ONLINE GEOMETRY QUALITY MANAGEMENT DURING DIRECTED ENERGY DEPOSITION USING LASER LINE SCANNER

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Abstract

Additive manufacturing (AM) is a powerful and promising manufacturing technology due to its advantages of material saving, mass customization and small-quantity production of custom-designed products. However, current situation of lacking quality management in 3D printing process is the key barrier of adopting this advanced technology. Geometry inaccuracy of 3D printed components is one of the main quality problems for AM, especially when the final product requires high precision in its geometry. In this study, an online geometry quality management method for continuous monitoring during the direct energy deposition (DED) process was developed using a laser line scanner. Our proposed methodology comprises: (1) real-time track-by-track scanning of multi-layer single-track component, (2) online geometry extraction of multi-layer single-track component during printing process, and (3) online plotting and comparison of the as-designed and as-built models.

1. Introduction

Metal additive manufacturing process is a complex process in which the geometry of deposited layer is controlled by several process parameters, such as feed rate, moving speed, laser power and gas flow rate. Use of static process parameters cannot always ensure good quality, problems such as overheating will occur in local areas which may lead to geometry error (Craeghs, Bechmann et al. 2010). Recent studies have shown that geometry inaccuracy of 3D printed components is one of the main defects (Heralić, Christiansson et al. 2012, Smith, Derguti et al. 2016, Koester, Taheri et al. 2018). Quality assessment of 3D printed part conducted after AM process are too late since the geometry defects are already generated and may not be able to solve. Therefore, to ensure the performance of final product by timely detecting geometry defects, it is important to assess geometry quality during printing process.

Experiments have been carried to evaluate the geometry quality of deposited layers during printing process. A lot of studies utilize coaxial system with IR camera or photodiode to measure the geometer of melt pool. Previous studies have shown that characteristics of melt pool such as dimensions and fluid flow can influence the dimension in deposited parts (Gockel, Fox et al. 2015), and a stable melt pool size and shape can reduce the geometrical anomalies of deposited parts (Lee and Farson 2016). However, melt pool size are not exactly represent the dimension of deposited parts. Heralić, Christiansson et al. (2010) have measured the dimension of deposited part other than melt pool size, but they conduct scanning of previous deposited layer rather than current layer. With respect to dimension quality monitoring of deposited part, additive manufacturing using other extrusion materials such as concrete and polymer also have some related studies. Lin, Shen et al. (2019) achieved online monitoring in polymer 3D printing where they perform scanning after printing several layers which will stop the printing process for inspection. In general, geometry discrepancy computation of just solidified melt pool without stopping or slowing down printing process and comparison of the as-built model with the as-designed model in real-time is yet to be attained.

To tackle the limitation of current studies, this chapter develops an online geometry quality assessment technique for estimating the dimensions of deposited layer, particularly focusing on the just solidified area, using laser line scanner. The achievements of this study include: (1) online track-by-track scanning of multi-layer multi-track component, (2) online geometry extraction of multi-layer multi-track component during printing process, and (3) online plotting and comparison of the as-designed and as-built models. This paper is organized as follows. Section 2 introduces the proposed online real-time quality assessment technique, including five parts: design module, printing module, scanning module, processing module and plotting module. Section 3 shows the experimental results using our developed online geometry quality system. Lastly, Section 4 concludes the whole paper and suggests future work.

2. Methodology

The proposed methodology is to develop online geometry quality assessment system during DED process, which can achieve measurement of each printed layer in real-time, extraction of geometry information and comparison of as-designed and as-built models in real-time. Figure 1 shows the overview of proposed quality assessment system.

