Quality Control for Fused Deposition Modeling Based Additive Manufacturing: Current Research and Future Trends

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***Abstract* - Additive manufacturing (AM) is a novel way of manufacturing in the recent decade, and it has complexity free and customization advantages over subtractive manufacturing. Fused deposition modeling (FDM) belongs to AM, and it fabricates products using liquefied thermoplastic material. Products are manufactured layer-by-layer based on 3D computer aided designs (CAD). As a new technology, quality of outgoing products is the key aspect that people focus on. Engineering process control (EPC) and statistical process control (SPC) are two ways to guarantee and improve product quality. EPC has already been used in FDM to give feedback control of the process based on detected variations. However, very infrequent work has been done on SPC in FDM to reduce variation in manufacturing process, so that assignable causes can be detected when they occur. This paper summarizes current research in quality control for FDM, including process and quality parameters, measuring instruments, and current EPC and SPC methods. Future trends in this research area are discussed finally.**

Keywords- fused deposition modeling; additive manufacturing; quality control; statistcal process control; engineering process control; run-to-run

I. Introduction

Additive manufacturing (AM) has been proposed and received a lot of attention in the recent decade. Before AM, subtractive manufacturing dominates the manufacturing industry. In subtractive manufacturing, cutting or other machining methods are used to remove the unnecessary parts of the workblank of products. Compared with subtractive manufacturing, AM has the following key advantages. (1) Complexity free - Products are fabricated directly, and no molding or machining process is needed in AM. Designers do not need to consider how their designed products can be made, but only product structure and function. Thus, high complexity products can be designed and manufactured. (2) Customization - AM does not need molds; thus, different products can be manufactured in one batch. In addition, AM has small-lot production property. It has been applied in many industrial areas such as aeronautics, astronautics, vehicle, electronics, healthcare, daily goods and art.

The advantages of AM will make it more popular in future manufacturing industries. As in subtractive manufacturing, quality of outgoing products is of the key importance. Customer satisfaction and competitiveness of a company depend on the quality of AM products. More important, quality of AM products in aeronautics, astronautics, vehicle, electronics, and healthcare has a great impact on the safety of the applications of products. Therefore, quality control in AM is needed urgently to guarantee and improve the quality of AM products.

There are seven types of AM: binder jetting, material jetting, material extrusion, directed energy deposition, powder bed fusion, sheet lamination, and vat photopolymerization [1]. Different types of AM are based on various mechanisms, and for diverse materials. Interested readers may refer to Reference [1] for details. FDM belongs to material extrusion. FDM equipment mainly consists of material spool, filament, drive wheels, liquefier, heating coils, nozzle, and work platform. Products are fabricated layer-by-layer based on 3D computer aided designs (CAD). FDM liquefies thermoplastic material through heat coils, and extrudes the liquefied material through a nozzle under a certain pressure. The nozzle moves along a pre-set path to finish fabricating one layer. Then, the work platform is positioned lower down one unit of material thickness, and extrusion of the next layer starts. Successive layers fuse together. FDM process continues until product fabrication is finished. FDM manufacturing process and FDM equipment structure are shown in Figure 1 andFigure 2.

