END-TO-END CAST IRON TRACEABILITY: MARKING UNIQUE CDOT CODES ON SAND MOLDS AND TRACKING PARTS FROM GREEN SAND MOLDING THROUGH ENTIRE PROCESSES

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ABSTRACT

This paper investigates the end-to-end traceability of production processes in CAST IRON manufacturing facilities using unique CDOT codes applied to sand molds. The aim is to ensure seamless traceability from mold preparation to shipment, recording all production data starting from the sand mold, thus enhancing production efficiency and product quality. Durable CDOT codes and laser marking devices are utilized for individual product identification. The results demonstrate that CDOT codes inscribed in the sand molds can transfer to the surface of cast products during the casting process, ensuring continuous traceability throughout all production stages, thereby proving the applicability of individual traceability in the casting industry.

Keywords
Cast Iron, Traceability, Sand Marking, Reading, CDOT Code, Barcode, Data Matrix, RFID

1. INTRODUCTION

Traceability in the casting industry has evolved significantly over the years, driven by technological advancements and increasing demands for quality and safety. This paper introduces a new code technology, the CDOT code, for implementing end-to-end traceability in cast iron manufacturing by marking in the sand mold and transferring it to the cast part during the casting process, focusing on its benefits, challenges, and outcomes.

The concept of traceability in the casting industry can be traced back to the early days of manufacturing when basic record-keeping was implemented to track production batches and ensure quality control. Initially, traceability systems were rudimentary, involving manual logging of production details and inspection reports. The primary objective was to identify and rectify defects in the production process to meet quality standards and regulatory requirements.

With the advent of digital technologies century and the increasing complexity of manufacturing processes, the need for more sophisticated traceability systems became evident. The introduction of barcodes and RFID tags in the late 20th marked a significant advancement in tracking capabilities, allowing manufacturers to monitor each badge more accurately and efficiently. These systems enabled the recording of detailed information about raw materials, work-in-progress, and finished goods, providing a comprehensive overview of the production process. For example, the study by Wadhwa et al. (2013) [1] explored the implementation of internal traceability systems in foundries, demonstrating how automation and digital technologies can enhance operational efficiency and product quality.

The need for end-to-end traceability in the casting industry is driven by several factors, including regulatory requirements, quality control, and customer expectations. Regulatory bodies often mandate traceability to ensure product safety and compliance with industry standards. For instance, the automotive and aerospace industries require detailed documentation of manufacturing processes to meet stringent safety and performance standards. Traceability allows manufacturers to quickly identify and address issues, minimizing the risk of recalls and enhancing overall product reliability [4].

From a quality control perspective, end-to-end traceability enables manufacturers to monitor and optimize every stage of the production process. By tracking materials, processes, and finished products, manufacturers can identify and rectify defects early, reducing waste and improving efficiency. Studies by Fisk and Chandran (1975) [2] emphasize the critical role of traceability in quality assurance and its impact on reducing production costs and improving product consistency. Customer expectations also play a significant role in driving the adoption of traceability systems. In today's market, customers demand transparency and assurance that products meet high-quality standards. Part-based traceability provides customers with confidence in the product's origins and manufacturing processes, enhancing brand reputation and customer loyalty.

Despite the clear benefits of traceability, implementing effective systems in the casting industry poses several challenges. One of the primary issues is ensuring the accuracy and durability of traceability marks. Traditional methods, such as labels and ink stamps, often fail to withstand the harsh environments of casting operations, leading to data loss and traceability gaps. For example, labels can peel off or become illegible due to high temperatures and rough handling. Laser marking, while more durable, requires precise control to ensure marks of the incumbent codes are readable and not damaged during subsequent processing steps like fettling, linishing, shot blasting, peening, heat-treatment, anodizing, alochroming and painting. The research by Laserax into the effects of surface treatments, such as shotblasting and e-coating, on laser-marked parts provides valuable insights into optimizing marking techniques for durability and readability [4].

Another significant challenge is the impact of high temperatures and material contraction on traceability marks. During the casting process, parts are often subjected to temperatures exceeding 700°C / 1292°F. As the parts cool, they undergo contraction, which can render the applied codes unreadable. This issue is particularly problematic for labels, which can peel off or deteriorate due to the high temperatures and rough surface textures of the cast parts. For instance, in high-temperature environments, traditional labeling methods often fail, as the adhesive properties degrade and the labels themselves can burn or disintegrate. Laser marking on hot surfaces requires special considerations to ensure that the marks do not distort or become illegible after the parts cool down. This challenge is well-documented in studies that investigate the effects of thermal cycling on traceability marks in high temperature applications [1].