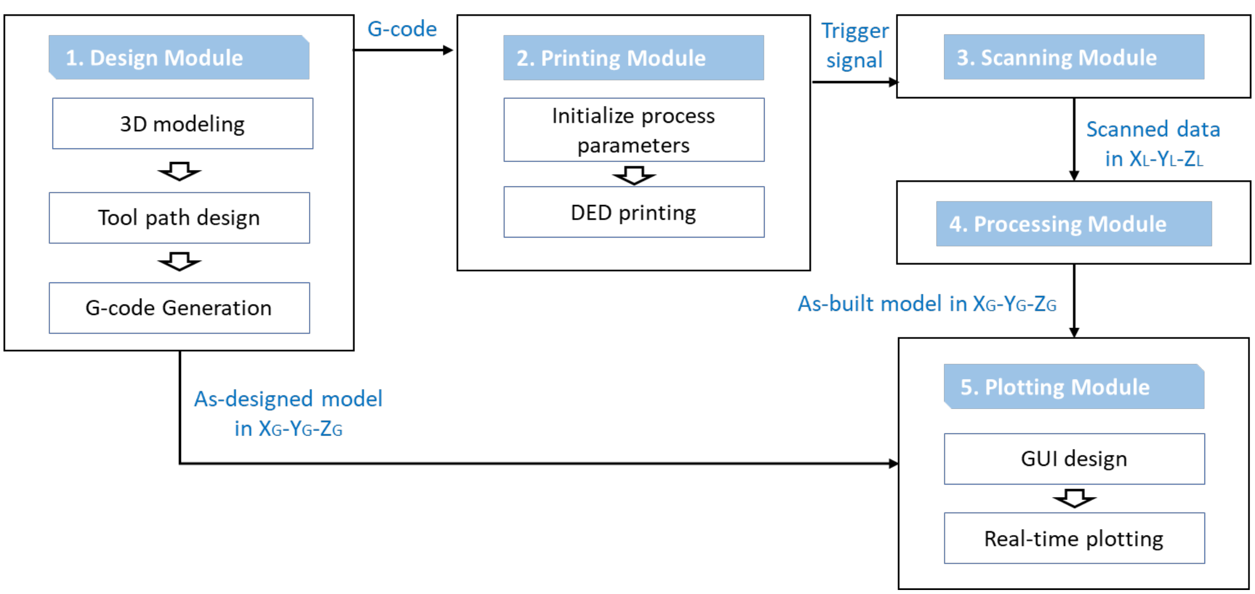


Figure 1 Overview of proposed online geometry monitoring methodology

(1) Design module

Design module is to generate 3D as-designed model which will be used to check geometry discrepancy with as-built model in plotting module and generate G-code file which will guide the 3D printing module to printed required components. Design module includes 3 main parts, 1) 3D model creation, 2) tool path design and 3) G-code generation.

First, to create 3D model, commercial software can be used such as TinkerCAD, Autodesk Fusion and Rhinoceros computer-aided design software. Normally, a Standard Tessellation Language (STL) file which is commonly used in AM process (Mueller 2012) will be generated as the as-designed model. The STL file represent the 3D model by triangular facets, where a set of X, Y and Z coordinates of three vertices of each triangular facet and a unit normal vector that indicate the outside direction of each triangular facet are stored. After create 3D model, the second step is to design the tool path. There are many different kinds of tool path pattern developed for AM process, such as zigzag, raster, contours, continues and hybrid tool path (Ding, Pan et al. 2015). Depending on the characteristics of as-designed model and quality requirements of printed component, different tool path will be designed. Since raster tool path is one of the most popular method in AM systems, this study adopts raster tool path in our quality assessment system. Using raster tool path, the as-designed geometry will be sliced layer-by-layer vertically and each layer is sliced track-by-track along one direction after determining the vertical slicing distance and horizontal slicing distance. Finally, to control the movement of nozzle following the designed tool path, a Geometric code (G-code) file should be generated and send to the 3D printer. G-code file is an extremely compact and concise programming language that give instructions to Computer Numerical Control (CNC) machine. It was first standardized in the 1960s by the Electronics Industry Association (EIA), and finally documented as RS-274D. In general, there are two kinds of codes, codes that begins with G are for movement in which XYZ coordinates of nozzle's position and speed of nozzle are declared, while codes begin with M are for machine functions such as turn on/off laser beam and change gas feed rate. Different machines may have different functions, thus may have different coding system. Normally, the g-code file can be generated from same software use for tool path design. But with the understand coding system, g-code can be generated by direct programming as well.

(2) Printing module

3D printing module is to generate the as-built components for quality assessment. During printing process, process parameters such as power intensity, powder feed rate, moving speed and shield gas feed rate, etc. determine the shape and size of deposited line. To obtain as-built components with desired geometry, process parameters are determined based on empirical value to make the expected size of deposited line conform to the as-designed slicing distances. After that, by importing g-code file of as-designed model, the printer will perform printing and as-built components can be obtained.

(3) Scanning module

To perform real-time data acquisition of the just solidified melt pool, scanning module is developed which contains 3 main steps, (1) Installation of lase line scanner, (2) scan parameters setting and (3) scanned profile transferring.