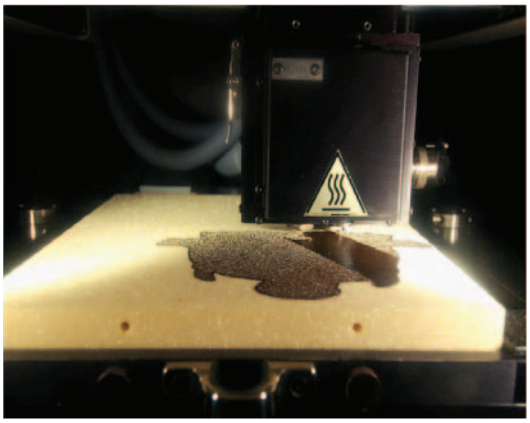

Figure 1 FDM manufacturing process

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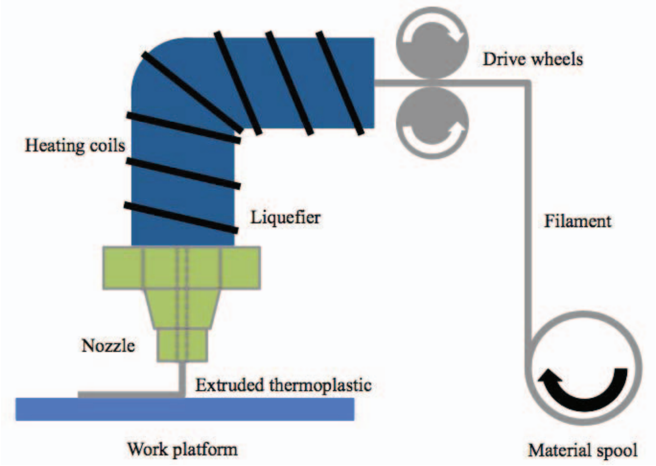

Figure 2 FDM equipment structure

FDM has many advantages. FDM equipment and material are relatively cheap compared with other types of AM. It fabricates strong parts with little material waste. Material change and post-processing are easy. It is office friendly, as it is small in size, and uses nontoxic material. The outgoing product is machineable, sandable and paintable. There are also some disadvantages of FDM. It is slow, as it makes one point at a time. Resolution of equipment and surface finish of product are poor. The outgoing parts are anisotropic and porous. Support material can be difficult to clean. Also, there are limited materials that can be used in FDM. The pros and cons of FDM are summarized in TABLE I.

TABLE I PROS AND CONS OF FDM

Pros	Cons
Cheap	Slow
Strong parts	Poor resolution
Little material waste	Poor surface finish
Easy material change	Anisotropic parts
Easy post-processing	Porous parts
Office friendly	Support material can be difficult to clean
Machineable, sandable, and paintable	Limited materials

FDM has many applications in prototyping, low volume production, and so on. Quality of products then becomes an important issue. In FDM, many factors might lead to the variation of a process. Some relate to the machine, like roller speed and filament feed rate; some relate to operations, such as environment temperature; and some relate to material, like material viscosity and stiffness. Variations of these factors may result in the deterioration of product quality. To correct the variations, engineering process control (EPC) is required to give feedback control of a process based on detected variations. Statistical process control (SPC) is also needed to detect the variation of a process, and to take diagnosis and corrective actions when variation happens to make the process in control or to improve the process.

This paper is organized as follows: Section II lists process and quality parameters; Section III discusses existed and candidate measuring instruments; Section IV states current EPC methods; Section V presents the SPC methods adopted; Section VI proposes tentative research topics for future research on quality control in FDM.

II. Process and quality parameters

There are different kinds of process parameters in a FDM process. Generally, parameters can be classified into machine specific parameters, operation specific parameters and material specific parameters. Machine specific parameters are the ones determined based on machine structure or function, such as nozzle diameter, filament diameter, and flow rate. Operation specific parameters are the ones set for operational purposes or have an impact on the process during manufacturing, such as layer thickness, road width, fill pattern, and environment temperature. Material specific parameters are the ones determined by material properties, such as viscosity, stiffness and thermal conductivity of material. Typical process parameters in FDM are listed in TABLE II. Reference [2] presented research on critical process parameter analysis in FDM, such as layer thickness, road width, deposition speed, and their interactions. Reference [3] investigated the thermal and mechanical properties of metal particle filled acrylonitrile butadiene styrene (ABS) in FDM. The impact of fill pattern on product quality was discussed in [4][5][6][7], and parts orientation in [8].

TABLE II PROCESS PARAMETERS IN FDM

Types	Process parameters
Machine specific	Nozzle diameter
	Filament diameter
	Roller speed
	Filament feed rate
	Flow rate
Operation specific	Layer thickness
	Road width
	Head speed
	Fill pattern
	Part orientation
	Extrusion temperature
	Environment temperature
Material specific	Viscosity
	Stiffness
	Flexibility
	Thermal conductivity

Quality parameters include profile specific parameters: dimension accuracy, surface roughness [9], and mechanical property, and defect specific parameters: underfill and overfill area [10]. TABLE III shows typical quality parameters in FDM. Examples of using dimension accuracy as quality parameter are in [11][12], surface roughness in [13][14], mechanical property in [15], and underfill and overfill area in [10].

