Direct Part Marking (DPM) Supported by Additively Manufactured Tags to Improve the Traceability of Castings

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Abstract. Manufacturers are increasingly required to trace and track their products throughout different stages of product lifecycle. Various identification techniques such as barcodes, RFID tags, magnetic strips, and optical character recognition (OCR) can be used to support traceability. This research is focused on using Direct Part Marking (DPM) for permanent identification of castings using 2D codes. 3D printed codes were used as pattern inserts in a series of experiments. The objective was to identify the most suitable 3D printing technology for creating permanent marks on castings manufactured using the nobake sand casting process. It was concluded that Polyjet technique creates more dimensionally accurate 3D printed tags and the generated markings are more readable compared to other tested methods.

Keywords: Direct Part Marking, Foundry Traceability, Part Identification

1 Introduction

Traceability of manufactured products refers to the capability to track and trace raw materials, parts, and finished goods throughout the production and distribution processes [1]. Tracing is the ability to extract the history of a particular product by retrieving the records held upstream in the supply chain while tracking is the ability to follow the downstream path of a product along the supply chain. Traceability provides manufacturers with real-time visibility into the operations involved in manufacturing of the products [2]. Manufacturers often strive to use modern tools and technologies to automate the traceability process to the extent possible. Automated identification and data capture (AIDC) technologies are widely used in industry to automatically identify objects, collect contextual data about the identified objects, and record the data in computer systems for future use and trace and track activities.

Some of the commonly used identification techniques include barcodes, two-dimensional (2D) codes, RFID tags, magnetic strips, and optical character recognition (OCR). Finished and semi-finished products with identifiers, such as barcodes and RFID tags, can be readily monitored at various stages of production and distribution with the aid of scanners. If identification systems are designed and implemented properly, AIDC systems can provide part-level visibility and maximize data value to quickly spot production problems or trends and take proactive actions [1].

Barcodes and 2D codes are typically printed on paper labels and attached to products or their packaging. In some cases, the codes are permanently marked on parts or products. Direct part marking (DPM) is a method of marking objects permanently with product information, which may include serial and part numbers, batch number, production date, and other useful information. DPM is particularly useful in harsh environments where labels would not last. Even the most durable label can fade, fall off, or disintegrate when exposed to extreme temperatures, chemicals, liquids, and other harsh environmental conditions. Direct part marking, due to its permanent nature, has proven to be an effective identification method in these situations.

This research focuses on foundry traceability. Due to the high temperatures of the molten metals and the rough surface quality, using RFID tags or barcode stickers is not practical for identification of castings. Therefore, DPM becomes the preferred method for part-level identification in foundry. One of the requirements of traceability in foundry operations is the ability to record the raw material batch, metal composition, and the complete history of pattern making and metal pouring process [3]. The information related to production history can be encoded using various coding standards and marked on castings during their production. The selected method for the DPM process in this work is to print the codes using various additive manufacturing (AM) techniques as tags that can be inserted onto patterns during the mold making operation and before metal pouring. DotCode was selected as the 2D code for permanent marking of castings. Marking of castings is challenging since sand casting often generates rough surfaces, which negatively influences the readability of the codes. Also, the size of the marking needs to be relatively small for aesthetic reasons.

The main research questions that motivate this work are: (1) what is the best 3D printing technology to produce quality tags for sand casting? and (2) what are the optimum casting parameters that result in the most readable codes with a minimum of post-processing steps?

The remainder of this paper is organized as follows. The next section provides a brief overview the related works. The DotCode standard is discussed next. The overall research method is discussed in Section 4. In Section 5, the results of the 3D printing experiments are presented, and Section 5 focuses on casting experiments. The paper ends with conclusions.

2 Related Work

There are different methods available for DPM including etching, dot peening, and laser marking. The focus of this paper is on creating permanent marks on castings manufactured using the *nobake sand casting process*. Although techniques such as laser marking or dot peening can still be applied to castings as a post-productions step, part marking directly during the casting process would be beneficial since its extends the scope of tracking activities to include the molding, casting, shakeout, and cleaning steps. Researchers have used multiple methods for marking of castings including sand embossing using paraffin-actuated reconfigurable pin-type tooling [4] or using CNC machined inserts [5]. An alternative process that has been used for creation of mold inserts is 3D printing which is advantageous for several reasons such as eliminating the need for using special purpose tools, and enabling rapid creation of 3D printed inserts based on the digital models of the codes. Uyan *et al.* [6] have successfully used 3D printed code inserts to be used during the mold making process. They used wax printing technique on ProJet MJP 3600W machine. Although this technique generates tags with high surface quality and accuracy, it requires some extra preprocessing that can be time consuming. In this work, three more affordable3D printing techniques are used and compared for printing of 2D code inserts.