The third major challenge involves the application of traceability codes to sand molds. When traditional coding methods are applied directly to sand surfaces, they can cause significant damage to the molds. This damage can lead to defects in the final cast parts, as the integrity of the sand mold alloy is compromised. For example, traditional stamping or engraving methods can disrupt the mold surface, resulting in misalignments and casting defects. This issue has prevented the successful implementation of traceability codes directly on sand molds in the past. The deformation caused by marking can affect the accuracy of the mold, leading to defects in the produced parts. Consequently, the industry has struggled to achieve reliable traceability from the sand mold stage through to the final product.

The CDOT codes provide a suitable solution in providing continuous and reliable traceability in CAST IRON production. CDOT codes offer a robust solution for marking sand molds, ensuring that traceability data remains intact throughout the casting process.

The expected outcomes of implementing CDOT codes for end-to-end traceability in cast iron are multi-faceted, encompassing improvements in process control, product quality, and production efficiency. One significant benefit is the enhanced ability to monitor and control production processes in real-time including the preparation of sand mold. By ensuring that each cast part is uniquely identifiable and traceable throughout the whole lifecycle of the part, manufacturers can achieve better quality control, reducing the incidence of defects and rework. Additionally, traceability data can inform decision-making and process optimization. For example, by analyzing traceability data, manufacturers can identify patterns and trends, enabling them to optimize production parameters and improve overall efficiency. The study by Vedel-Smith and Lenau (2012) [3] supports the feasibility and benefits of using digital marking technologies for casting traceability, highlighting the potential for improved process control and product quality. Furthermore, the use of CDOT codes is expected to enhance compliance with regulatory requirements and industry standards. By providing a detailed record of the production process, CDOT codes can help manufacturers demonstrate compliance with safety and quality standards, reducing the risk of regulatory penalties and enhancing customer trust.

In summary, this study aims to demonstrate the practical benefits of implementing CDOT codes for end-to-end traceability in cast iron production. By investigating the use of CDOT codes, this research seeks to address the current challenges in traceability and provide a viable solution for the casting industry, providing a comprehensive solution for enhancing traceability, improving product quality, and optimizing production processes in the casting industry.

2. TECHNOLOGY SCOUTING

2.1. Analysis of Existing Technologies

In evaluating the current technologies used in traceability within the casting industry, four primary methods were analyzed: Data Matrix with laser engraving, RFID tagging, labeling, and the newly introduced CDOT code.

2.1.1. Data Matrix with Laser Engraving

Data Matrix with laser engraving involves using high-energy lasers to etch codes onto the surface of parts. This method is renowned for creating durable and precise marks, making it suitable for various industrial applications. However, its application in the casting industry is fraught with challenges. As discussed under the durability test section, Data Matrix marking is applied directly to the sand mold, the codes fail to transfer effectively to the casted part. Additionally, direct engraving on hot parts is unfeasible due to the risk of damaging the part and the engraving equipment.

Post-casting, when the part has cooled, the codes are susceptible to degradation during processes such as sandblasting, heat treatment, painting, anodizing, and other e-coating applications, which often result in the complete loss of readability and, consequently, traceability. Research indicates that while laser-marked codes initially appear robust, their durability is significantly compromised by these subsequent processes, leading to unreliable traceability outcomes.

2.1.2. RFID Tagging

RFID (Radio Frequency Identification) tagging is commonly used for tracking and identification in various industries due to its ability to store substantial data and be read without a direct line of sight. However, embedding RFID tags within sand molds has proven ineffective as the tags do not transfer to the cast part. When placed directly on the part, RFID tags face numerous obstacles. The harsh conditions of horizontal green sand cast iron manufacturing, including high temperatures, molten iron impact and mechanical impacts, often cause tags to dislodge or malfunction. Additionally, the presence of metals such as aluminum leads to RF reflections, hindering accurate identification. Studies have shown that despite their potential, RFID tags are prone to degradation during abrasive treatments such as sandblasting, heat treatment, and coatings, further reducing their reliability for continuous traceability as Emre Ozturk; Mike J. Dikkers states (RFID Tag Failure after Thermal Overstress) [6].