First step is to installed laser line scanner on the nozzle of 3D printer to performed scanning during printing. The printer moves in X direction that deposited the printed line on substrate. Line scanner is fixed on the nozzle and moves together with the nozzle, projecting a laser line perpendicular to the printing path and measures the printed line. Secondly, scan parameters such as exposure time, profile frequency and measuring range should be set properly to ensure the performance of measurement. After setting the scanning parameters, real-time scanning can be start when receiving the trigger signal that indicates the start of printing process. According to Ben-Ari (2006), the real-time system is a system that can guarantee response of an event within specified time constrains. The event in our system is start capturing profile and the response of this event should be finish plotting. There are three tasks in the meanwhile, capturing profile, processing profile and plotting results. Since the time for capturing profile is constant and this task is parallel with the processing task and plotting task, the response time only consider plotting time and processing time. To ensure a real-time system, the time delay of each profile should be smaller than the time interval between neighboring profiles.

(4) Processing module

One of the main objectives of this study is to measure the geometry attributes of 3D printed components. In our study, track width and track height area since they can well-represent the geometry of the printed components. In this study, the geometries been considered are multi-layer single-track geometry. The definition of geometry attributes for multi-layer single-track geometry is presented on Figure 2. In this paper, edges are defined as intersections of current layer and previous layer or substrate. Track width is the horizontal distance between edges which are determined while the as-built printed model is extracted. The cumulated height of each layer is taken as the average height of scanned points with top 95% percentile height values in as-built model, while the track height of each layer is differences of cumulated height between neighboring layers. As the as-designed model is plotted together with the as-built model, there will be geometry difference between both models. To better understand the geometry discrepancy, figure 2 shows the side view of deposited layers. The green line shows the as-designed sliced line while the black curve shows the as-built profile. When doing tool path design, the as-designed model is sliced into rectangular lines, but in 3D printing the cross-section of as-built components is a curve so that it can never fully conform to the as-designed shape. Therefore, to check the difference between as-designed model and as-built model, the height of each points to its as-designed height is calculated which represents geometry discrepancy, while the area of discrepancy within as-designed width is defined as discrepancy area.

The objectives of processing module are to extract geometry attributes output the as-built model in global coordinate system, there are three steps. Firstly, matching as-built and as-designed model is transforming the as-built model in line scanner's coordinate system to printer's coordinate system. The coordinate system of the line scanner and 3D printer are local coordinate system and global coordinate system, respectively. In this study, we assume the X axes of local and global coordinate systems are parallel. The transforming of as-built model from local coordinate system to global coordinate system includes rotation and translation. Transformation of points in local coordinate system to global coordinate system can be solved by applying a 2D transformation matrix.With the coordinate transformation matrix obtained, the coordinate transformation can be performed after collecting each 2D profile. The next step is to extract the track width. Here, a gaussian curve is fitted to the transformed as-built profile and the area within two standard deviation of the mean is taken as the area of printed part. The last step is geometry attributes calculation. After previous steps, the as designed-model is registered together with the as-built model. In our study, track width, track height, discrepancy, and discrepancy area are computed based on the definition mentioned previously.