TABLE III QUALITY PARAMETERS IN FDM

Types	Quality parameters	References
Profile specific	Dimension accuracy	[11][12]
	Surface roughness	[13][14]
	Mechanical property	[15]
Defect specific	Underfill area	[10]
	Overfill area	[10]

These above mentioned process and quality parameters reflect manufacturing process status or product quality of FDM, and changes of these parameters indicate the variation of an FDM process, and result in the reduction of quality of outgoing products.

III. MEASURING INSTRUMENTS

Measuring instruments acquire process and quality information during FDM process. Reference [16] and [17] presented a discussion about different measuring instruments used in metal-based AM. Measuring instruments currently used in AM that can be used in FDM include regular cameras [10], infrared cameras [18], thermocouples, 3D scanners [19], and ultrasonic transducers [20]. These instruments are nondestructive, and they can provide online measurements. Regular cameras, infrared cameras, and 3D scanners are noncontact instruments, while thermocouples, ultrasonic transducers are contact ones.

1) Regular cameras

Regular cameras can be fixed at the top and/or side of an FDM machine. Images are acquired under visible light. These images contain information about profiles or defects, such as shape, size, homogeneity, and so on.

2) Infrared cameras

Infrared cameras can also be installed at the top and/or side of an FDM machine. Images are recorded under infrared light. Temperature values of a surface under the camera are measured. The recorded temperature reflects the operational environment of an FDM process.

3) Thermocouples

Thermocouples can be mounted to the platform, nozzle, and/or surface of liquefier of FDM equipment. Temperature at a certain location can be acquired. It has information about operational environment.

4) 3D scanners

3D scanners can provide high-speed high-density geometric measurement of a product. Point cloud data of the surface of a product can be recorded, and they contain information about quality of products, such as shape, size, surface roughness and so on.

5) Ultrasonic transducers

Ultrasonic transducers can be attached to the bottom of a platform of FDM equipment to obtain backwall echo signals. These signals reflect the dynamics of layer build-up, such as layer-by-layer fusion and distortions.

Measuring instruments mentioned above are currently mainly for research purposes. As research on quality control of FDM becomes more mature, measuring instruments can be embedded in FDM equipment for feedback control and process monitoring.

IV. ENGIEERING PROCESS CONTROL

EPC is a process adjustment technique. Some measurable variables in a process are acquired, and predicted for the next observation. The difference between the predicted value and the target one is used to determine the adjustment of some controllable variables based on the established relationship between the measurable and controllable variables, so that the deviation of the next observation is minimized.

In FDM, research on quality control mostly focuses on EPC, which acquires measurable process parameters or quality parameters, and adjusts controllable process parameters or design of product to minimize deviation of the next observation. As an extension to Reference [21], EPC in FDM is categorized into four types: (1) adjusting controllable process parameters based on the deviation of measurable process parameters; (2) adjusting controllable process parameters based on the deviation of product quality; (3) adjusting design of product based on the deviation of product quality; (4) adjusting design of product based on the deviation of measurable process parameters. Examples of research on these four types of EPC in FDM and some other AM processes (as examples when corresponding research in FDM is rare) are as follows.

1) Adjusting controllable process parameters based on the deviation of measurable process parameters

Song and Mazumder measured temperature of a melt pool, and controlled laser power using a real time controller, implementing generalized predictive control algorithm based on an established relationship between laser power and melt pool temperature [22]. Hu and Kovacevic measured weight of powder feeder, and gave feedback to modify powder delivery rate to reach a precise material delivery in laser based AM [18].

2) Adjusting controllable process parameters based on the deviation of product quality characteristics

Sood et. al. presented a method to optimize process parameter settings in order to minimize percentage change in length, width and thickness of product in FDM [23]. Faes et. al. developed a 2D laser triangulation system to obtain geometric error in *z*-direction of FDM manufactured product, so that extruder feed rate or nozzle movement speed can be changed to correct the geometric error of a product [24]. Boschetto et. al.

presented a theoretical model of 3D profile of product based on process parameters and part shape. Surface roughness of FDM product can be predicted, and then be used for parameter optimization [25].

3) Adjusting design of product based on the deviation of product quality characteristics

Pandey et. al. proposed an adaptive slicing method based on the build edge profile to improve the quality of FDM manufactured product [26].

4) Adjusting design of product based on the deviation of measurable process parameters

Tong et. al. proposed STL file and slice file compensation methods to modify corresponding files based on parameter errors in FDM system [27][28].