3 DotCode

There are various standards for 2D codes including QR Code, Data Matrix, Maxi Code, Aztec, and DotCode. Fig. 1 shows some of the commonly used 2D codes. In this research, DotCode was selected for direct part marking. DotCode is a 2D matrix symbology consisting of dots arranged in a rectangular array. One advantage of DotCode is that there is no maximum capacity to the amount of data that can be stored in a single code. However, the limit is often imposed by the printers that are restricted to a size limit of 124 dots in either direction. To ensure that the scanner can read the code without picking up any additional pattern around the code, a DotCode must be surrounded by a “quiet zone”, which is three dots wide, on all four sides of the printed code. Smaller and tighter dot geometry results in smaller tags, but also a tag that is more difficult to consistently fabricate and cast into the part.

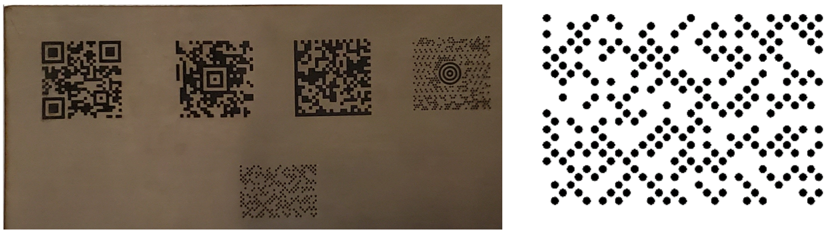


Fig. 1. Different types of 2D codes generated using the laser engraving method (left) and an example DotCode (right).

4 Research Method

In this work, three-dimensional (3D) printed tags were used as pattern inserts for direct marking of castings. Three different 3D printing technologies, namely, fused deposition modeling (FDM), stereolithography (SLA), and PolyJet were evaluated. The tags were printed in extruded (bumps) and protruded (dimples) patterns. Tags were also printed in different dimensions to test if changes in dimensions have any impact on the readability of the codes. The tag measurements were 50 x 30, 40 x 30, 30 x 20 mm. The quality of the printed tags was compared qualitatively and quantitatively to identify the most suitable 3D printing technology with minimal deviation from the original geometry. For quantitative comparison, a digital 3D measurement system was used to measure the diameter of the dots and their distances with adjacent dots. Tags with lower variation in diameter and distance were deemed better in quality. Finally, each of the tags were used on the cope and drag surfaces (separately) of a plate pattern to mark aluminum castings with DotCodes. The readability of the codes was tested using a code scanner mobile app.

5 Tag Printing Experiments

FDM Method: Three different FDM printers, namely, Craftbot, Makerbot Replicator z18, and Voxelizer were used. The Craftbot 3D printer gave better output for bigger tags, but the results were not as desirable for smaller tags. The Makerbot Replicator z18 did not generate desired tag quality for either bump or dimple patterns. The Voxelizer 3D printer managed to get better results than other FDM 3D printers for the bump pattern. Some of the printed tags using Voxelizer are shown in Fig. 2.

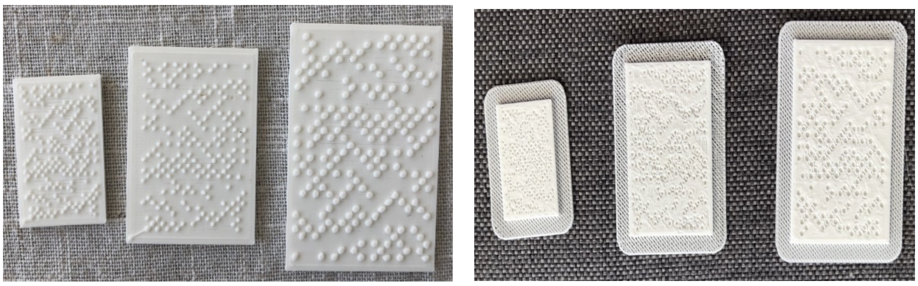


Fig. 2. Tags with bump (left) and dimple (right) patterns printed using Voxelizer.

SLA Method: Most of the dimple patterns were not printed as desired using the SLA print method. The issue encountered was with resin getting stuck in the dimples. It was difficult to remove resin from dimples even after machine washing and manual cleaning. Tags were printed multiple times to get accurate results. In the end, only one tag was produced with satisfactory results. SLA printing was a time-consuming method as it took 2 hours and 20 minutes, including washing and curing, to generate one set of tags in all dimensions. Fig. 3 shows some of the tags printed using SLA technique.