2.1.3. Labeling

Labeling involves attaching printed labels to parts for identification, offering a straightforward and cost-effective solution. However, as discussed under the durability test section, labels may face significant challenges in the casting industry. The risk of labels mixing with the molten material during casting, which leads to their destruction and potential contamination of the alloy, means they are used exclusively for labeling the products that emerge post-operation. On casted parts, labels struggle to survive the harsh foundry conditions. They may fall off due to rough surfaces and mechanical impacts, and high temperatures and abrasive treatments such as sandblasting and heat exposure further degrade the labels, causing the loss of printed codes.

2.1.4. CDOT Code

The CDOT code, developed by Cosmodot Inc., is a high-density two-dimensional (2D) symbology specifically designed to endure aggressive processes and unfavorable conditions. CDOT codes can be applied to parts, raw materials even to sand molds using laser marking devices, ensuring their transfer from the mold to the casted part during the casting process. This results in transferred code on the part's surface, which remains intact and readable throughout all subsequent processes, unless the code on the surface is completely removed or altered during a machining operation.

CDOT codes have demonstrated resilience during sandblasting, heat treatment, painting, anodizing, and other e-coating applications with varying parameters and levels. They maintain readability with any 2D camera without requiring special lighting or lens configurations, providing continuous traceability from the mold to the finished product. This technology offers a comprehensive solution for ensuring robust and durable marking, making it the preferred choice for manufacturers seeking reliable traceability in the casting industry.

2.2. Technology Evaluation

The evaluation process involved rigorous testing of the aforementioned technologies under real-world casting conditions to assess their durability, readability, and overall effectiveness in ensuring traceability.

2.2.1. Durability Tests and Readability Analysis

Durability tests focused on evaluating each technology's resilience under extreme temperatures, abrasive conditions, and chemical exposure. It is continued by readability analysis assessed the clarity and legibility of each technology during cast iron sand molding stage and various post-casting processes.

Following casting, identifiers protrude from the part for readability with barcode readers. The marking process governs the shape and depth of the characters, while the casting process quality and consistency also influence them. Additionally, factors affecting laser marking depth include the type of sand, grain size, glue additives, sand compression, and the number of laser passes.

During the durability tests, Data Matrix codes are laser-marked onto the sand molds but fail to transfer effectively for readability onto the casted part during the casting process. Because the Data Matrix codes became unreadable after the cast iron process, subsequent challenging process tests were not implemented.

Figure 1 & 2: Unreadable, Low Contrast Data Matrix on Sand Mold and on Casted Part

RFID tags, when embedded in sand molds, failed to transfer to the cast part. When applied directly to the part, the tags often dislodged or malfunctioned due to metal interference and high temperatures, rendering them impractical for usage. RFID tags didn’t provide reliable data retrieval due to metal interference and harsh conditions, compromising traceability.

Labels tested in horizontal green sand cast iron manufacturing failed to maintain integrity. They dislodged or deteriorated during the casting process and subsequent treatments, rendering them unsuitable for continuous process based end-to-end identification and traceability.

Conversely, CDOT codes demonstrated durability. Codes applied to sand molds successfully transferred to cast parts and they maintained readability throughout subsequent processes, unless the code on the surface is completely removed or altered during a machining operation. The codes were readable without special lighting or lens configurations, ensuring continuous traceability.

These evaluations underscore the superior performance of CDOT code in ensuring reliable and continuous traceability horizontal green sand cast iron manufacturing, making it a leading option for manufacturers seeking robust and durable marking solutions and marking type.

3. IMPLEMENTATION OF CDOT TECHNOLOGY

Ensuring continuous traceability of products such as brake discs and drums at the cast iron facilities, from unique coding of negative molds to the finished stage of manufacturing, is crucial for recording casting data, product alloys, emission values without loss, and recording all data during grinding, painting, stacking, processing, quality control, and packaging processes. Matching individually coded products enhances customer service efficiency. To date, uninterrupted product traceability has not been achieved due to the inability to mark green sand molds with marking types and systems and ultimately yielded reliable readable results.

