EVALUATION OF 3D PRINTED TAGS FOR

DIRECT PART MARKING OF

METAL CASTINGS

by

Nicté Sobrevilla Rosas, B.S.

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Committee Members:

Luis Trueba, Co-Chair

Farhad Ameri, Co-Chair

Maysam Khaleghian

DEDICATION

Dedico mi tesis a mi familia y a mis amigos.

A mi papá, Andrés Sobrevilla del Valle, a mi mamá, Marta Patricia Rosas Rivera, a mi hermana, Azul Sobrevilla Rosas.

A mis abuelos, José Sobrevilla Calvo, Maria del Carmen del Valle Rivera y Rosalinda Rivera Lizárraga.

A las familias Rosas and Sobrevilla.

A todas las personas que me han apoyado toda la vida, sobretodo estos ultimos dos años.

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A las mujeres.

A las personas migrantes.

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ABSTRACT

Direct Part Marking (DPM), or the marking of individual parts with an identifying marking, is becoming increasingly important as manufacturing leans into Industry 4.0. DPM, specifically in metal cast parts, has the potential to improve tracking from cradle to grave, starting from the moment a part is cast. Incorporating DPM allows engineers to narrow down defects for analysis and continuous improvement, and for costumers to have more precise and reliable access to information on their manufactured part. In this work we focus on the additive manufacturing of 3D printed tags to a cast part during the casting process. We performed two separate experiments to test the efficiency and viability of this technology. The first experiment tested the feasibility of printing tags in a resin printer and casting them. Through analyzing and comparing dimensions of designed tags, printed tags, and markings (cast tags) we learned that we could replicate designed tags with an accuracy of 93%. The accuracy of a marking being able to be measured was 65%. The main problem encountered when reading these markings for information was contrast. After identifying this problem, our following experiment addressed this issue by creating new tags with different patterns and after being cast, testing different ways of post processing the marking to increase contrast. We learned that the main key to having a marking read the alphanumeric contents accurately was by having contrast between the background of the tag and its largest 'L shape defining feature, or base.

There is potential for this technology to be implemented into industry and for it to be more automated with large contributions to current environmental efforts.

1. INTRODUCTION

1.1. Introduction

As technology and production move in the direction of automation and Industry 4.0, it is critical that we integrate these ideas into the fields of manufacturing and metal casting [2]. Direct Part Marking is one of the technologies that has shown the most promise in these efforts, specifically when it comes to environmental issues and designing with the environment in mind [3]. Improvement in this area could aid in flow simulation [4], better life cycle tracking [5], and increase overall sustainability in manufacturing. Direct Part Marking is the process of marking a specific part or item with an identifying label [6]. Creating these marking can be done by laser etching matrix codes into parts [7] , using motorized pins to create matrix codes [8], additive manufacturing into silica sand molds [1], and many other ways. Researchers have found that laser marking methods produce to the best readability when compared to other techniques mentioned, but they can wear down easily and cannot be done in conjunction with the casting process, only as a separate step afterward [9]. There has also been research into additive manufacturing through printing codes onto sand cores [10]. They have proved somewhat successful but can only be used in the context of silica sand. None the less, this demonstrates the need for increased traceability is shared and that the field of research is active. Our research differs from these methods because it is not to be performed after the part is cast, but rather during the casting process. Apart from the different techniques of adding information to a part through the manufacturing process, there have also been different types of codes tested in aspects of manufacturing, such as dot code, QR codes, and data matrix codes [11]. A Finnish research group from Aaito

University attempted using data matrix tags, but instead of replicating the matrix code exactly, they divided the matrix into a grid of circles and utilized dots to represent the darkened areas [1].

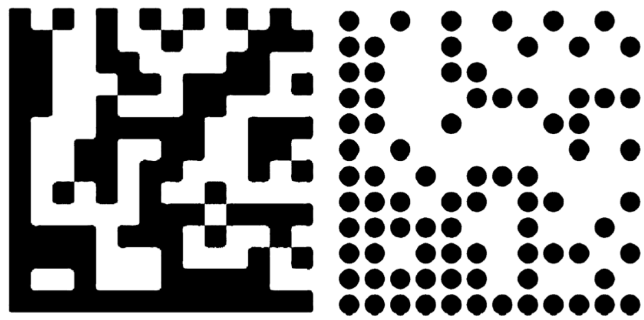

Figure 1.1 Typical Matrix Code modified by researchers at Aaito University. Researchers converted each square in original matrix to dots in order to test an easier pattern to cast [1].

An example of the square to dot conversion is shown if Figure 1.1. These part markings were not able to be read due to contrast issues. Additionally, this method faced another problem, The tags that were used during this experiment were made from wax, which failed to fully evaporate during the casting process. None of the technologies mentioned have proven to meet the demand to its full extent, hence the need for more research in this field. The methods that have been investigated thus far lack sufficient accuracy of tags, struggle with readability due to contrast, and are not fast enough to be economically feasible. Our project differs in that we cast the markings on the part using 3D printed resin tags that were attached to the pattern. We investigate textural differences to determine if they provide increased contrast for improved optical reading after casting. Marking the castings during the casting process could prove to be more efficient time wise since it is incorporated into the process instead of being a separate step. Another key advantage is that it could more accurately track the part through processing from the moment that it is cast instead of later down the production line.

This research project builds on past works [12] but differentiates itself by trying different processing techniques to improve readability and quality of castings using 3D SLA printed data matrix codes that were cast onto parts during the casting process. This work is based on Desavale's work [12] and is a continuation on some research questions that remained to be answered. We wanted to test different 2D codes, as previous work only examined dot codes. Apart from this, we know that research on this topic goes back over 10 years, but no solution has been found to be sufficiently successful in the case of green sand additive manufacturing during the casting process.

1.2. Choosing and Describing the Codes

Figure 1.2 Examples of matrix codes containing an alphanumeric code of 'AB0123456789'. Left code has a contrasting background and base. Right code has a matching background and base.

Before beginning preliminary experiments, it was important to consider different types of codes and to reconsider the direction of our research project. Desavale's work focused on dot codes, but they were hard to cast and label dimensions were significantly bigger than those proposed for our project. Compared to other types of codes, matrix codes have the advantage of being modular, meaning that depending on the amount of information that is programed into the code, the amount of squares in the code will increase or decrease [13]. This is important since other types of codes, such as QR codes, have a defined matrix. Because we were only looking to fit in a serial number, a phrase, or a website into our labels, we did not need the complexity of QR codes. In addition, having less squares per label was advantageous for casting purposes, since there are less defining features and less room for defects. It was because of these reasons that we chose to pursue the experiment with Data Matrix codes.

For the purposes of this work, we have labeled parts of the code to be able to better describe the different zones. There are several defining features. The first feature is the 'L' shape that lines the bottom and left-hand side of the matrix code. This helps determine orientation and size of the matrix. The 'L' feature, that we will call the base, is normally a contrasting color to the background. The background is the region that is outside of the square matrix. Lastly, the filler is the region inside the square matrix that is the opposite color as the base. For Figure 1.2 on the left, the background is white, the base is black, and the filler is white. For Figure 1.2 on the right, the background is black, the base is black, and the filler is white.

2. PRELIMINARY STUDIES

2.1. Experimental Procedure

The preliminary experiments were based on the previous work by Desavale [12]. Desavale found that dot codes did not have a sufficient reading success rate to be useful and believed that the tag sized needed to be increased to be able to have tags print and cast cleanly. Because dot codes were proven to be unreliable as well as other reasons discussed in the previous chapter such as matrix size and potential for amount of data, multiple types codes were considered, but the data matrix tag was the most promising since only 70% of the tag needs to be present for the information to be decoded and can read from any angle. [14]

The design for the two initial tags were data matrix codes created by using a free online 2D generator [15]. The first design used the text 'Go Bobcats!', while the second design, an 11-digit alpha numeric code, emulated an industry serial number by stating 'A012345689'. After having the 2D images of both matrix codes created, we used free software to convert them into STL files [16]. This software took our binary image and would allowed us to set parameters for the height, length, and width of the tag, as well as the elevation difference between the top and bottom elevation. This process was free, fast, and created a positive and negative image (Figure 2.1). We chose to create two different sizes of tag to test accuracy and ability to cast at different dimensions. We set the outside lower elevation dimensions to be 25.4 mm, or 1 inch, for the larger tags and 12.7 mm, or 0.5 inch, for the smaller tags. The height of the bottom base to be .75 mm and the top elevation to rise above that by .75 mm.

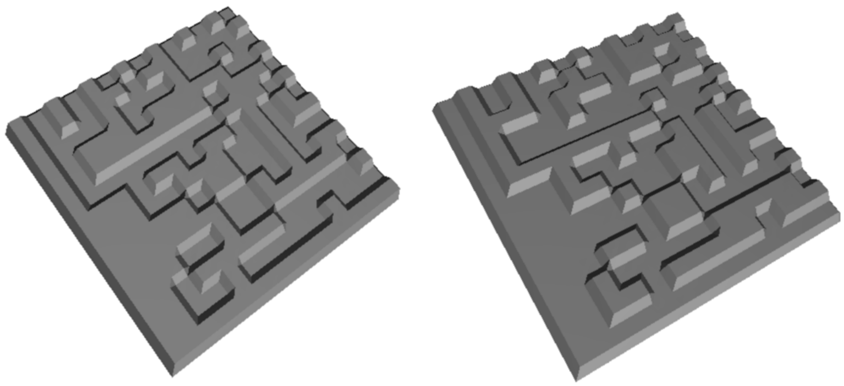

Figure 2.1 Tags with the pattern corresponding to the text 'AB0123456789'. Tag on the side is an example of a positive tag, tag on the right is negative.

Both the positive and the negative tags where first printed on 5-by 5-centimeter tags, using the Anycubic MonoX 6k SLA printer and gray Anycubic colored resin. This took about 17 minutes (two 5 cm x 5 cm tags).

After printing, these tags were washed and cured. They were washed for two minutes in an alcohol solution and cured for 4 minutes under ultraviolet light. The printing of all tags took 7 minutes on the Anycubic printer. The combinations of tags at this point of the process are presented in Table 2.1 below.

Table 2.1 Matrix describing the types of tags produced. Two different texts are used, with either a positive or a negative pattern, in both 1 inch x 1 inch and 0.5 inch x 0.5 inch.

