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CLOSED LOOP CONTROL UTILIZING IN-SITU PATTERN PRINTING AND READING FOR QUALITY LEVEL DETERMINATION IN ADDITIVE MANUFACTURING

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Abstract

HP's Multi Jet Fusion (MJF) is a powder-based technology that selectively melts polymer powder, using a fusing agent, in a layer-by-layer fashion to create 3D parts. One of the challenges for wide adoption of additive manufacturing is the assurance of the print process and part consistency through a cost-effective and non-destructive fashion. Non-destructive part quality measurements can be achieved through a method of printing two-dimensional patterns at desired locations throughout the part. The readability of these patterns provides either the signals to actuate process changes during the print or information on part quality during and after printing. This method can also be used for covert part marking to provide design intellectual property security.

1. Introduction

Additive manufacturing (AM), the process of building a part layer-by-layer, is a key contributor to the industrial revolution, Industry 4.0, which is characterized by the combination of automation and information technology in advanced production systems [1][2]. 3D printers are an example of these advanced production systems, utilizing data to improve production effectiveness and efficiency through design optimization and process control [3]. Additive manufacturing has benefits over traditional manufacturing methods due to increased design complexity, small batch production, and short lead times, which has led to the additive manufacturing industry growing 33.5% to 9.795 billion in 2018 [4].

However, AM scale-up from prototyping to mass production has been difficult due to in-process variability that can affect part quality [5]. All AM technologies have sources of process variability that are dependent on their specific parameters and materials utilized in their print process. There are many different additive manufacturing technologies and materials, Multi Jet Fusion (MJF) being one of the powder bed fusion (PBF) polymer printing archetypes. The MJF print process starts with a computer aided design (CAD) model that is sliced to form a stack of 2-dimensional (2D) images. The MJF machine then begins printing pre-print layers by spreading powder and warming them using overhead warming in combination with fusing infrared (IR) emitting lamps. After an adequate warming base has been formed, the first CAD model 2D geometry slice image is printed using a black IR absorbing fusing agent on the powder and melted using the fusing lamps. A new layer of powder is spread on top of the previous layer and the process (print, fuse, spread) is repeated until the full object is formed. This printing process describes the basic MJF production system HP Jet Fusion 4200/5200 series 3D printing solution. However, MJF technology is not limited to utilizing only one fusing agent; it has the potential to perform in-situ chemistry on a voxel level by selectively jetting distinct functional agents.

This MJF print process has several possible sources of process variability related to the different printing steps (print, fuse, spread). The MJF printer hardware functionality related to each of these steps can change due to wear. Image quality can suffer from these worn parts that are not detectable using current software and pen alignment tests. This variation can cause MJF parts to have different material properties and levels of quality. Currently, detection methods for AM-produced part material properties require testing with a tensile tester, impact tester, hardness tester, or other mechanical equipment that permanently damages the part. There are also several non-destructive approaches for measuring 3D printed parts without damage, including ultrasonic flaw detection and Archimedes principal density measurement. However, these methods cannot be implemented in-situ of a 3D printing process and require expensive equipment, measurement time, and an expert to conduct calculations. The density measurement process in particular wets the part, which may not be ideal for some materials or applications, and the ultrasonic flaw detection is limited by the process being unable to detect small defect sizes and incapable of reaching certain depths into the part [6]. An efficient and effective non-destructive method for measuring the MJF print processes, hardware, and material properties of printed parts is needed to enable an easily adoptable additive manufacturing solution.

2. Materials and Methods

2.1 Powder material

All experiments in this paper were conducted with HP 3D high reusability PA12 from HP Inc, Palo Alto, CA USA. PA12 material properties can be found in table 2 [7].

Table 2. HP 3D high reusability PA12 material properties.

	Value	Method
Powder melting point (DSC)	187 ℃ 369 ℉	ASTM D3418
Particle size	60 μm	ASTM D3451
Bulk density of powder	0.425 g/cm^3 0.015 lb/in^3	ASTM D1895

2.2 Sample Preparation

Samples were produced using an MJF experimental platform. This printer is outfitted with a multi-agent print carriage, clear IR absorbing fusing agent, cyan agent, yellow agent, magenta agent, black fusing agent, fluorescent agent, IR warming lamps, two 650 W tungsten halogen IR fusing lamps mounted on either side of the print carriage, print bed, powder supply, and spreader.

2.3 Measurement Methods

The image capturing sensor utilized for measuring code readability was an 8-megapixel iSight camera. The software for reading the quick response (QR) codes was the “QR Scanner” application.