PolyJet Method: As shown in Fig. 4, all of the tags printed using the PolyJet method were of very good print quality; the material appeared strong and solid. The bumps and dimples both printed well.

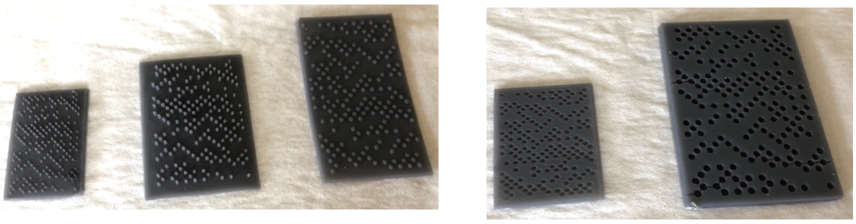
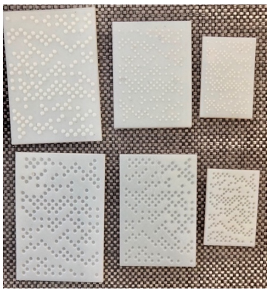


Fig. 3. Tags with bump (left) and dimple (right) patterns printed using SLA method.



	Technology	Std Dev	Mean
Bump 40*30 mm	FDM	0.097	1.1
	Polyjet	0.061	1.04
	SLA	0.07	1.02
Dimple 40*30 mm	FDM	0.11	1
	Polyjet	0.043	1.01
	SLA	0.122	1.125

Fig. 4. Tags printed using PolyJet method (left) and the measurements obtained from VR-5200 digital measurement system (right).

A digital 3D measurement system (Keyence VR-5200) was used to measure the dimensions of the printed tags. The diameter of the dots (bumps and dimples) and their spacing were the dimensions of interest that were measured for various tag sizes. The mean and the standard deviation for those dimensions were used to measure of the accuracy of the prints. More accurate prints have mean values closer to the nominal values and with smaller standard deviation. Fig. 4 (right) shows the measurements obtained for one set of tags. Based on the measurements obtained using VR-5200, the PolyJet tags demonstrated higher quality and accuracy. The next best technology was SLA.

6 Casting Experiments

The objective of this experiment was to mark castings using the 3D printed tags and evaluate the readability of the 2D codes created on the surface of the castings. Steps involved in the casting process included pattern making, sand preparation, molding, melting, pouring, cooling, shake-out, degating, finishing, and inspection. The sand types that are often used for sand casting include green sand and resin bonded sand. As compared to green sand molds, resin bonded sand molds and cores have better mechanical properties and generally produce more dimensionally accurate castings. In this project, AFS GFN 80 round silica sand with a phenolic urethane nobake binder was used. The castings were made of aluminum alloy A356.

Fig. 5. Mold pattern with tags inserted (left); the drag (lower half of the mold) after drawing the pattern (right).

Fig. 5 (left) shows the 3D printed tags attached to the match plate pattern. One of the challenges during pattern preparation was to ensure that all tags were sitting flat on the pattern. PolyJet and FDM tags were sturdier and therefore, stayed relatively flat on the surface. SLA tags were curled after curing, and they did not lie flat on the pattern surface.

Another challenging step was drawing the pattern from the mold without damaging the bump and dimple features on the sand. While drawing the patterns, some of the tags adhered to the sand. The tags remaining in the mold needed to be carefully removed so that the sand around the tag did not become damaged. Figure 5 (right) shows the drag (lower half of the mold) after drawing the pattern.

After producing the castings, it was observed that all dots associated with the SLA tags were damaged. Hemispherical dots and the dots with fillets survived the metal casting process. This observation confirmed the initial assumption that dimple and bumps with a hemispherical shape or fillets yield better results and cylindrical shapes with sharp edges must be avoided. During the casting process, tags placed in the drag were accurately reproduced, but cope-placed tags were not.

After solidification and shake-out, several post-processing steps were needed to obtain readable markings. A mild detergent-water solution and metal brush were used to clean the residue without damaging the markings. Figure 6 (left) shows the markings after the first cleaning step. The *Scandit* mobile app was used to read the codes after cleaning. However, due to low contrast between the bumps and dimples and the flat surface of the code, the app was not able to provide a reading. To improve the contrast, three methods were used: Cleaning with a Scotch-Bright disk, light grinding with abrasive paper, and painting followed by light grinding.