Text	Positive or Negative	Size	
Go Bobcats!	Positive	1 x 1	0.5 x 0.5
Go Bobcats!	Negative	1 x 1	0.5 x 0.5
Serial number	Positive	1 x 1	0.5 x 0.5
Serial number	Negative	1 x 1	0.5 x 0.5

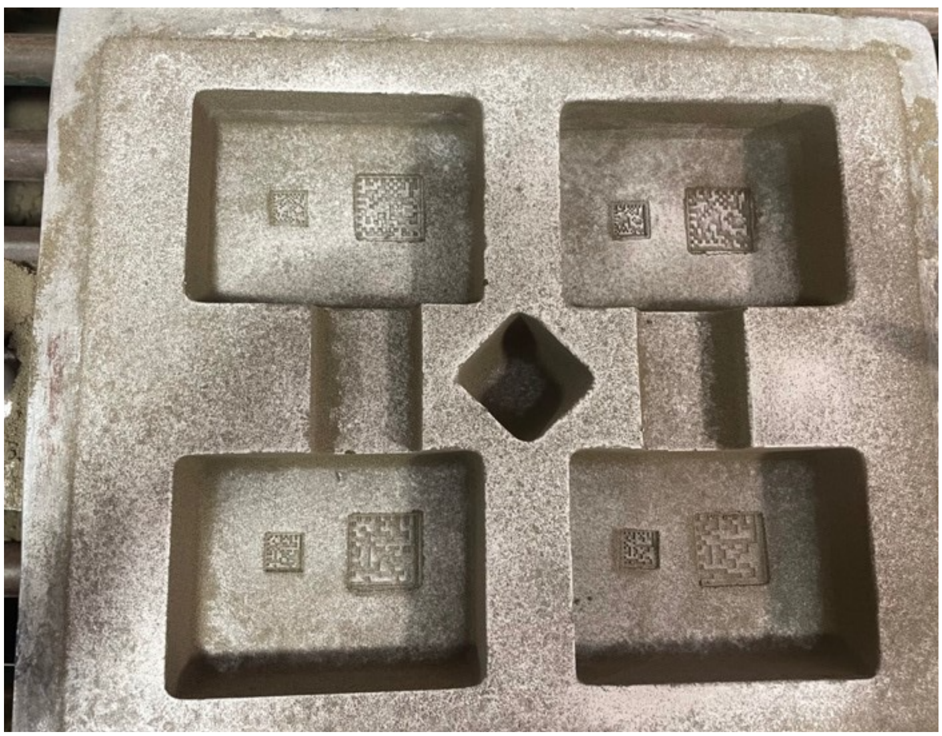

Figure 2.2 An example of the how the mold looks after removing the pattern. Each block contains both a 1 inch x 1 inch tag and a 0.5 inch x 0.5 inch tag.

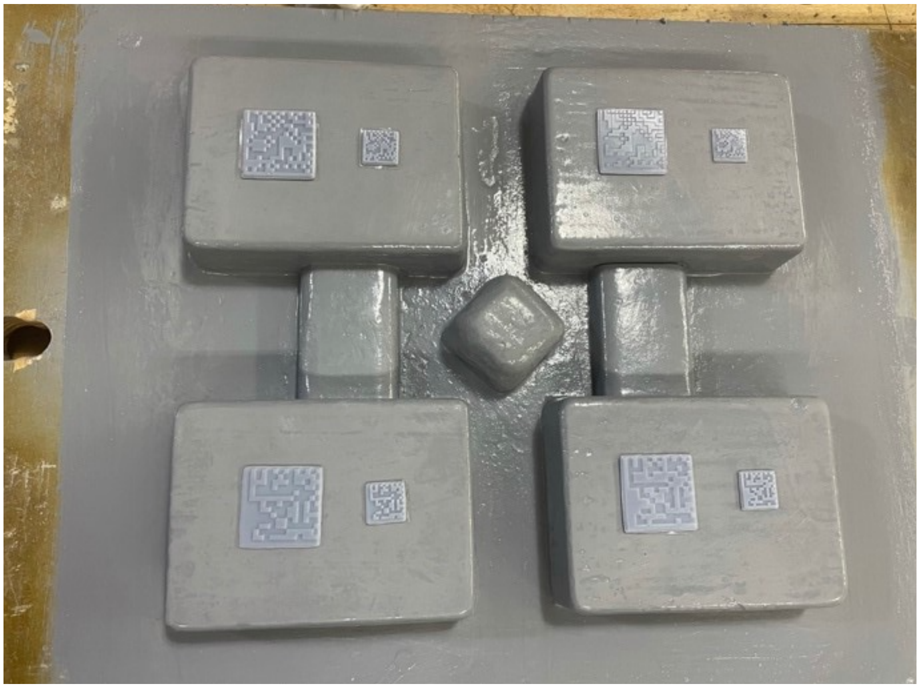

Figure 2.3 The pattern that was used to create the mold in Figure 2.2. The printed tags are attached using double sided tape.

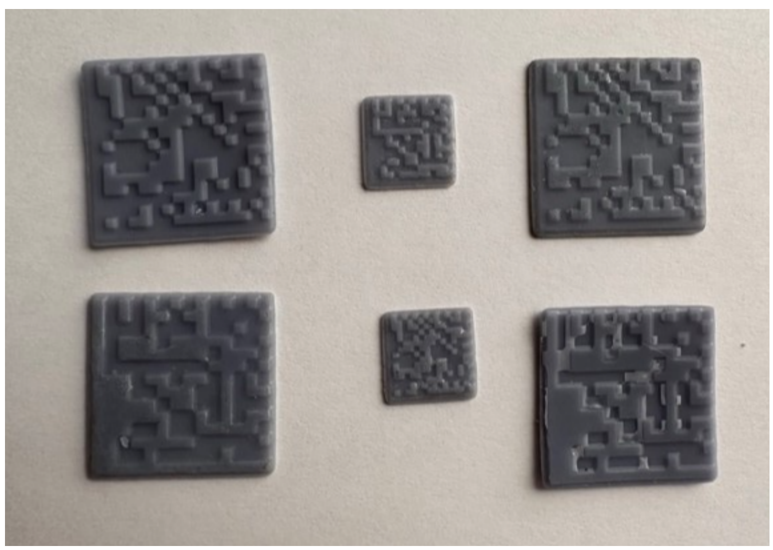

Figure 2.4 A sample of several tags in both 1 inch by 1 inch and 0.5 inch by 0.5 inch sizes.

A match plate pattern was produced from a wooden board and then painted with pattern coating to improve the surface finish. The tags where then attached with double-sided tape and prepared for casting (Figure 2.3). The pattern was used to make two molds in green sand (Figure 2.2), resulting in each tag being produced twice (once in the cope and once in the drag) in aluminum alloy A356. Each tag was then scanned using a Keyence VR-5200 wide area 3D measurement system, giving us a clear 3D model. One of the problems encountered during this process was that because the scanning was performed using structured white light, the reflective properties of the aluminum prevented some areas from being scanned.

We then tried to scan the tags using both a Honeywell portable industrial scanner and the Scandit App on an IPhone 14 smart phone. Without processing, this was unsuccessful. However, the 3D models from the scanner were modified, setting color thresholds for elevation differences Figure 2.5

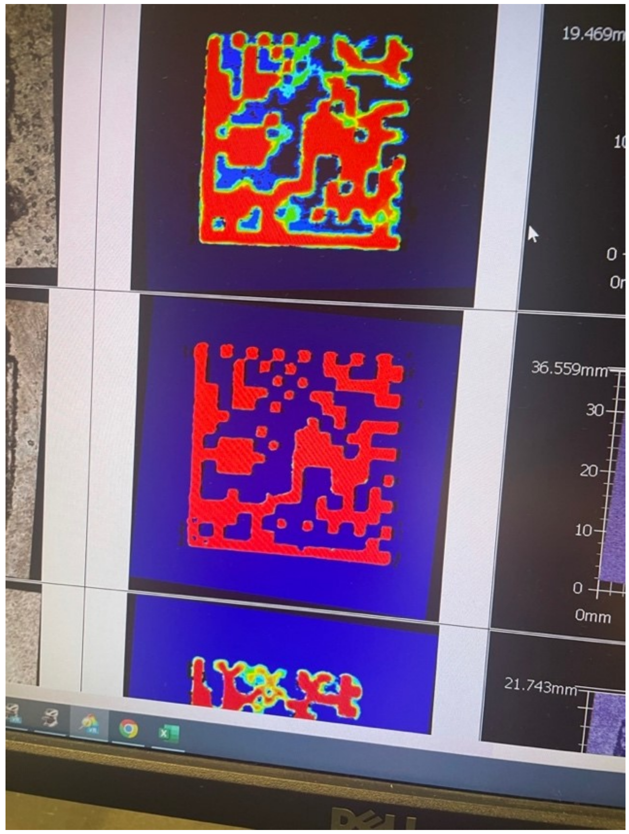

Figure 2.5 An image of the topography of the tag with high contrast. Top code shows the initial topography graph without any manipulation. Bottom code shows the topography map with higher contrast and threshold manipulation.

These were successfully read by both scanner methods. This implies that the key to creating functional 3D codes is to have greater contrast between light and dark areas of the code so that the code can be easily read. This leads us to believe the reason the tags were not readable is that there is not enough contrast between the negative and positive areas without any additional processing, mostly due to the reflective properties of our metal. The issue of contrast has proven to be a challenge to other research groups as well [17], and it is one of the main focuses of the work going forward.

2.2. Results

Quantitative data was collected to understand the effectiveness of designing codes, printing tags, and casting markings. It was important to understand the accuracy at each point of the process to help us understand shrinkage, successful readability, and most efficient approach. Dimensional measurements were taken for each tag in the X and Y direction, which is referred to as the width and the length. Each tag was then measured on two identifying features, each having their own x and y dimensions. Data found is shown on the table below.