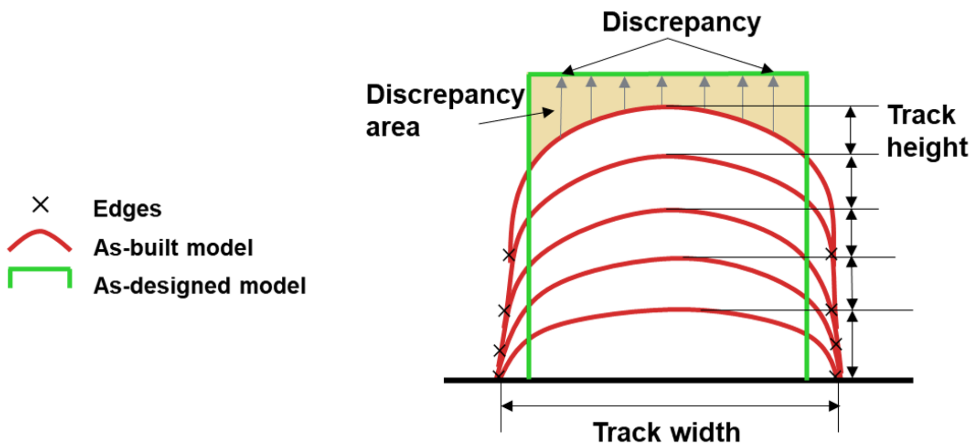


Figure 2: Geometry attributes extraction for multi-layered single-track geometry

(5) Plotting module

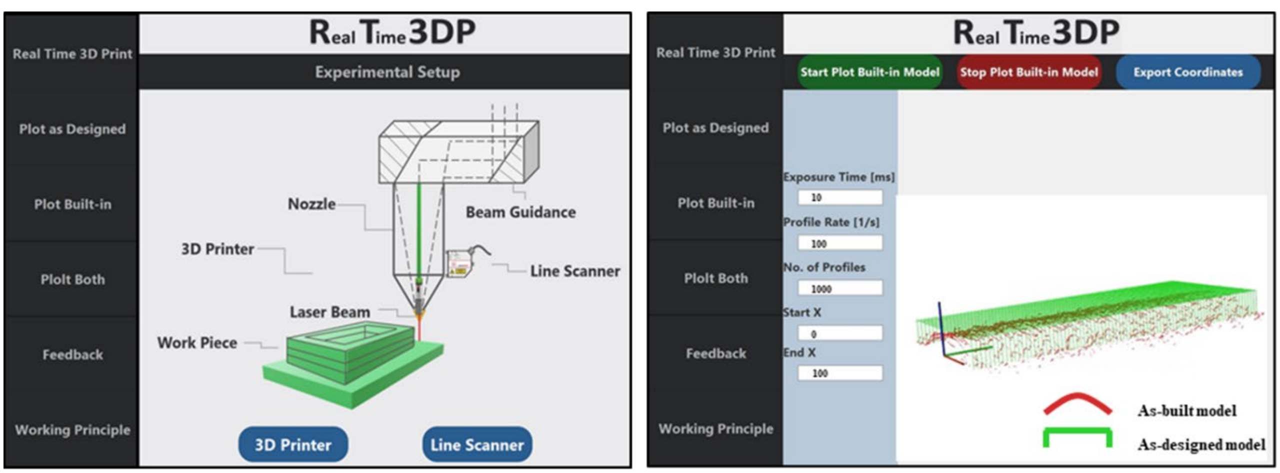
In this paper, a 3D real-time plotting graphical user interface is developed (GUI) in order to plot both as-designed model and as-built model during the printing process. The GUI is compatible with the laser line scanner used in this study. The interface gives access to the users to define initial scanning parameters such as exposure time, profile rate, number of profiles, and range of scanning on X-direction before the as-built model plotting commences. Both the as-designed and as-built models are registered and plotted in the plotting module. The as-designed model is sent from the design module formed in the global coordinate system and is plotted by extracting the basic geometrical information from the G-code file generated in the design module. The extracted X, Y, and Z-coordinate position of the model is plotted as point cloud in a point cloud library. The plotting module also receives the as-built model in the global coordinate system from the processing module. The transformed coordinate information of the as-built model in the processing module is plotted on real-time. At last, the as-designed model is registered together with the as-built model for geometry comparison.

3. Experimental results

In the current study, InssTek MX-400 DED metal printing machine is the one which is used on the experimental procedure. In DED metal 3D printing, the metal powder spread from the nozzle with high density power laser forms a layer depositing on a substrate. The substrate selected for this study is a box-shaped metal with 120 mm length, 50 mm width, and 13 mm height. For the current experiment the as-designed model is a simple one-layer line. The modeled line has a geometry of 60 mm length, 2.5 mm width, and 0.17 mm height. G-code file of the as-deigned model generated by Rhinoceros software is imported on the 3D printer to be printed. The stream of powder used to print the 3D component is stainless steel.

Micro-Epsilon scanCONTROL 2900/BL laser line scanner is used to capture profiles. scanCONTROL 2900-10/BL has a resolution of one micrometer with 1280 pixles per profile which makes it to reproduce the smallest of details with high precision. The measuring speed is up to 300 hertz having a semiconductor laser light source with 405 nanometers wavelength. Since the printed component in the current experiment is less than 10 mm, a blue laser scanner with 10 mm measuring range is used. In addition, scanning parameters are selected based on experiments to guarantee the performance of scanned profile, including exposure time and profile rate. The exposure time is the time period to open the shutter and capture reflected light from the target surface. A large exposure time will allow sufficient reflected light to be captured and thus obtain a clear reflected line on the sensor. But too much reflected light will make the reflected line thick and lower down the accuracy. Because different materials have different reflection properties, for example, dark objects like black rubber or shiny metal surfaces may require a longer exposure time, a suitable exposure time need to be determined based on experiment. Finally, this parameter is determined to be 5ms by experiments.

Results of processing and plotting are shown in figure 4 and figure 5.