Scotch-Bright disk: 3M's Scotch-Bright is a line of abrasive products applied to clean the metal surfaces. Disks of Scotch-Bright mounted on a die grinder were used to abrasively clean the metal surfaces to improve contrast.

Abrasive Paper: A 320 grit silicon carbide abrasive paper was used to remove surface oxidation and dirt while also leveling out the surface. Aluminum is a relatively soft metal, so it did not take too much effort to level off the surface. After following these cleaning methods, some of the part markings were readable under oblique lighting conditions, but not all were readable.

Application of Flat Black Paint: This step involved spraying flat black paint and further polishing the surface. Figure 6 (right) shows the markings after the secondary preparation step. This step significantly improved the readability with the Scandit app. Markings produced with PolyJet tags with bump patterns were immediately recognized without using any special light setting while markings with dimple patterns required use of light at a 30–40 degree angle to be scanned. The Scandit app has a small scanning area, and it therefore works better for smaller tags (30 mm x 20 mm). As a result, markings made with 30 mm x 20 mm PolyJet tags were easily read by the app. For larger tags, it was necessary to move the reader further away from the casting, which consequently increased the time needed by the app to capture an accurate image and generate a correct reading.

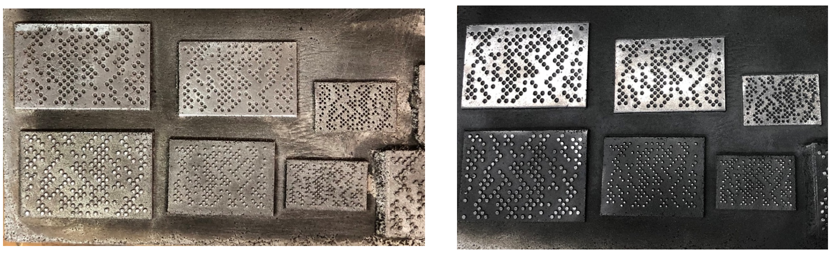


Fig. 6. Tags after initial cleaning (left) and after painting and polishing (right).

Markings made with FDM-printed tags did not work well even after post-processing steps since most of the dots were connected to each other while 3D printing.

7 Conclusions and Future Directions

The experimental study was undertaken to evaluate which 3D printing technology produces better quality DotCode tags for use as pattern inserts in direct part marking of metal castings. DPM is a reliable method of permanent identification of parts exposed to harsh environments. Direct marking of sand castings is challenging since the 2D codes are often not immediately readable and some extra steps are needed to improve the readability. One of the objectives of this work was to simplify the process by reducing the post-processing steps.

Several experiments were conducted using different 3D printing methods and sand casting setups. Both bump and dimple code patterns were used in the experiments. In nearly all experiments, extra steps were needed after casting to improve the contrast and readability of tags. Post casting processes included surface cleaning using abrasive media and painting the tags with flat black paint. Use of paint significantly improved the readability as the matt finish of the paint was more easily read than the reflective surface of the cleaned metal. Also, oblique lighting improved readability.

The Scandit mobile application was used to read the tags. Markings made with PolyJet tags were read most easily with those made with SLA tags being the next easiest to read. Polyjet and SLA tags remained flat after printing and post processing. SLA produced accurate prints except that some tags had resin remaining and adhering in the holes of the tags. SLA produced the bump pattern best as it gave accurate output regardless of size of the tags. The SLA tags were curled and created difficulty in the casting process. It was concluded that FDM technology is not suitable for DotCode printing since the codes generated using FDM tags were the most difficult to read. FDM printing might work for larger tags, though. Overall, it was concluded that PolyJet technology is the best method in terms of sturdiness of the 3D printed tag, the quality of print, as well as suitability for the sand casting process. It was also observed that bump patterns produced with PolyJet tags were easiest to read because they did not require special lighting whereas the dimple patterns did .

Several avenues remain for further research in this area. For example, different types of 3D printing technologies such as digital light processing (DLP), selective laser sintering (SLS), and drop on demand (DOD) could be investigated to produce 3D tags. While DotCode was used in this experiment, DataMatrix codes may prove more robust because the marking is still readable when approximately 17% of the code is damaged. Use of pattern parting compounds such as liquid parting may also improve tag performance as pattern drawing was a major source of marking damage experienced in this study. Different metals such as stainless steel, copper-based alloy, iron, nickel-based alloys can be tested to measure the performance and durability of tags over several alloy systems. In addition, compatibility of the tags with green sand should be investigated. Marking parts with cylindrical surfaces is another challenge that needs to be addressed. Finally, industrial scanners will be used in future research instead of mobile phone apps to better replicate industrial use.

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