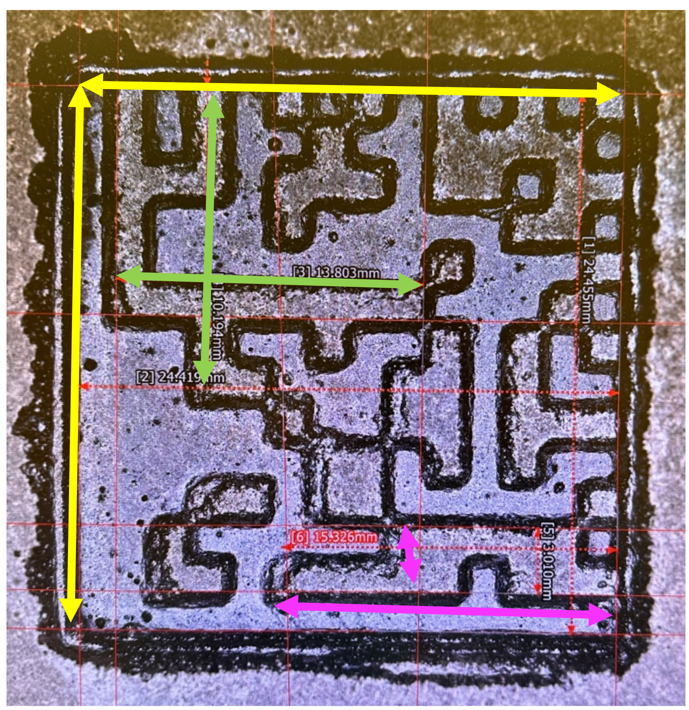

Figure 2.6 Positive Serial Number Tag. Yellow lines show length and width. Green arrows are first defining feature. Purple arrows are second defining feature.

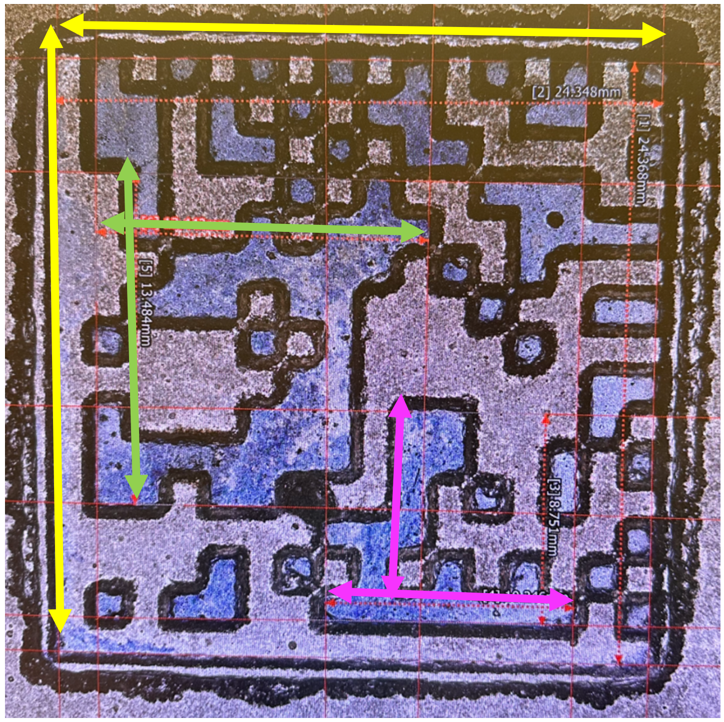

Figure 2.7 Negative Bobcat Tag. Yellow lines show length and width. Green arrows are first defining feature. Purple arrows are second defining feature.

For this experiment, ‘readability’ describes the markings dimensions being clear enough to be analyzed, with measurements being able to be read from defined features. Markings that are not readable can be missing a corner or edges that are too disfigured to be able to have a clear defining point that is measured. In the reading of dimensions, there were 32 cast markings or samples to be read, 27 were readable enough to get clearly defined measurements. 5 were not able to be read or measured, and 6 had unreliable measurements.

Table 2.2 Numerical Analysis of Preliminary Experiments

Accuracy of printed tag versus designed tag	99.88%
Accuracy of cast markings versus printed tag	93.98 %
Accuracy of cast marking versus designed tag	93.87%
Accuracy of length on designed tag versus cast marking	96.73%
Accuracy of width on designed tag versus cast marking	98.32 %
Number of samples	32
Readable samples	27
Unreadable samples	5
Unreliable measurements	6
Sufficient definition	21
Percent reliable measurements	65.63 %

2.3. Discussion

The preliminary experiment helped us understand the characteristics and accuracy of the casting process, as well as develop some key ideas that needed to be explored further. The accuracy of the printer and casting process was high, with the tags only marginally shrinking. We learned that the shrink rate from the tag to the marking was about 6%, not consistent with the standard expected allowance of aluminum. The average shrink allowance for aluminum is about 1% [18].However, this number is not consistent and depends on the shape and size of the casting. With a success rate of 65.63% of reliable measurements, we feel confident that markings are able to be cast with higher accuracy with more practice and improvements, and felt that we were ready to test the effects on contrast. Because of the experiment with a color threshold for a topography map, we knew that this was the key to having successful text readings from our scanner. Because of this, we chose to pursue different techniques to contrast and its effect on readability.

2.4. Further Research Direction

Although this experiment helped further our understanding of the importance of contrast, we still needed to find a way to test it. We tested this by choosing different processes to help improve contrast, casting another series of tags on aluminum, both in one inch and half inch dimensions and then test how different processes affect readability. Four designs that were be tested, a positive and a negative of the serial number tags, as well as versions of these with cones on the bottom elevation. The new tags contain cones to diffuse light and create contrast, meaning that the dark part of the QR code will be on the bottom. We will be preforming 5 different post processes on all the tags: as cast, inked, surface ground, painted, and painted and ground. Since on our mold each ‘block’ can hold both the one inch and half inch versions, we can say that each block is able to hold one tag. Although each block has two sides we can attach tags to (the cope and the drag), this is another factor we would like to explore the differences in. This means that each block can hold 4 tags. With 15 blocks needed to complete one iteration, this means we will need 4 molds at 4 blocks per mold to complete one full iteration of the castings. To measure repeatability, we will perform at least three iterations of the casting. This means we will have a total of 60 cast blocks.

Our goal was to investigate which process helps us read the codes successfully, and we decided to test this using two different methods. We used test the Scandit App on a iPhone 14 as well as the Honeywell industrial scanner. These will test if any processes increase readability (if any), as well as the reading method.

We hope that by having multiple castings at different stages of processing we can get more quantitative data and find accurate and promising methods that can lead us to a more permanent and streamlined direct part marking solution.

3. READABILITY STUDIES

3.1. Introduction

After learning that we can confidently cast tags into metal and create markings, we needed to take the next step to find how we could make the scanning and reading of these marking successful. Though five different techniques, we build off previous findings to increase contrast through post cast processes. We test readability, or the ability for a marking to be scanned and it's alphanumeric content to be read accurately, by using two scanners, four different tag types, and five additional processes to determine which method, if any, is an effective process. The goal of the experiment was to answer the following key questions:

1. Which reading method is most successful?
2. Is there a difference in success rate between the scanners?
3. Is one pattern size more effective than the other?
4. Is there a difference in readability between patterns?
5. Is there a difference in readability success between the cope and the drag?
6. Was the mask effective? And if so, how much?

Table 3.1 describes key numbers of the experiment. There are 4 different types of markings, (Positive, Negative, Positive with Dots, Negative with Dots), 5 types of treatments (As-Cast, Inked, Ground, Painted, Painted and Ground), 3 iterations of each combination, 2 different sizes (1 inch x 1 inch, 0.5 by 0.5 inch), two reading methods (Scandit and Honewell scanner), and two sizes (1 inch x 1 inch and 0.5 inch x 0.5 inch). There are a total of 480 readings for each reading set (with mask or without mask) (1 code x 2 tag styles x 2 backgrounds x 5 finishes x 2 scanners x 2 locations x 2 sizes x 3 iterations = 480 readings). Total readings for the experiments were 960 (480 readings per set x 2 masks).

Table 3.1 Summary of Experimental Factors

Factor	Levels				
Code	Data Matrix				
Tag Style	Positive			Negative	
Background	Smooth			Textured	
Finishing	As-Cast	Inked	Ground	Painted	Painted and Ground
Location	Cope			Drag	
Size	1 inch			0.5 inch	
Mask	Yes			No	
Scanner	Scandit			Honeywell	

3.2. Experimental Procedure

3.2.1. Pouring Castings

The first step to our experiment was creating the castings containing all tags and iterations. As previously stated, we needed to cast a total 60 tags to have three iterations of each process on all 4 tags. The printed tags were attached to a coated wooden pattern. The coating prevented the sand from adhering to the pattern as well as improving surface finish of the casting. At the Texas State foundry, four green sand molds were made at a time, each producing four block castings. 3D printed tags were attached to the pattern using double sided tape. Aluminum A356 was poured at a temperature of 1350ºF. To complete 60 castings required 6 pours. The castings were de-gated using a band saw.

3.2.2. Processing Castings

Figure 3.1 Blocks removed from mold. These blocks are still attached to each other as well as the runner and gating system. Right hand blocks were inked using a standard ink pad to test effect.

There were five different ways that the tags were processed. These include as-cast, inked, ground, painted, and painted and ground. Before processing, all cast blocks for each tag were assigned a number (1-15), and a random number generator assigned each casting to a group of 3, each group being processed differently. This was to ensure randomization to eliminate systemic error. Each block casting was processed individually, and each process was used on both the drag and the cope. The following section explains further details about each process.

As-cast blocks were only separated from initial gating and runner system, and no processing was done to them. They are read in their original condition under standard overhead lighting.

Figure 3.2 As-Cast block with a positive pattern.

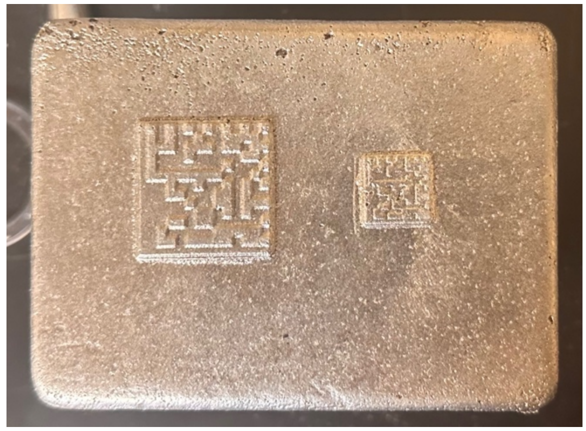

Figure 3.3 As-Cast block with a negative pattern.