(a) (b)

Fig 3. GUI design (a) Home window of the graphical user interface developed and (b) Real-time plotting of the as-designed and as-built models

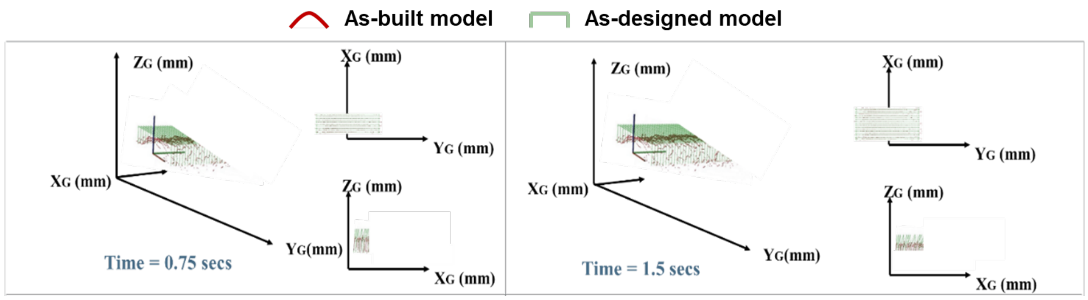


Figure 4. Representative online plotting and comparison of as-designed and as-built models at time = 0.75 secs and 1.5 secs

The microscopic images of the printed components are taken at several cross-sections of the components, width and height of each cross-section can be measured manually. Figure 6 shows the comparison of profiles obtained from laser line scanner, including experiment profile and reference profile, and microscope.

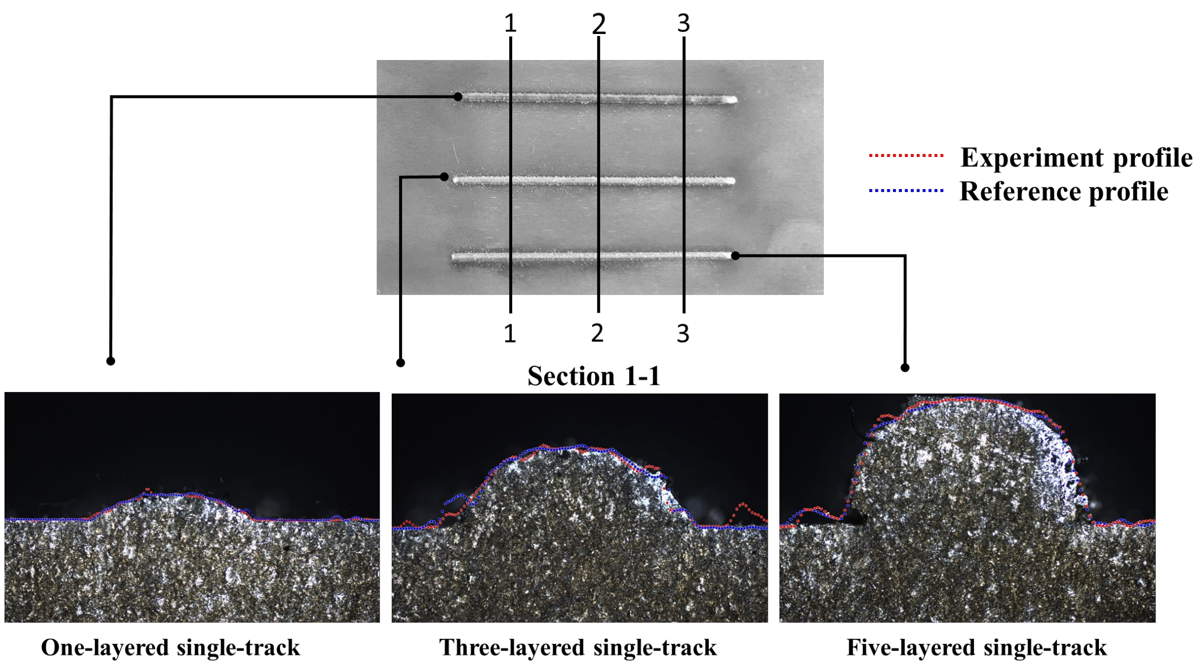


Figure 5 Comparison of profiles obtained from laser line scanner and microscope

4. Conclusion

This paper presents the development of online geometry quality management system during DED process, achieving online measurement of each printed layer, online extraction of geometry information and online comparison of as-designed and as-built models. The developed system includes five modules, (1) design module, (2) 3D printing module, (3) Scanning modules, (4) processing module and (5) plotting module. To validate the proposed system, experiments were conducted on the test specimen which is a multi-layer single-track geometry. The scan data of the specimen were processed by the proposed geometry management technique to extract geometry attributes. The performance of real-time is tested and analyzed by experiments. It was shown that the developed system can output the geometry attributes and plot as-designed and as-built model of each deposited layers in real-time with a frequency of 30hz, represents real-time quality assessment of single-track with 467mm length can be achieved under a printing speed of 14mm/s, each profile cover 0.47 mm of printed line.

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