The pros and cons of the four types of EPC are summarized in TABLE IV. Research has been done on the last three types of EPC in FDM, but is rarely found on the first type. Also, some researchers only pointed out possible applications for EPC, but no implementation was given.

TABLE IV PROS AND CONS OF FOUR TYPES OF EPC

Types	Pros	Cons
1)	• Deviation correction based on direct cause; • Adjustment performance is independent with the complexity of product; • Relatively easy online measurement.	• Not directly measure the deviation of quality characteristics of product.
2)	• Directly measure the deviation of quality characteristics of product.	• Deviation correction based on indirect cause; • Adjustment performance is dependent with the complexity of product; • Relatively hard online measurement.
3)	• Directly measure the deviation of quality characteristics of product; • Deviation correction based on direct cause.	• Adjustment performance is dependent with the complexity of product; • Relatively hard online measurement.
4)	• Relatively easy online measurement.	• Not directly measure the deviation of quality characteristics of product; • Deviation correction based on indirect cause; • Adjustment performance is dependent with the complexity of product.

V. STATISTCAL PROCESS CONTROL

Statistical process control is a series of methods that are used to detect and reduce variation in a process, and to improve process capability. Based on Shewhart variation theory, there always exist variations in manufacturing processes, and variations can be classified into chance causes and assignable causes [29]. SPC is used to detect process shift due to assignable causes, so that practitioners are able to take corrective actions to avoid the production of non-conformity products. SPC has been widely used in subtractive manufacturing, and brought great benefits to the manufacturing industry. However, these methods cannot be used in FDM directly, as FDM is seldom used in mass production, so that there is not a large amount of data of the same kind of product.

SPC can be categorized into univariate monitoring, multivariate monitoring, profile monitoring and image monitoring based on the format of the objective it monitors [30]. In univariate monitoring, the monitored objective is one or several independent variables, such as the dimension of a given shape. In multivariate monitoring, the monitored objectives are multiple dependent variables, such as the height and weight of a product. The monitored objective is a profile or function in profile monitoring, such as force data. Image monitoring is based on image data, such as the point cloud data of the surface of a product, or temperature data of a surface. Profile monitoring and image monitoring are research focuses in recent years as the monitored objectives are profiles or images in many manufacturing processes.

Very infrequent research has been done on SPC in FDM. One case that uses SPC in FDM, which also combined with EPC is in Reference [10]: Fang proposed a method to predict the underfill or overfill errors for the next layer using exponentially weighted moving average (EWMA) based on errors of the previous layers, and adjusted positioning speed and/or flow rate based on the predictions. CUSUM control charts were used to monitor the errors for each layer to detect whether the process was out of control. This research was a preliminary exploration on EPC and SPC in FDM for low complexity and single type defect FDM processes.

VI. FUTURE TRENDS OF QUALITY CONTROL IN FDM

As stated in the above sections, EPC has already been used in FDM, but research and applications of SPC in FDM are very rare. To solve the problem that there is not a large amount of data of the same kind of product in FDM, information extracted from FDM process should be normalized based on product design or path of nozzle for each layer, so that they can be used in SPC. Based on current research and applications of quality control in FDM, future trends of this research area are discussed as follows.

1) EPC of multi-parameter based on fused information

Most work of EPC in FDM is feedback control of single controllable parameter based on single measurable parameter. There are much more information in the manufacturing process that can be used in feedback control, and multi-parameter can be adjusted at the same time. EPC of multi-parameter based on fused information could be a future topic of quality control in FDM.

The scheme of EPC in FDM is shown in Figure 3. Measurable process parameters and product quality characteristics are measured during FDM, and deviations of the next observation are predicted. A relationship between input (controllable process parameters and design of product) and output (measureable process parameters and product quality characteristics) is established. Then, optimum adjustments of controllable process parameters and design of product are determined to minimize deviations of the next observation.