Figure 3.4 As-Cast block with a positive pattern and dots on the filler portion of the matrix code.

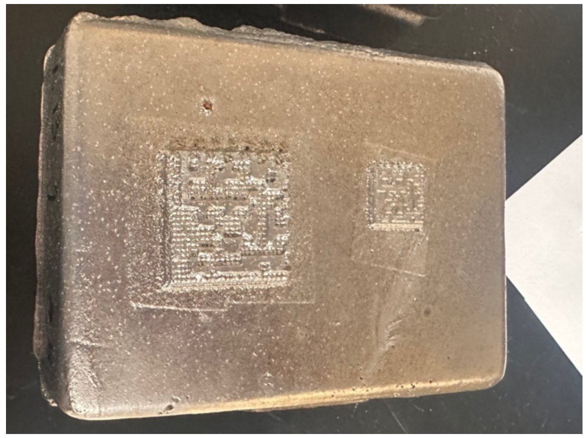

Figure 3.5 As-Cast block with a negative pattern and dots on the base portion of the matrix code.

Inked processing consisted of taking the as-cast block and rolling ink over the raised portion of the marking. Black, water-soluble ink was used with a rubber ink roller. Ink was first applied to a sheet of paper where the roller was run first to help distribute the ink and build a thin layer. The roller was then lightly rolled over each marking to color the raised elevation. This method proved to be tricky as the amount of pressure applied could vary. If too much pressure was applied, the ink would smear into lower regions. If too little pressure was applied, ink would not adhere to the metal surface and skip certain regions of the marking. Also, important to note, looking at the code with the ‘L’ region correctly lined up, paint had a better success rate when applying if roller was dragged from top to bottom, instead of left to right. This is due to one of the features on the left-hand side dropping off and causing ink to smear.

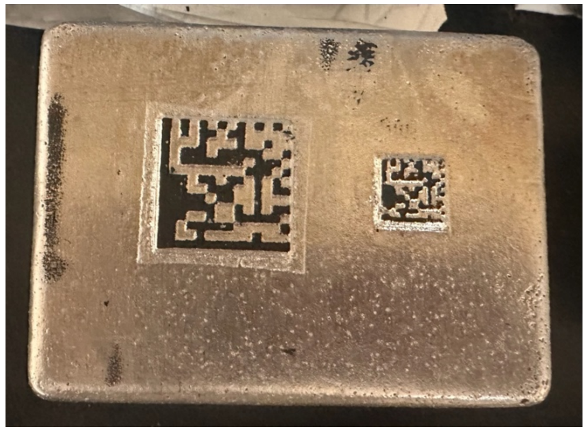

Figure 3.6 Inked block with a positive pattern.

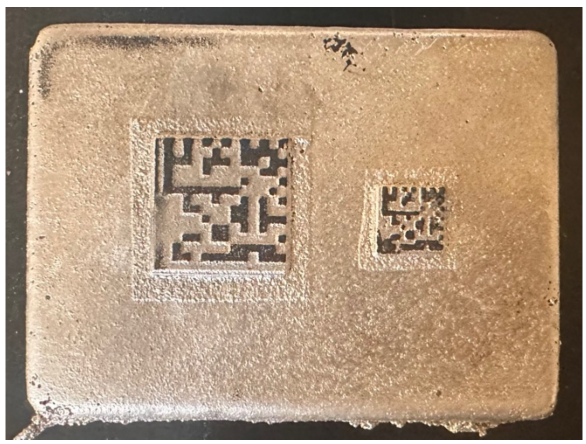

Figure 3.7 Inked block with a negative pattern.

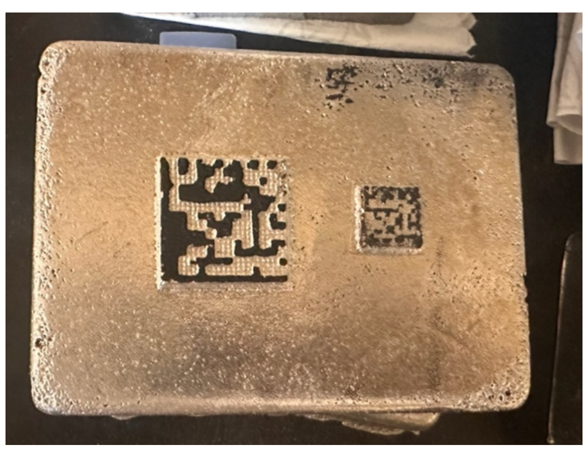

Figure 3.8 Inked block with a positive pattern and dots on the filler portion of the matrix

code.

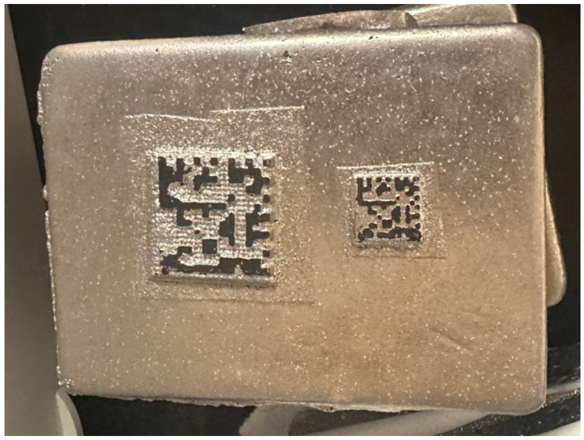

Figure 3.9 Inked block with a negative pattern and dots on the base portion of the matrix code.

Samples that were processed as Ground started from the as-cast block, sandpaper of 120 Grit was used to grind the top surface of each marking, creating a more reflective or 'light' surface on the top elevation.

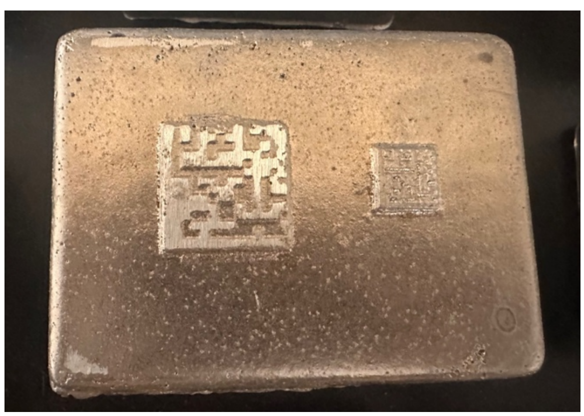

Figure 3.10 Ground block with a positive pattern.

Figure 3.11 Ground block with a negative pattern.

Figure 3.12 Ground block with a positive pattern and dots on the filler portion of the matrix code.

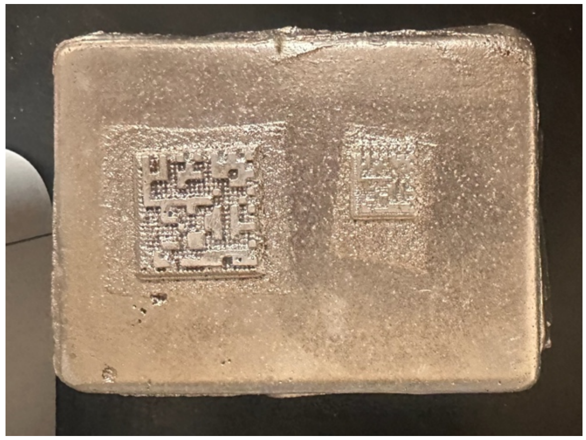

Figure 3.13 Ground block with a negative pattern and dots on the base portion of the matrix code.

Painted samples started from the As-Cast block, each block was spray painted using a black matte paint to reduce the reflectivity of the metal but maintain the difference in elevation.

Figure 3.14 Painted block with a positive pattern.

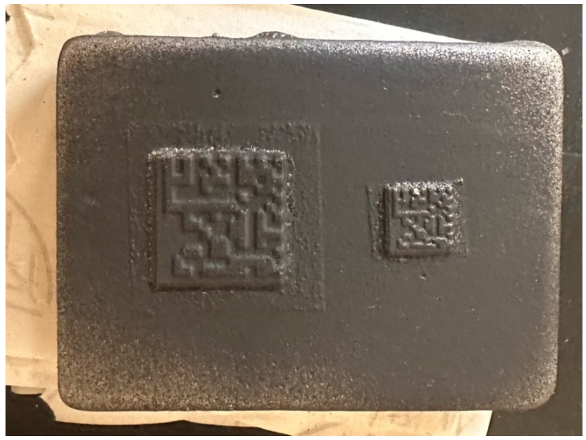

Figure 3.15 Painted block with a negative pattern.

Figure 3.16 Painted block with a positive pattern and dots on the filler portion of the matrix code.

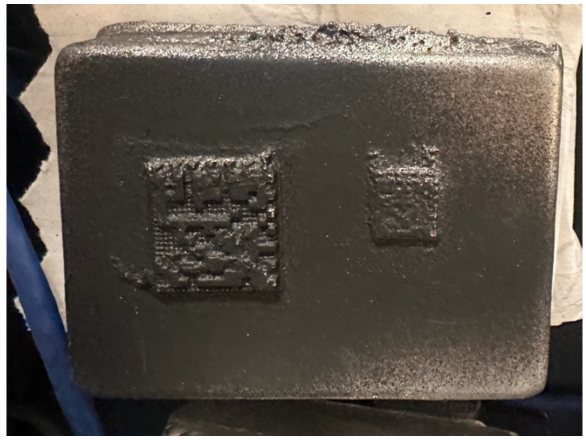

Figure 3.17 Painted block with a negative pattern and dots on the base portion of the matrix code.

Pained and ground blocks started from the as-cast block, then each block was spray painted with a matte black paint. After letting the paint dry for 24 hours, the block was then ground using 60 grit sandpaper. This meant that the top elevation of each tag had the paint removed, creating a reflective and contrasting surface of the original aluminum. The background, due to the matte paint, remained a solid black.