One of the main challenges in cast iron manufacturing is to lose traceability during shot blasting processes as the casted parts sequences interfere right after casting process. This only allows the manufacturing site to track the manufacturing processes on a batch basis, instead of part base. It also prevents to make the casting-related defects/repair analyses for each part along with defects/repair process parameters. Losing traceability also affects the other digitalization efforts (Industry 4.0) of the cast iron foundries.

With the end-to-end part-based traceability, the manufacturing site aims to achieve the maximum resolution of each charge of the furnace and gain ability to retain all required process information from casting onwards. It will also enhance communication with traceable casting pots to track parameters of the melting process.

3.1. Purpose and Objectives of Field Pilot Study

The primary objective of this field study is to assess the effective use of the unique CDOT code transferred onto sand molds containing silica sand, bentonite, and coal dust with a moisture content between 3.5% and 4.5% and an AFS value of 42. The CDOT code is expected to transfer onto the casting part after melted ore is poured into the sand mold at 1400°C / 2552°F. Each sand mold will be marked with a unique CDOT code to test its operability, marking speed to align with production cycle time, and the reading rates of the serially casted products.

CDOT code marking will be applied directly onto the sand molds. The marking in this stage is not intended for the final product. The molds consist of negative and positive molds, which automatically integrate to each other to form the final mold. Testing should evaluate whether some markings are applied to the lower degree and others to the upper degree. In the first tested line produced by Savelli (https://www.savelli.it/), both negative and positive molds have a cycle time of 18 seconds. During these 18 seconds, the degree moves for 5 seconds and remains stationary for 13 seconds. Negative and positive molds pass sequentially on the same line. In the Heinrich Wagner Sinto (https://www.wagner-sinto.de/en/) line each mold has a cycle time of 22.5 seconds. During these 22.5 seconds, each mold moves for 5 seconds and remains stationary for 17.5 seconds. Top and bottom molds pass from different lines.

Based on that information, a minimum of 50 serial production samples were planned to be produced, aiming to perform coding in accordance with cycle time. Sample sand molds were planned to be marked with CDOT codes using laser marking techniques, followed by scanning after code transfer. Serial production of at least 50 sand molds of the disc brake was planned, transferring CDOT codes using laser marking techniques. After the integration of negative and positive molds, melted ore at 1400°C / 2552°F will be poured into CDOT code marked sand molds and CDOT code expected to transfer in the casted part remaining its readability without any specific image formation on the camera.

The implementation of CDOT technology in iron casting procedure is expected to mark a significant advancement in traceability systems for the manufacturing industry.

3.2. Used Technologies & Applied Scenarios

CDOT does not require any specific hardware, enables to be printed with any type of printer including laser engraving, inkjet, thermal techniques and many more, and to be read with any cameras that can transfer the image into decoder, including smart cameras, 2D code readers, handheld readers, mobile terminals, mobile phones etc. For this test a 50W and 60W JPT MOPA (Master Oscillator Powered Amplifier) laser marking device used for marking sand molds along with 300, 150 and 110 lenses. The dimensions of the CDOT codes for this application identified as 20x20 mm, 30x30 mm, and 40x40 mm to test compatibility of different sizes. For the reading tests, a mobile phone with CDOT Mobile App for scanning is used.

Three different scenarios were tested during the study. The first one is to mark and read the sand mold samples. The second one is to mark the CDOT codes to sand molds aligned with the cycle time of the production and conduct readability tests before serial production trials. The last one is to test CDOT codes marked in the sand molds aligned with the cycle time and conduct readability tests of the transferred code on the casted part during the ore pouring process followed by all other processes like sandblasting, deburring, painting etc.

3.3. Preparation and Initial Testing

3.3.1. Mark and Read the Sand Mold Samples

The implementation process began with a thorough analysis of EKU's manufacturing environment. The foundry, with its high temperatures and abrasive conditions, presented a unique set of challenges for part traceability. Initial tests were conducted using sample sand molds provided by EKU's manufacturing team. These tests were crucial in determining the optimal parameters for applying CDOT codes to the sand molds.

