved by selecting suitable method as per the requirement of surface finish. The study of various works indicates that systematic implementation of post processing technique can improve the R_a value of parts. Most authors have put in efforts in designing the processes for post processing operations. In doing so, many assumptions such as the Abrasive size, feed rate in HCM, concentration of chemical, flow rate of abrasives, Laser power were assumed.

From this survey it is found that the surface finish can also be improved by using some post processing tech-niques. Out of post processing techniques, on-going research focused on chemical treatment on polymer and metal printed parts and Laser micro machining on polymer, metal and ceramic.

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