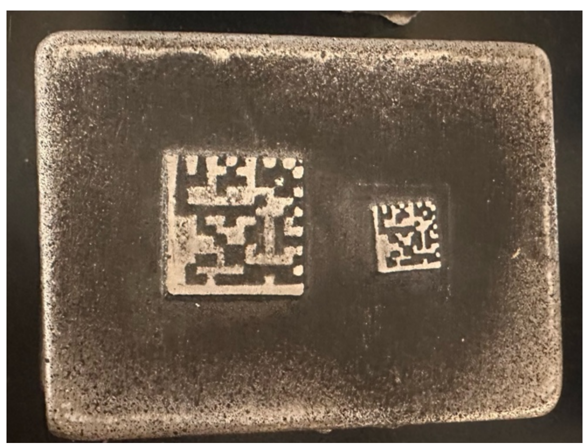

Figure 3.18 Ground and pained block with a positive pattern.

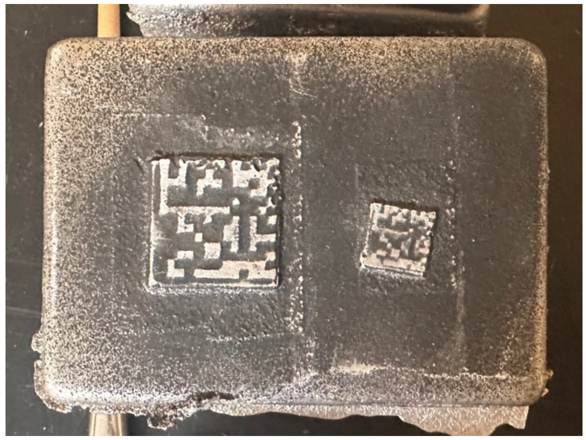

Figure 3.19 Ground and painted block with a negative pattern.

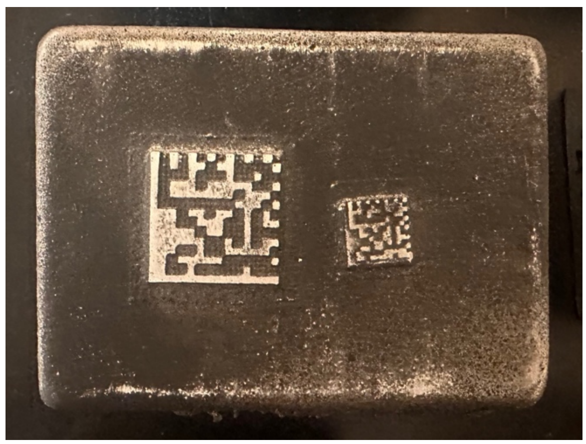

Figure 3.20 Ground and painted block with a positive pattern and dots on the filler portion of the matrix code.

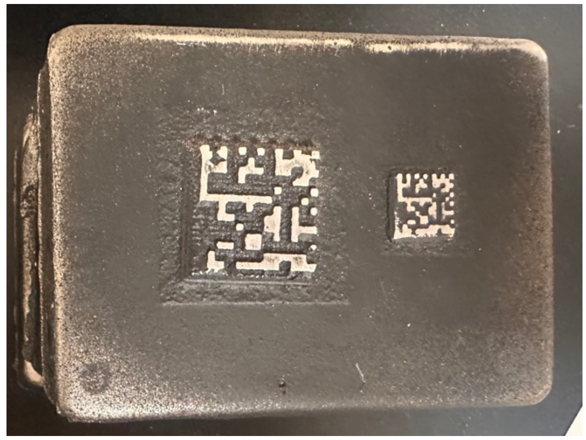

Figure 3.21 Ground and painted block with a negative pattern and dots on the base portion of the matrix code.

3.2.3. Reading Processed Castings

After processing the castings, each was read both by the Scandit Application and the Honeywell industrial scanner. They were both used under direct overhead fluorescent room lighting. Each reading method was attempted for about three seconds, first pointed directly from above and then in a circular motion.

After some experimentation and finishing the first set of readings, the results were less than expected. We had a theory that some of the processes, such as painted and ground specifically in the negative dots tag, were not reading due to lack of contrast not only in between the two colors within the tag, but also from the background. This means that there are three key parts to the matrix code, the background, the base, and the filler. The background must be a color that matches the filler. The base is the 'L' shaped feature of the matrix code that lines the left and bottom side, helping to orient the tag. The filer must be the same color as the background and is the color opposite to that of the base. In most cases, the background is white, the base is black, and the filer is white. To help test this theory we used a standard index card with a 1 inch by 1 inch cut out, that was then placed over the tag.

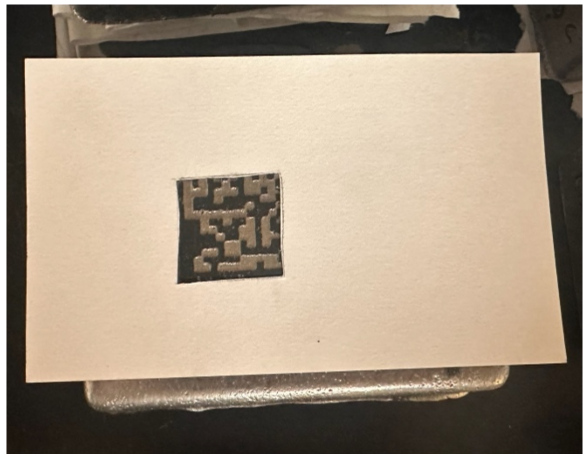

Figure 3.22 1 inch marking framed by a mask.

3.3. Results and Discussion Without Mask

The first set of reading experiments were done without the 1 inch x 1 inch mask. A successful read means that it displayed the accurate text of 'AB0123456789'.

Table 3.2 Summary of Total Readings and Success Rate

Total number of Castings	60
Total Number of Attempted Readings	480
Number of Successful Reads	66
Success Rate	13.54%

3.3.1. Success in Reading Methods

Table 3.3 Number of Successful Readings Per Process

	As-Cast	**Inked**	**Surface Grind**	**Painted**	**Painted & Ground**	**Total**
Scandit	0	18	10	0	19	47
Honeywell	0	5	5	0	9	19
Total	0	23	15	0	28	66

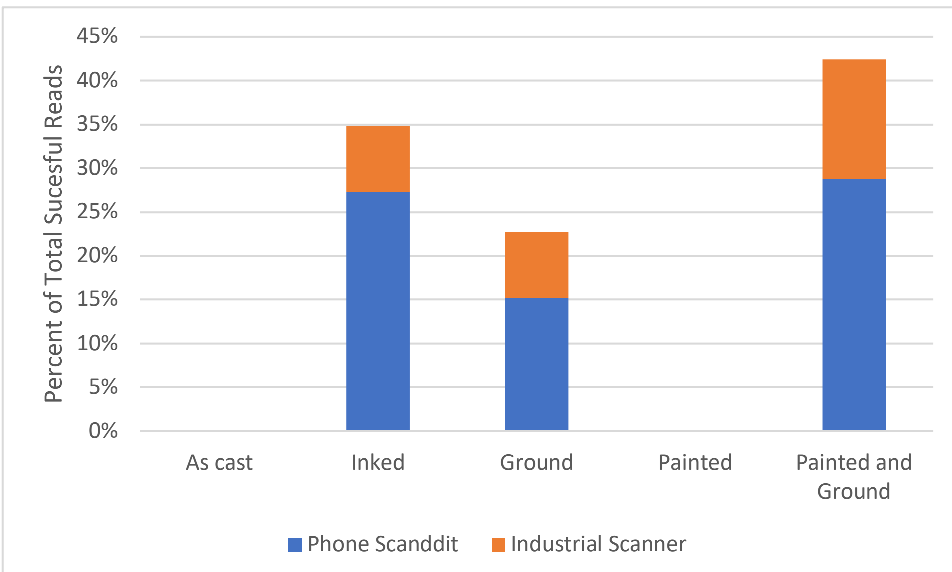

Figure 3.23 Summary of percent of total successful reads by processing method.

Different reading methods had different success rates when combining both sizes. Painted and ground had the highest success rate of 42%. Painted and ground was the processing technique that created the most contrast since it went through two different processes. The matt black pain was applied first, followed by grinding the top elevation to remove the paint. This technique created two distinct tones as compared to other techniques. Other techniques featured less contrast since the tones of the marking were close. For example, the contrast between as-cast aluminum and ground aluminum is minimal when compared to painted and ground. Because this technique had the largest contrast, it was the most successful when being read.

3.3.2. Difference between scanners

Table 3.4 Number of Successful Readings per Scanner Type

Scanner Type	Successful Readings	Percent of Successful Readings
Scandit	47	71.22%
Honeywell	19	28.78%
Total	66	100 %

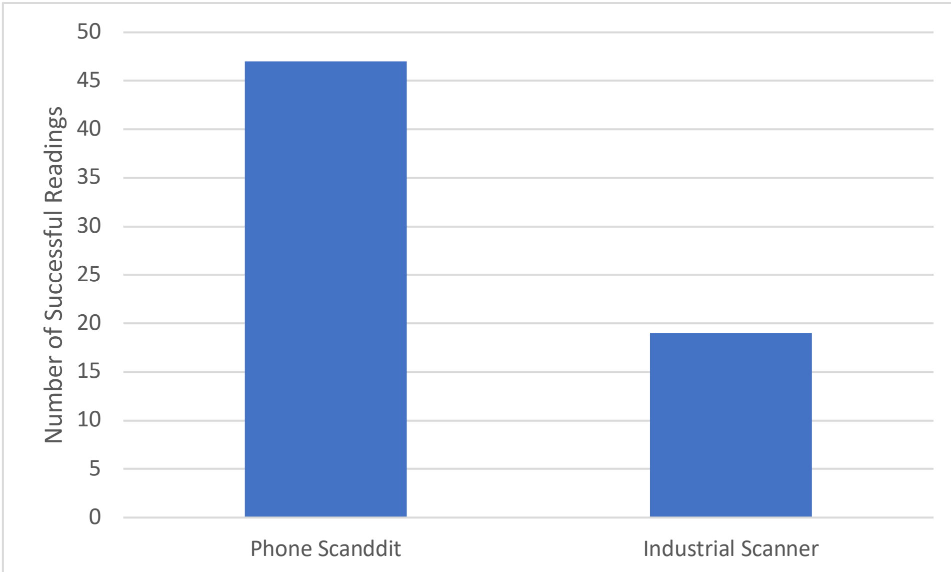

Figure 3.24 Comparing Number of Successful Readings by Each Scanning Method.