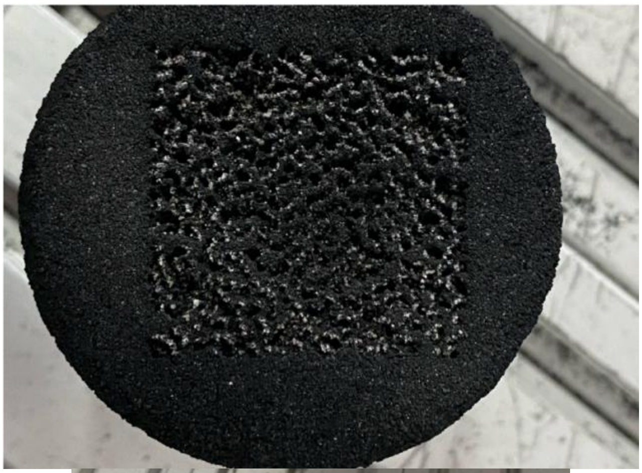

Figure 4 & 5: CDOT code on sand sample

Six sand mold samples were taken from the EKU laboratory, and experiments were conducted using different 50W and 60W fiber lasers to test power, speed, and depth for the initial application of depth and CDOT code on the sand surface for proper adaptation. Particularly due to the composition and compression values of the sand, depth studies for the creation of codes on the sand were carried out. After establishing the coding process and CDOT code depth values, scanning was performed using the CDOT mobile application. All scanning processes were successfully completed.

3.3.2. Marking the CDOT Codes to Sand Molds Before Serial Production

Experiments were conducted to transfer the CDOT code onto a sand mold sample during bell production using a 50W Yb Fixed Pulse Fiber Laser and F-Theta163 Lens-1064 300 lens.

Figure 6: CDOT code first trial with 50W fiber laser with 300mm lens

Further experiments were carried out using a 50W Yb Fixed Pulse Fiber Laser and F-Theta163 Lens-1064 150 lens during bell production to transfer the CDOT code similarly onto the product. The CDOT code was successfully transferred onto the disk sand mold selected for production along the line. Upon completion of production, the disk was separated, and scanning was performed using the CDOT mobile application. All scanning processes were successfully completed.

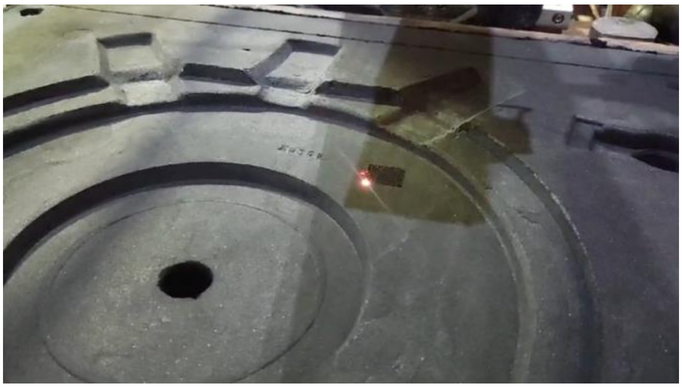
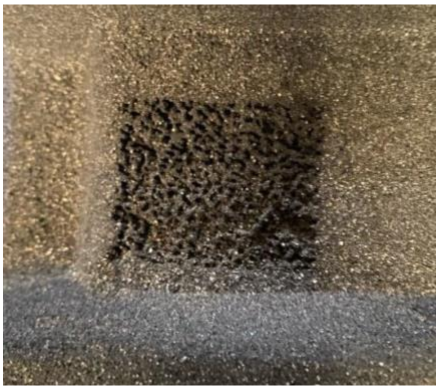

Figure 7 & 8: CDOT code second trial with 60W fiber laser with 110mm lens

3.3.3. Marking the CDOT Codes to Sand Molds in the Serial Production

Using a 50W fiber laser machine and a 150-lens, cast iron production line was carried out for one day. The pulse width output of up to 50W in Mopa Fiber Source is fixed as 200ns (nanoseconds), and printing trials per pulse are performed with a power of 1.25mj (millijoules). Printing times were recorded, and outputs required for adaptation to cycle time were obtained. Using a 60W Yb Fixed Pulse Fiber Laser and F-Theta163 Lens-1064 110 lens, a 14-second cycle time was successfully achieved to be aligned with the line cycle times of 12-14 seconds based on the outputs obtained. To achieve accurate results, the output pulse width assigned as 2 - 500 ns (nanoseconds) with a power of 2mj (millijoules) per fixed pulse in 60W Mopa Fiber laser sources. Therefore, adjustable frequency range is widely used in new generation 60W Mopa lasers, and pulse power per production is balanced. This ensures smooth and complete transmission of CDOT codes in the expected cycle time. Particularly, it has been successfully implemented in materials with burning response such as sand.