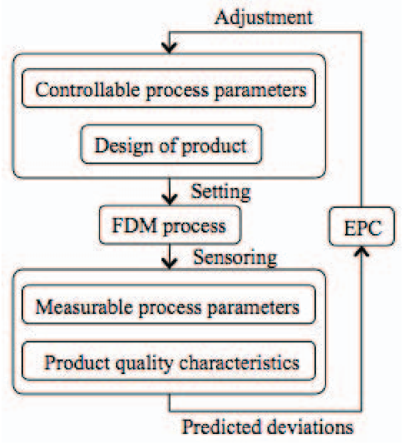

Figure 3 EPC scheme in FDM

2) SPC based on profile data of machine and operation specific parameters

In FDM, some parameters, especially machine and operation specific parameters, might drift or deviate during a manufacturing process. In addition, they are profile data for one run. Research on SPC in FDM could be done to monitor these profile data to detect whether manufacturing processes are out of control.

3) SPC based on regular image data of quality characteristics

Images taken using regular camera or 3D scanner are directly related to properties of products or defects, such as dimension, surface roughness, underfills, overfills, and so on. Information in these images reflects the quality of outgoing products. Research could be done on online taking images on product surface, extracting parameters, and monitoring the parameters based on proper SPC methods.

4) SPC based on infrared image data of operation specific parameters

Infrared images taken by infrared camera are temperature data over a certain area, like platform in FDM. The temperature data are spatial-temporal correlation data. These temperature data provide information about operational environment of a FDM process. SPC on these spatial-temporal data is also a research area that could be focused on.

5) Run-to-run process control

Run-to-run process control scheme combines EPC and SPC [29] in quality control. One controllable parameter $\boldsymbol{x}$ is determined initially. In EPC, the one step forward prediction of an output characteristic of interest $\boldsymbol{y}$ is calculated and compared with the target value $\boldsymbol{T}$. The difference between the two is used to decide the adjustment of the controllable parameter $\boldsymbol{x}$ based on the established relationship between $\boldsymbol{x}$ and $\boldsymbol{y}$ to minimize the deviation of $\boldsymbol{y}$ of the next observation. In SPC, the observed current value of $\boldsymbol{y}$ is compared with the target value $\boldsymbol{T}$, and the error between the two is monitored. When the process is detected as out of control, assignable causes might happen, and if so, corrective actions could be taken to the process or the EPC scheme could be modified.

The scheme of run-to-run process control in FDM is shown in Figure 4. Initial controllable process parameters and design of product are set. During the FDM process, measureable process parameters and product quality characteristics (outputs) are acquired. Deviations of the next observation are predicted to determine the adjustments of controllable process parameters and design of product (inputs) by EPC based on established relationship between inputs and outputs. Current deviations are monitored using SPC methods to remove assignable causes in the FDM process, and to modify the EPC scheme when necessary. Run-to-run process control has already been used in the semiconductor manufacturing industry [31], and it could also play an important role in FDM.

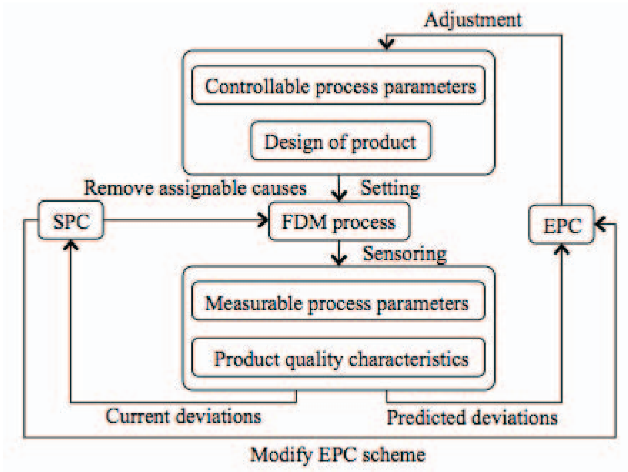

Figure 4 Run-to-run scheme in FDM

VII. SUMMARY

FDM is proposed and has many applications in the recent decade. Research on quality control of FDM is urgently needed to help improving the manufacturing process, and guarantee the quality of outgoing products. This paper discusses the current research in quality control in FDM, including process and quality parameters, measuring instruments, EPC and SPC methods. Some tentative topics of future research in this area are proposed finally: (1) EPC of multi-parameter based on fused information; (2) SPC based on profile data of machine and operation specific parameters; (3) SPC based on regular image data of quality characteristics; (4) SPC based on infrared image data of operation specific parameters; (5) Run-to-run process control.

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