The IPhone 14 with the Scandit app had a significantly higher success rate then the industrial Honeywell scanner. The Scandit app was able to get clear resolution and recognize color and shadows and read without as much practice or experimentation. The Honeywell scanner uses a red light and a blue light to identify codes and shadows, and its dedicated job is to read 2D codes. However, it only read 28% of the successful reads. For industry, a simple camera scanner would be a better investment, as it is not only cheaper, but significantly more effective. This method is effective because it does not require a large learning curve, meaning foundries of all sizes could benefit from this technology. In addition, with most people having a smartphone today, the ease of information is increased. An average consumer of a product could have access to recycling information, life cycle tracking, and any other information they might benefit from without having to invest in a separate device. This ultimately aids in the goal of our experiment and supports the hypothesis that this technology aids in environmental efforts and accessibility to information.

3.3.3. Pattern Size Readability Difference

Table 3.5 Comparison of Successful Readings on Different Size Markings

Scanner Type	**1 inch**	**0.5 inch**
Scandit	38	9
Honeywell	16	3
Total	54	12

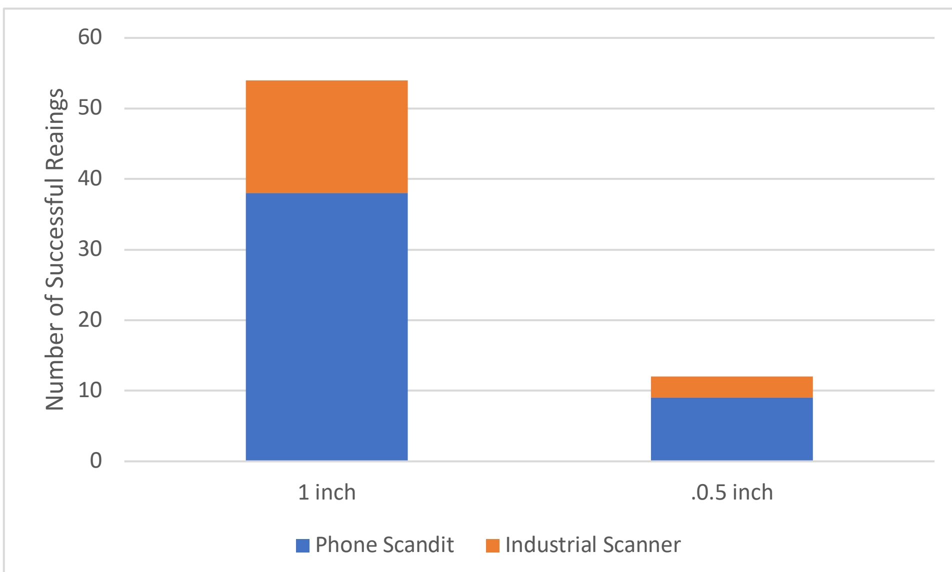

Figure 3.25 Compares the number of successful readings of the 1 inch and 0.5 inch markings. Blue color represents successful readings with Scandit application while orange shows successful readings for the Honeywell scanner.

The larger 1 inch tags proved to be significantly more successful when reading markings with both scanning methods. This is supported due to a larger tag being able to get better definition during the creation of the molds. Any deformation or shrinkage has a larger effect on the smaller tags due to them having a smaller surface area. In addition, processing the markings is more difficult because of the accuracy required when painting or grinding. These challenges are more subdued on the larger markings, contributing to their higher accuracy and ease of readings. In the future, other ways of molding, such as using a machine, experimenting with different tempers of the sand, or processing performed by a machine, could be explored to improve definition in the smaller tags.

3.3.4. Readability Between Patterns

Table 3.6 Comparison of Successful Readings per Pattern Type

Pattern Type	**Successful Readings**
Positive	27
Negative	10
Positive with Dots	28
Negative with Dots	1
Total	66

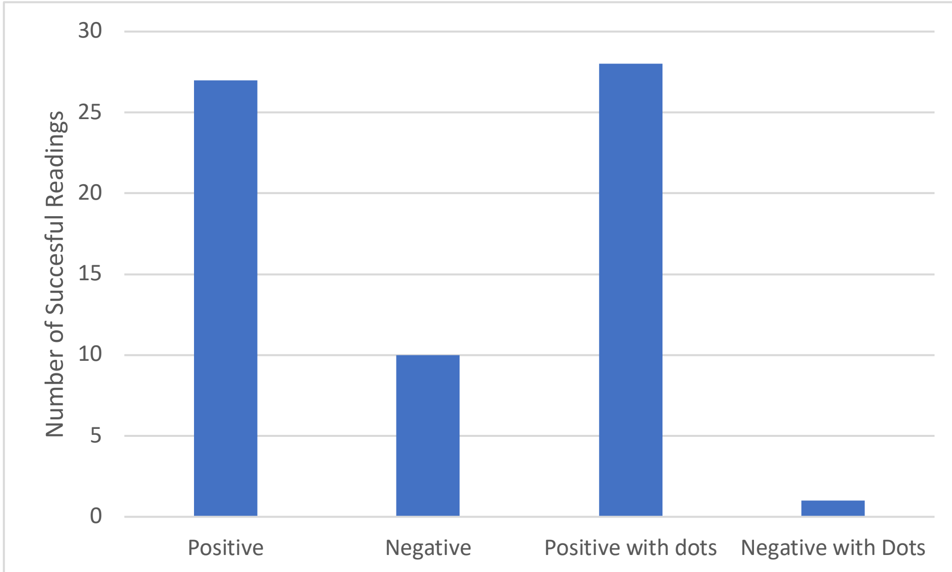

Figure 3.26 Displays the number of successful readings per pattern type.

When comparing patterns, positive patterns had a higher success rate overall, with positive with dots having 1 more positive reading than simple positive pattern. Positive patterns having the most success is supported by the fact that when procced with inked and ground they replicated the contrast that is traditional in the 2D matrix codes, the base being darker than the filler and background. The positive patterns were also easier to process because the biggest defining feature, the base, was the surface that was being processed. This made processing more accurate and easier, clearing overall definition of the code and increasing its readability.

3.3.5. Readability Between Cope and Drag

Table 3.7 Comparison of Successful Readings in the Cope and Drag

Location	Successful Readings	Percent of Total Successful Readings
Drag	37	56 %
Cope	29	44%
Total	66	100%

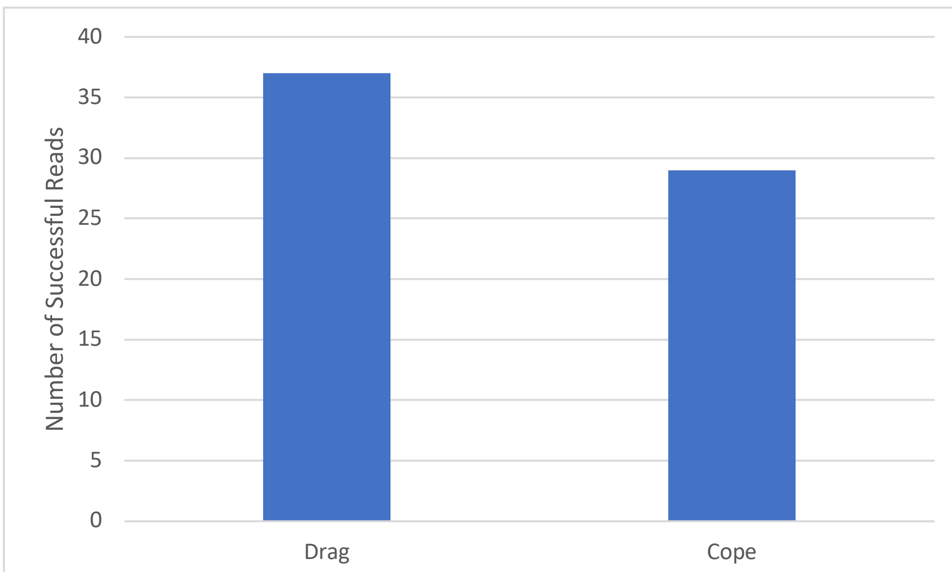

Figure 3.27 Graph displaying successful readings between the cope and the drag.

Looking at successful readings between the drag and the cope the drag was slightly more accurate. When casting the blocks, the drag location is facing down, allowing the metal to fill the gaps and detail of the mold more fully. In addition, as the metal begins to shrink, shrinkage occurs mostly in the cope due to the metal settling at the bottom. Some of the castings produced featured shrinkage, which significantly reduced accuracy, especially in the smaller 0.5 inch markings. These deformations influenced processing, making it more difficult to replicate processes on all the markings. Due to these defects, cope location markings were harder to read.

3.4. Results and Discussion Mask

This set of readability experiments uses the 1 inch x 1 inch mask. A successful read means that it displayed the accurate text of ‘AB0123456789’.

Table 3.8 Summary of Total Readings and Success Rate

Total number of Castings	60
Total Number of Attempted Readings	480
Number of Successful Reads	24
Success Rate	5.00%

3.4.1. Success in Reading Methods

Table 3.9 Number of Successful Readings Per Process

	As-Cast	**Inked**	**Surface Grind**	**Painted**	**Painted & Ground**	**Total**
Scandit	0	9	1	0	9	19
Honeywell	0	4	0	0	1	5
Total	0	13	1	0	10	24

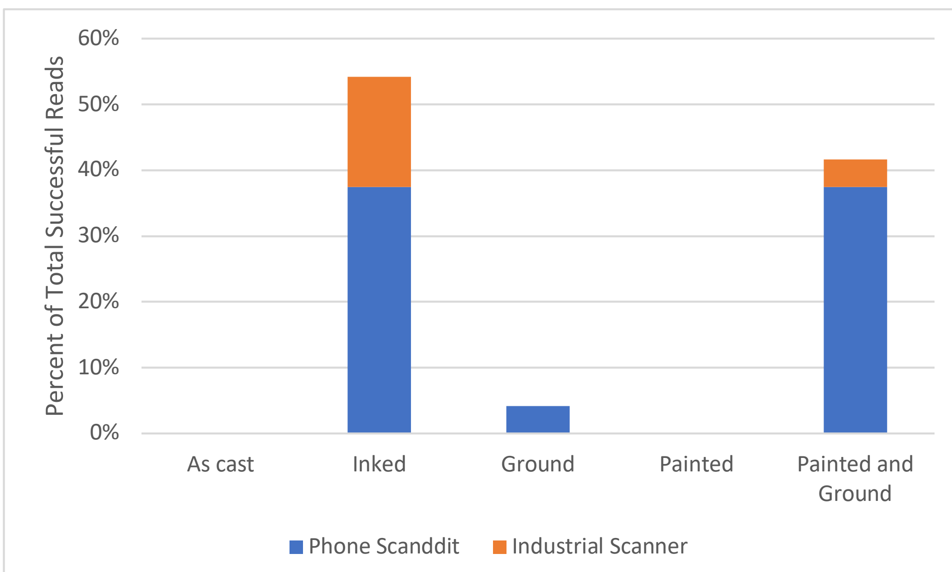

Figure 3.28 Summary of percent of total successful reads by processing method with a mask.