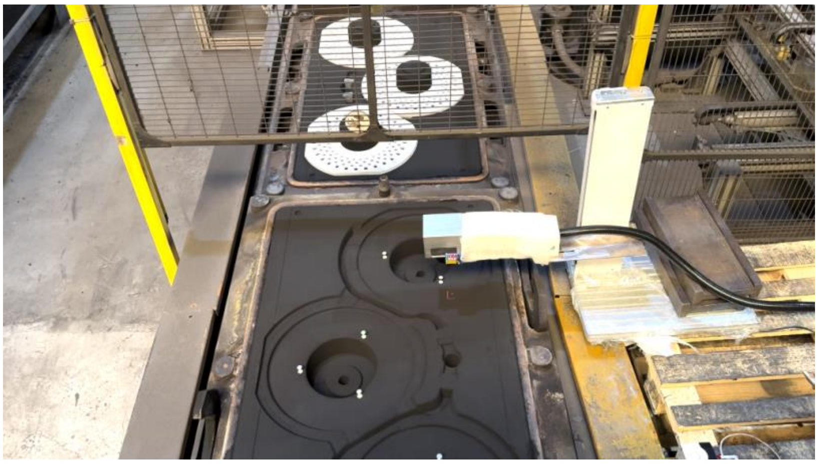

Figure 9: Laser marking setup on serial production

Figure 10: %100 Readable CDOT code engraved in the sand mold with 60W fiber laser and 110mm lens in the production

After matching the cycle time, the serial coding stage was passed, and 69 unique CDOT codes were transferred to sand molds according to the production time on disks produced during one shift.

Figure 11: CDOT code transfer from sand mold to brake disc during pouring ore stage

After the casting process, 69 disks were separated and scanned was carried out with CDOT mobile application. All reading operations are successful in all multiple trials that also include reading in different angles, distances and especially in line with production defects.

Figure 12: %100 readable CDOT code marked on sand mold, transferred to part during ore pouring


Figure 13: CDOT code reading on transferred CDOT code

3.4. Experiment Outcomes

Enabling end to end traceability in cast iron industry by having unique CDOT codes in each disc brake sand mold and the capability of preserving the same CDOT code after the ore pouring stage at high temperatures of 1400°C / 2552°F provides positive outcomes. First of all, the unique traceability prevents the mixed parts sequence caused by sandblasting, after the casting process on automatic molding lines, allowing each part to be traced individually. Secondly, it also enables to make the casting-related defects/repair analyses for each part along with defects/repair process parameters, allowing to conduct root cause analysis. As this system provides a proper infrastructure for data acquisition the digitalization efforts of the sand-casting industries will also be enhanced drastically. The manufacturing site will also achieve the maximum resolution of each charge of the furnace and gain ability to retain all required process information from casting onwards. It will also enhance communication with traceable casting pots to track parameters of the melting process.

3.5. Findings and Considerations

Ensuring the compatibility of the laser engraving with the required cycle time is critical. The significance of choosing a laser lens that consistently delivers uniform outputs cannot be overstated. Variability in focus during the printing of each series of sand molds has notable effects that must be meticulously managed. Effective automation planning that aligns with the production line's speed is essential for seamless operation. It is also critical to ensure that the CDOT code maintains a minimum size of 30 x 30mm for optimal readability and traceability.

Developing a project setup plan that facilitates the reapplication of the same code to products after they undergo machining processes is vital. Furthermore, during serial production, it is crucial that the installed laser automation adapts to the model information from the ERP system, ensuring compatibility with cycle time requirements. The area designated for marking the CDOT code must also adapt in real-time to system parameters, accommodating product variability and maintaining consistent quality and traceability throughout the production process.

4. CONCLUSION

The implementation of CDOT code in cast iron manufacturing process has opened new avenues for advancing traceability and quality control in the foundry industry. This comprehensive system, which includes marking, reading, and data integration capabilities, stands as a significant improvement over existing methods, promising substantial benefits and setting a new standard in manufacturing traceability.