A Mitutoyo 500-197-30 Digimatic 200 mm stainless steel digital caliper was used to measure the geometry of 3D printed parts.

3. Results and Discussion

Machine-visible contrasting agents were used to print QR codes onto MJF printed parts. The agent contrast is important due to the test pattern requirement to be easily detectible under specific lighting sources. Examples of visible spectrum contrasting and UV spectrum contrasting patterns printed are shown in figures 1, 2 and 3. The amount of contrast necessary between the test pattern and background is dependent on the image capturing sensor and pattern detector. An 8-megapixel iSight camera image capturing sensor was used in combination with the QR Scanner application under both natural illumination and a UV light source. Print pattern generation was adjusted by modulating the QR code size to control readability of printed patterns sensitivity to print processes quality. Figure 1 shows three different sized QR codes with the largest 1 cm x 1 cm code chosen due to its sensitivity to print quality and easy detectability when fused correctly.

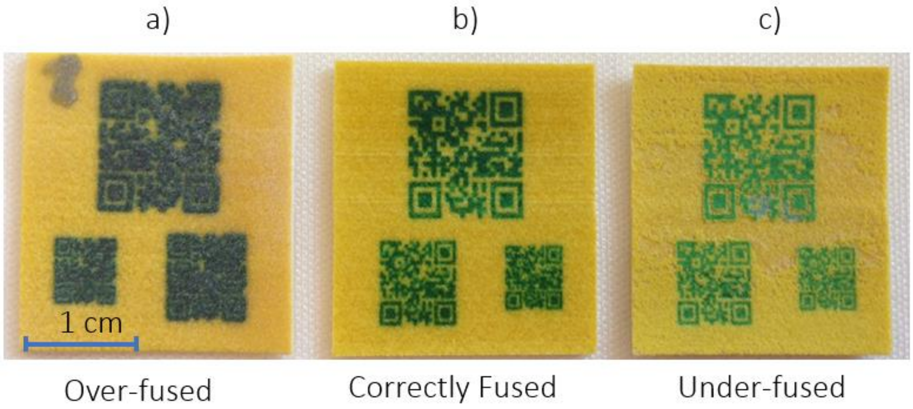

Figure 1. Quick response codes printed with cyan agent on a yellow part under ambient lighting with varying levels of fusing and readability.

The fusing conditions and thermal uniformity of a part can be discerned by utilizing the readability of printed codes. Three parts were printed utilizing varying amounts of fusing energy to create different density yellow parts with cyan codes, shown in figure 1. The far-left part (a) is over-fused and was unable to be read using our test setup due to the excessive flowing of the melted polymer. The middle part (b) has nonuniform fusing, which can be seen by the color gradient ranging from dark to light as you view the largest test code from top to bottom; however, it was still readable using our test setup. The far-right part is under-fused and unreadable due to the under-fused code not having a detectible amount of contrast.

The criticality of fusing conditions and uniformity is dependent on the part quality specifications designated by the machine-readable code generated and can be controlled by changing the test pattern complexity. Using the printing pattern geometry shown, the middle part was determined to be within quality specifications.

Other than print fusing quality, print quality can also be determined utilizing a similar method. This pattern recognition process was utilized to detect hardware and software deficiencies during the MJF printing process on an MJF test bed that were undetectable using other methods.

The MJF test bed passed pen alignment tests and the parts shown in figure 2 passed caliper geometric measurement assessment. However, the print quality deficiency was detected utilizing the pattern detection method described. Failure diagnosis determined the failure sources to be a combination of controller misprinting the pattern by printing on both the forward and backward passes, instead of just the forward passes, and backlash from belt wear, which caused the second pass printing to be misaligned with the forward pass print. This combination of software and hardware issues made small defects in part quality, which were undetectable using traditional tests.