Different reading methods had different success rates when combining both sizes and using the Mask. Inked had the highest success rate with 54%. Not only did it provide the most contrast, but the highest accuracy. Inked processing took some practice to be able to replicate application consistently, but it was quicker than other processes. Any mistakes that were made outside of the base were addressed by the overlay of the mask, since it created more definition. Because of its advantage and highest accuracy, when using a mask, the inked processed is most effective.

3.4.2. Difference between scanners

Table 3.10 Number of Successful Readings per Scanner Type

Scanner Type	Successful Readings	Percent of Successful Readings
Scandit	19	79%
Honeywell	5	21%
Total	24	100 %

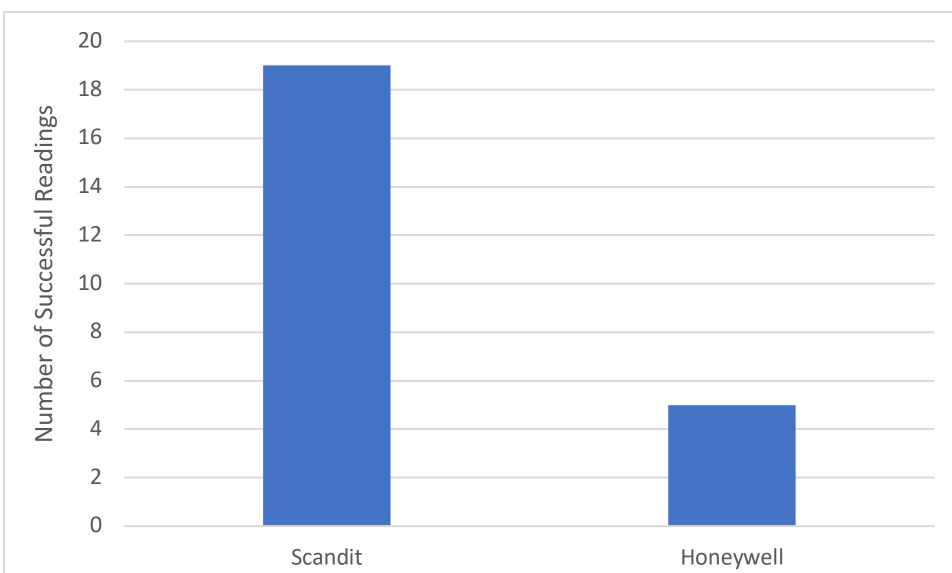

Figure 3.29 Compares the number of successful readings from the Scandit App and the

Honeywell industrial scanner.

Like the results without a mask, the Scandit app was able to get a significantly higher success rate of correct readings than the industrial scanner. The percent success rate is very similar to that of the readings without the mask. Percent of Scandit success without the mask were 71%, and with the mask it was 78%. This supports or experiment and is consistent with previous results. It also supports the idea that a simple IPhone or camera scanner system would be a better investment in any size foundry. These finding are also encouraging in terms of information accessibility, like those in previous readings.

3.4.3. Pattern Size Readability Difference

Table 3.11 Comparison of Successful Readings on Different Size Markings with Mask

Scanner Type	**1 inch**	**0.5 inch**
Scandit	17	2
Honeywell	5	0
Total	22	2

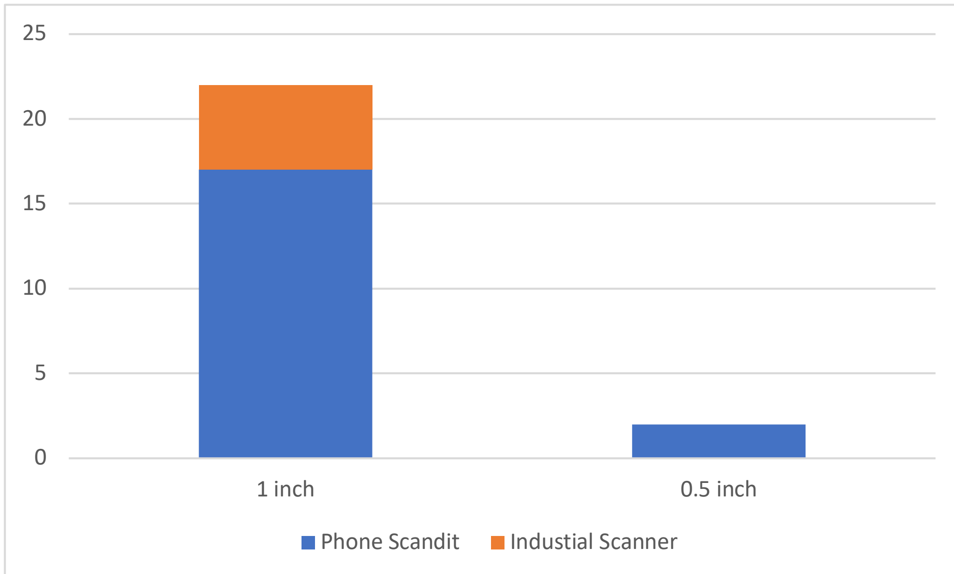

Figure 3.30 Compares the number of successful readings of the 1 inch and 0.5 inch markings when reading with a mask. Blue color represents successful readings with Scandit application while orange shows successful readings for the Honeywell scanner.

Consistent with previous readings, the larger 1 inch tags proved to be significantly more significant than the 0.5 inch tags. In readings with a mask, the 1 inch tags were 11 times more successful than the smaller one inch tags. The smaller 0.5 inch tags were also only able to be read using the Scandit app. The 1 inch tags were also easier to align with the mask, providing more defined features. However, the mask did not significantly improve or influence the readability of the sizes compared to results without the mask.

3.4.4. Readability Between Patterns

Table 3.12 Comparison of Successful Readings per Pattern Type

Pattern Type	**Successful Readings**
Positive	10
Negative	4
Positive with Dots	6
Negative with Dots	4
Total	24

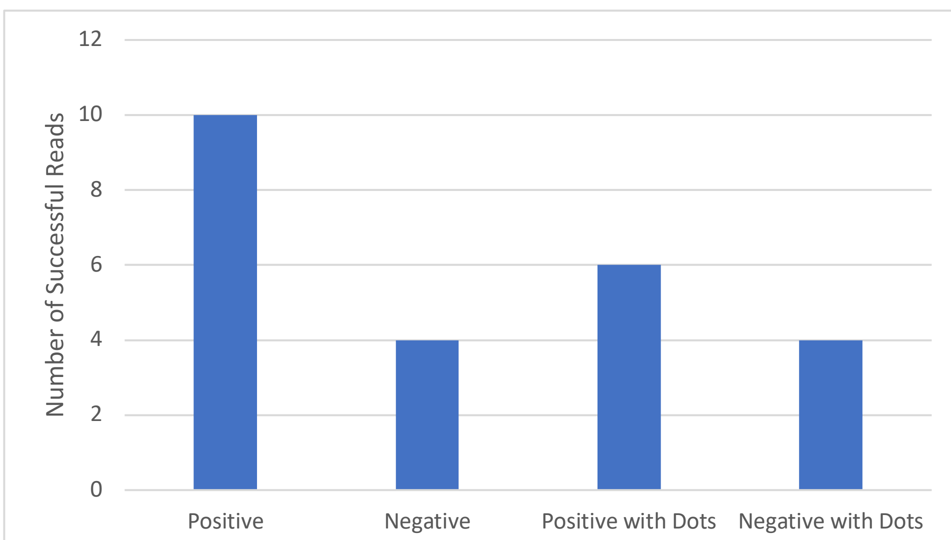

Figure 3.31 Displays the number of successful readings per pattern type when reading with a mask.

The distribution of successful readings with the different patterns and reading with a mask is more even than that without a mask. However, the positive markings still were the most readable. Specifically with the mask, this could be due to the positive tags being mostly processed on their top elevation, in this case the base. Our processes change the color or texture of the top elevation, and because in positive tags this is the darker portion of the code, when framed with the mask, the contrast is increased. This influences readability and allows the positive tags to be read more consistently than other marking types.

3.4.5. Readability Between Cope and Drag

Table 3.13 Comparison of Successful Readings in the Cope and Drag

Location	**Successful Readings**	**Percent of Total Successful Readings**
Drag	16	66.66 %
Cope	8	33.33%
Total	24	100%

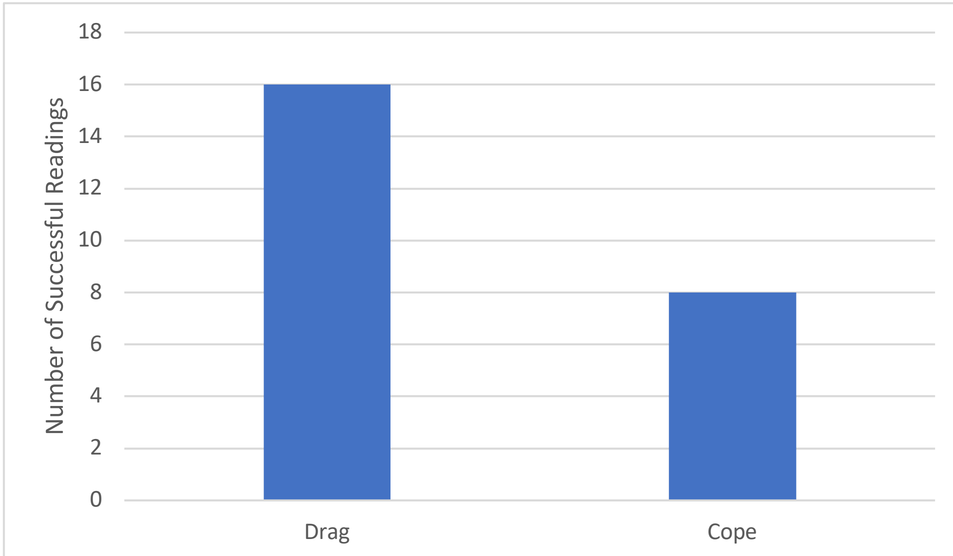

Figure 3.32 Compares the number of successful readings between the drag and the cope locations.