The primary advantage of the CDOT code is its ability to provide unique part traceability from the very beginning of the casting process. This means that each product can be tracked individually from the sand mold stage through to the final inspection. This level of detailed traceability is crucial for identifying and rectifying issues at the earliest possible stage, thereby reducing waste and improving overall product quality. By linking process parameters directly with individual products, the system enables precise control over the manufacturing process, facilitating immediate adjustments to optimize production and quality outcomes.

In foundries with automated molding lines, a common challenge is the disorganization of products during the shakeout process, which can complicate traceability efforts. The CDOT code effectively addresses this issue by maintaining the order and traceability of each product through unique identification codes that persist through the entire manufacturing process. This ensures that each product can be reliably tracked and traced, significantly enhancing process control and reducing the potential for errors.

One of the most significant impacts of the CDOT technology is its ability to correlate casting process parameters with individual product identifiers on a detailed level. This enables foundries to conduct in-depth analyses of casting defects and rework rates, correlating these issues with specific process conditions. Such granular traceability allows for targeted interventions and process improvements, reducing the occurrence of defects and minimizing the need for rework. This level of detail also supports advanced quality control measures and continuous improvement initiatives, aligning with the principles of Industry 4.0 and fostering a culture of data-driven decision-making.

The digitization of foundry operations is another major benefit facilitated by the CDOT system. By providing a robust foundation for digital traceability, the system supports the integration of various digital tools and technologies. This enhances the ability of foundries to leverage data analytics, machine learning, and artificial intelligence for process optimization and predictive maintenance. The comprehensive traceability data generated by the CDOT system can be used to develop sophisticated models for predicting equipment failures, optimizing maintenance schedules, and improving overall operational efficiency.
The transition from batch-based traceability to maximum resolution traceability is a game-changer for the foundry industry. Traditional traceability systems often operate at the batch level, which can obscure the details of individual product histories and complicate defect analysis. The CDOT system, by contrast, provides a detailed, product-level traceability that enables foundries to maintain comprehensive records for each

individual item. This high-resolution traceability ensures that any issues can be quickly traced back to specific process conditions, enabling faster and more effective problem-solving.

Moreover, the ability to store all relevant information from the casting process onwards ensures that foundries can maintain a comprehensive and accurate record of each product's history. This is particularly important for industries with stringent regulatory requirements, such as the automotive and aerospace sectors. The detailed traceability provided by the CDOT system supports compliance with these regulations, enhancing customer confidence and reducing the risk of non-compliance penalties.

In addition to the benefits already mentioned, the CDOT system also supports communication with traceable ladles, allowing for the monitoring of melting process parameters. This integration ensures that all aspects of the casting process, from melting to final inspection, are covered by the traceability system. This holistic approach to traceability not only improves product quality but also supports more efficient and effective production processes.

The CDOT system also lays the groundwork for advanced automation in foundries. By providing a reliable method for product identification, the system enables the development of automated inspection and sorting systems. These automated systems can significantly enhance production efficiency and accuracy, reducing the need for manual intervention and minimizing the risk of human error.

The practical advantages of the CDOT system were clearly demonstrated during its implementation at the sand-casting foundry. Despite the initial challenges, such as ensuring the durability of the marks through the casting process and integrating the system with existing production management tools, the project achieved remarkable success. Even under the distortion of codes due to high temperatures during casting, to account for material expansion and contraction, the challenges were compensated by the CDOT code, leading to a final system that achieved a readability success rate of 100%.
In conclusion, the CDOT technology implementation at the cast iron foundry has demonstrated its potential to transform traceability in the foundry industry. By providing detailed, product-level traceability, the system supports advanced quality control measures, process optimization, and compliance with regulatory requirements. The integration of digital tools and technologies further enhances the benefits of the system, aligning with the principles of Industry 4.0 and paving the way for future advancements.

The success of this project not only sets a new standard for the industry but also opens the door to further innovations and improvements in manufacturing traceability. Looking ahead, the continuous refinement and expansion of the CDOT code will ensure that cast iron remains at the forefront of traceability technology. By leveraging the comprehensive data generated by the system, the company can continue to optimize its processes, improve product quality, and maintain its competitive edge in the market. The future of foundry traceability is bright, and the CDOT code is poised to play a crucial role in shaping this future.

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