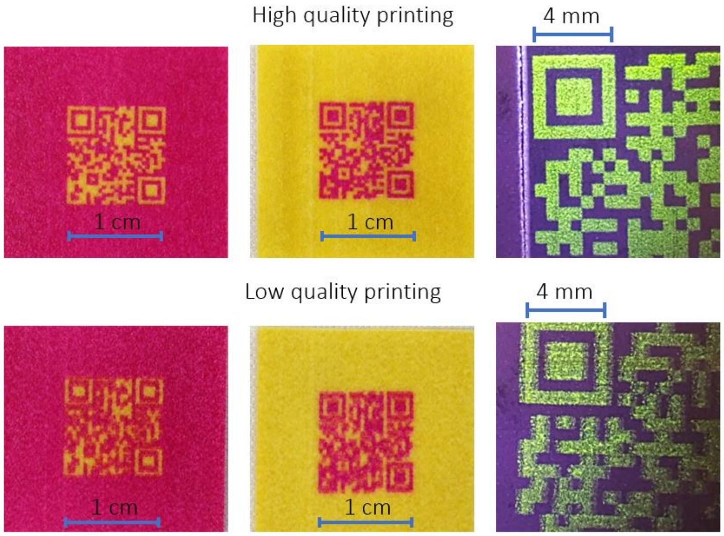

Figure 2. Visually contrasting quick response codes (yellow code on magenta part, magenta code on yellow part, and florescent code on nonfluorescent black part) printed with readable QR code on top and poor image quality unreadable code on bottom.

Besides print and fuse quality determination, discreet embedded QR codes in 3D parts are also achievable. An MJF fusing process and ink placement combined with a new functional agent that fluoresces under ultraviolet light sources enables this capability. To create the discrete fluorescent code, the following print process is utilized: one pre-fusing pass, one agent placement pass, and two fusing passes. For each powder layer, during the forward pass, there is one pre-fusing pass that heats the powder before the inks are printed to ensure splashing is minimized and good agent-powder interaction is achieved to promote the best image quality. This is accomplished by turning on the leading fusing lamp (mounted on the left-hand side of the printing carriage) during the forward pass. Directly after the leading fusing lamps (mounted on the right-hand side of the printing carriage) heat the powder, the ink is placed. Both leading and trailing fusing lamps are then turned on during the backward pass to fuse the layer. A new powder layer is spread, and the process is repeated.

The MJF 3D printing experimental test platform has multi-agent capabilities with five of the agent channels utilized in these experiments. The agent setup and printing modes for the agent channels are shown in Table 1 for the printing of embedded fluorescent QR codes.

Table 1. Agent channels and weight percent agent in nylon 12 polymer powder for producing discrete embedded fluorescent QR codes.

Agent Channel	1	2	3	4	5
Agent	Y	C	M	FA	FL
Wt%	6.27	6.27	6.27	0.01	17.60

Y – Yellow agent
C – Cyan agent
M – Magenta agent
FA – Black fusing agent
FL – Fluorescent agent

The fluorescent QR code dye overlaps with the printed part area dye, which makes it invisible under ambient room lighting conditions. The fluorescent dye concentration of the QR code needs to be high enough to be readable by the sensor under ultraviolet light, yet low enough to be invisible to both the sensor and human detection during ambient lighting conditions. This phenomenon can be seen in Figure 3, where a poor unreadable image quality (lower) and readable image quality (upper) part are compared side by side under both ambient light and UV lighting conditions. The unreadable poor image quality part can either be used to discretely determine print quality or serve as a counterfeiting measure.

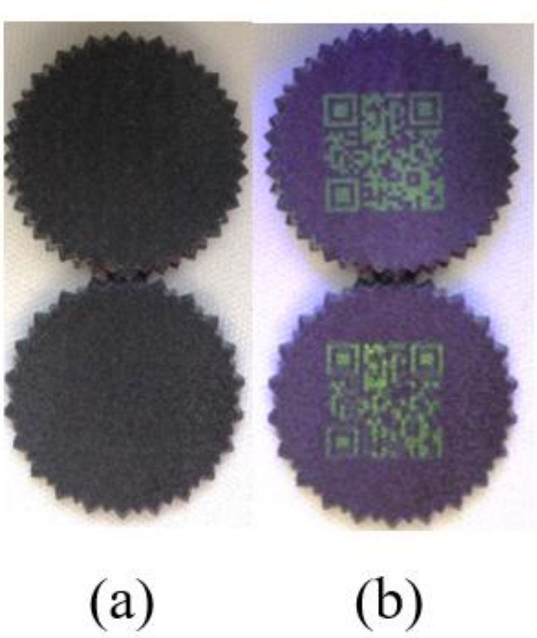

Figure 3. Two printed gear parts with discreetly embedded fluorescent quick response codes under ambient lighting conditions (a) and ultraviolet lighting conditions (b).

4. Conclusion

A non-destructive method of printing two dimensional patterns at desired locations throughout the part with the readability of the pattern providing print quality information has been achieved. This method enables covert part marking as well, to provide design intellectual property security to address the process-variability and intellectual property protection concerns of the manufacturing industry.

A patent has been granted covering this method [8]. Although we have successfully demonstrated quality control using the readability of a printed pattern, a robust automated reading system implemented during the printing process and an automated pattern generation algorithm are being explored.

5. Acknowledgements

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