Looking at successful readings between the drag and the cope the drag was significantly more accurate. With metal being able to fill the mold more fully during solidification, we expected the drag to be more successful. We experienced shrinkage with the cope locations, and this is supported by the lack of definition and lower success rate. These results are like the results without a mask, with drag having 66% of the successful readings without a mask. This is supported with the ratio of drag and cope successes being similar, since the mask should not interfere with these results directly.

3.5. Effectiveness on Successful Readings with a Mask

The idea to create a mask came after doing a short experiment in which we tried to scan the same code with a white background that contrasted the base, and a black background that matched the base. When reading the code with the contrasting background, the scanner was able to read the codes without a problem. But when the background matched the base, the exact same code is not recognized. In certain codes, like negative with dots when painted and ground, the background matches the base. We realized that if it had a light background, it would maybe read. We created a mask of 1 inch by 1 inch. We achieve a success rate of 5%, 7% lower than the same experiment without the mask. However, this was a cheap and easy way to innovate the design, and the reason why it was decided to rescan our castings using the masks. However, the sue of the mask did not improve readability at all, therefore would not be recommended as an additional process in the future.

3.6. Discussion

3.6.1. Analysis of Contrast

One key factor that was identified during the research was the contrast between all sections of the tag. Not only is it critical that there is a clear difference between the base and the filler, but also between the base and the background. We can separate tags that feature contrast between the base and the background as Contrasting. The tags that share background and base color are Non-Contrasting.

Table 3.14 Non-Contrasting Tag Readability with no Mask

	As-Cast	**Inked**	**Surface Grind**	**Painted**	**Painted & Ground**	**Total**
Scandit	0	13	10	0	14	37
Honeywell	0	4	5	0	9	18
Total	0	17	15	0	23	55

Table 3.15 Contrasting Tag Readability with no Mask

	As-Cast	**Inked**	**Surface Grind**	**Painted**	**Painted & Ground**	**Total**
Scandit	0	5	0	0	5	10
Honeywell	0	1	0	0	0	1
Total	0	6	0	0	5	11

Table 3.16 Comparing Contrasting Versus Non-Contrasting Markings

	As-Cast	**Inked**	**Surface Grind**	**Painted**	**Painted & Ground**	**Total**
Contrast	0	17	15	0	23	55
No-Contrast	0	6	0	0	5	11
Total	0	23	25	0	28	66

In markings without the mask, contrasting tags are 5 times more successful than tags without contrast. This supports the theory that contrast, not only between the filler and the base, but also between the base and the background is key to a successful reading.

Table 3.17 Non-Contrasting Tag Readability with Mask

	As-Cast	Inked	Surface Grind	Painted	Painted & Ground	Total
Scandit	0	9	1	0	2	12
Honeywell	0	4	0	0	0	4
Total	0	13	1	0	2	16

Table 3.18 Contrasting Tag Readability with Mask

	As-Cast	Inked	Surface Grind	Painted	Painted & Ground	Total
Scandit	0	0	0	0	7	7
Honeywell	0	0	0	0	1	1
Total	0	0	0	0	8	8

Table 3.19 Comparing Successful Readings in Contrasting versus Non-Contrasting Markings

	As-Cast	Inked	Surface Grind	Painted	Painted & Ground	Total
Contrast	0	13	1	0	2	16
No-Contrast	0	0	0	0	8	8
Total	0	13	1	0	10	24

The total number of successful readings with the mask was 24. Contrasting tag successes were 16, while the number of successful readings for the non-contrasting tags was 8. 66% of the successful readings for tags with a mask came from tags with contrasting base and background.

This is a key observation that was made during the reading of the tags, and a conclusion that can lead to feature work. The ration of success in contrasting versus non-contrasting marking is significantly higher in readings without a mask, but both sets have shown that it is necessary to have the contrast between the base and the background to improve readability.

3.7. Conclusions

Contrast is the key to being able to read data matrix codes, specifically when it comes to separation between the background and the base. Without the mask, 80% of results came from markings that had this type of contrast. As-Cast markings provided no successful readings, and it is now clear that there needs to be post processing done to some extent to be able to have a successful reading. Our work proved to continue to differ from previous studies, both in its application of greensand, but also in the different processes that were chosen. The techniques used to process the castings taught us the degree that contrast is needed, not only in the base and background, but also in the fact that edges and shadows are not enough to create enough differentiation to achieve readability, and that the overall code really needs to have a defined perimeter. We also learned that adding the mask did not increase our success rate but lowered it. This might be due to now instead of having two tones of color, you now have three.

As expected, the cope and the drag comparison proved that the drag is consistently better at forming defining features and therefore better readings. It is also clear that positive codes are most effective, specifically the positive codes with dots on the lower elevation to diffuse contrast. The 1 inch tags provided better accuracy when being processed, and were significantly more successful compared to their smaller counterparts, specially when reading without a mask. The Scandit app also had a significant advantage over the Honeywell industrial scanner, and would be the recommendation if this technology was to be implemented into industry.

Overall, the most successful combination for markings was a 1 inch positive with dots marking on the drag location. This marking would then be processed with paint and then ground, and read without a mask and using a camera scanner. This method was successful on all 3 iterations when being read.

3.8. Future Works

We gained great understanding of additive manufacturing and 3D tags during out two-year research project. However, there are many questions and paths regarding possibilities that still need to be pursued. We had great success with the 1 inch by 1 inch tag size, but not with the .5 inch by .5 size. It would be interesting to see if there is an ultimate size that is somewhere in between, as well as how small the tag can be while still obtaining meaningful results. As a separate project, analysis of the different techniques and specifically time to process could greatly contribute understanding of this topic. This information could help calculate the financial margins necessary for implementation of this technology into industry. Lastly, the scanner types could still be explored. An IPhone or IPad scanning system seems the most accessible, but there is potential to program some specific scanner system that searches for specifical features such as base, background, and filler. This would be ideal as well since consumers of parts could use their conventional phone to find how to best recycle or dispose of products efficiently.

There is also the potential idea of programming or using an existing program that scans the tag topographically and can create an image using the elevation as a threshold to create contrast. This would be like our initial 3D scans and could eliminate any post processing required.

This technology has applications in the automobile, technology, environmental engineering, and many other fields. There is a potential that still needs to be explored, with the goal of introducing this project into industry.

APPENDIX SECTION

Readability Results (DRAG)

Positive tags | readings total: 60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	AB0123456789
Industrial Scanner	no	AB0123456789	no	no	AB0123456789

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	AB0123456789	no	AB0123456789
Industrial Scanner	no	no	no	no	AB0123456789

attemped readings 10

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	AB0123456789
Industrial Scanner	no	no	no	no	AB0123456789

0.5

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	AB0123456789	no	AB0123456789
Industrial Scanner	no	no	AB0123456789	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	AB0123456789

attemped 10

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	AB0123456789

Negative tags | readings total: 60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	AB0123456789	no	no	no

attemped 10

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

0.5

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

attemped 10

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Positive Dotted Tags | readings total: 60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	AB0123456789	no	AB0123456789
Industrial Scanner	no	AB0123456789	AB0123456789	no	AB0123456789

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	AB0123456789	no	AB0123456789
Industrial Scanner	no	AB0123456789	AB0123456789	no	AB0123456789

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	AB0123456789
Industrial Scanner	no	no	no	no	AB0123456789

0.5

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Negative Dotted Tags | readings total: 60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

0.5

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Appendix Figure A Displays the tables and results used in the readability results of the drag.

Readability Results (COPE)

Positive tags	readings total:	60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	AB0123456789	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	AB0123456789	no	AB0123456789
Industrial Scanner	no	no	no	no	no

0.5

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	AB0123456789	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	57w09	no	no
Industrial Scanner	no	no	no	no	no

Negative tags	readings total:	60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

0.5

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Positive Dotted Tags	readings total:	60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	AB0123456789	no	AB0123456789
Industrial Scanner	no	no	AB0123456789	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	AB0123456789	no	AB0123456789
Industrial Scanner	no	no	AB0123456789	no	AB0123456789

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	AB0123456789
Industrial Scanner	no	AB0123456789	no	no	no

0.5

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

Negative Dotted Tags	readings total:	60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

0.5

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Appendix Figure B Displays the tables and results used for readability studies in the drag.

Readability Results (DRAG) with Mask

Positive tags	readings total:	60

1 inch

attemped readings 10

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scandit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scandit	no	AB0123456789	no	no	no
Industrial Scanner	no	AB0123456789	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scandit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

0.5

attemped 10

Iteration A					
Phone Scandit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Iteration B					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C					
Phone Scandit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Negative tags	readings total:	60

1 inch

attemped 10

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scandit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scandit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	AB0123456789

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scandit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

0.5

attemped 10

Iteration A					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Positive Dotted Tags	readings total:	60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scandit	no	no	AB0123456789	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scandit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

0.5

Iteration A					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Negative Dotted Tags	readings total:	60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scandit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scandit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scandit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

0.5

Iteration A					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C					
Phone Scandit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Appendix Figure C Displays the tables and results used for the drag while using a mask.

Readability Results (COPE) with Mask

Positive tags readings total: 60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	AB0123456789	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

0.5

Iteration A					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Negative tags readings total: 60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

0.5

Iteration A					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Positive Dotted Tags readings total: 60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	AB0123456789	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	AB0123456789	no	no	no
Industrial Scanner	no	no	no	no	no

0.5

Iteration A					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Negative Dotted Tags readings total: 60

1 inch

Iteration A	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C	As cast	Inked	Ground	Painted	+
Phone Scanddit	no	no	no	no	AB0123456789
Industrial Scanner	no	no	no	no	no

0.5

Iteration A					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration B					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Iteration C					
Phone Scanddit	no	no	no	no	no
Industrial Scanner	no	no	no	no	no

Appendix Figure D Displays the tables and results used for the cope when reading with a mask.

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