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Traceability and quality assurance of sand casting foundries using QR code-based tracking system

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Abstract. Traceability is a critical requirement in modern foundry operations for ensuring quality, consistency and accountability throughout the production process. Conventional mold identification methods such as handwritten markings, tags or metal stamping that are often prone to damage, misinterpretation and data loss. This paper proposes a QR code–based digital traceability framework designed to provide end-to-end tracking of molds, cores and castings within the foundry environment. The system combines QR code embedding, optical data acquisition, and centralized database management to facilitate real-time monitoring, defect correlation and process optimization. The use of QR code ensures durable and reliable identification under typical foundry conditions, advancing the move toward intelligent, data-driven manufacturing in foundries.

1. Introduction

Foundries, forming the backbone of metal component manufacturing, are thus integrating digital technologies to improve product quality, resource efficiency and process transparency. The global foundry sector is undergoing a rapid transformation driven by the emergence of Industry 4.0, which emphasizes the convergence of Cyber-physical systems (CPS), Industrial Internet of Things (IIoT), Artificial intelligence (AI) and data-driven manufacturing. Traditional foundry operations, once dependent on manual craftsmanship and experience, are increasingly adopting digital monitoring, traceability and process automation to enhance efficiency and precision [1, 2]. Within this digital transformation, traceability has emerged as a vital enabler of intelligent manufacturing, ensuring quality assurance, process consistency and regulatory compliance across the casting value chain [3]. Foundry industries rely heavily on precision and repeatability in pattern making, mold preparation and casting processes, yet tracking and identifying each mold or casting during production remains a major challenge, especially in large-scale operations. Traditional marking methods such as chalk, tags or punch numbers often result in data loss, human error and mismatches during post-processing. The lack of effective traceability mechanisms further hinders quality monitoring, mold life tracking and defect root cause analysis.

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To overcome these limitations, researchers and industries have explored digital traceability frameworks leveraging technologies such as barcodes, RFID and optical recognition systems for automated identification [4]. For instance, systems integrating RFID for indoor tracking and GPS for outdoor tracking have demonstrated enhanced real-time monitoring, asset visibility, reduced search time, and improved maintenance planning, ultimately leading to higher operational efficiency and cost savings [5]. A robust digital traceability system enables the unique identification and tracking of materials, molds, and castings at every stage of production, creating a critical linkage between process parameters and final product quality. Such systems allow foundries to perform effective root cause analysis, defect prediction, process optimization and lifecycle management of molds and patterns. The relevance of this integration becomes clear when considering that process parameters such as sand composition, moisture levels, mould materials, chill design and additives including binders, coal and alloying elements directly influence the surface finish, porosity and strength of sand-cast components. Optimizing sand, mould and metal conditions can therefore minimize defects, reduce material wastage, improve yield and lower production costs [6]. Moreover, for alloys with wide freezing ranges, understanding how the freezing range influences defect sensitivity can greatly reduce defects and improve overall casting performance [7].

At the same time, rising demands for regulatory compliance, customer audits and sustainability reporting require accurate and easily accessible production histories, further underscoring the importance of digital traceability in modern manufacturing environments. Despite these needs, many foundries still rely on manual labeling and tracking methods such as chalk markings, paper tags or metal punch numbers. These traditional methods are vulnerable to wear, misreading and data loss during molding, handling and high-temperature operations. They also lack integration with digital systems and provide limited real-time visibility, making defect tracing and process deviation analysis labor-intensive and error prone. This persistent gap highlights the need for a digitally compatible identification system that is reliable, durable and seamlessly integrable with existing industrial control and information systems. A well-structured Lean Six Sigma roadmap can significantly enhance quality, eliminate waste, and enable sustainable improvements within a casting environment [8]. To further strengthen the shift toward smart foundries, there is a need for a digitally compatible identification system that is reliable, durable and seamlessly integrable with existing control and information systems. Among various technologies available such as Radio Frequency Identification (RFID), optical character recognition (OCR) and barcoding, the Quick Response (QR) code has emerged as a promising candidate. QR codes offer high data capacity, error correction capability, low implementation cost and compatibility with optical scanning devices commonly used in industrial environments. They can store essential production metadata including pattern ID, batch number, operator ID, process parameters and timestamps within a compact 2D matrix format. In this context, the present study explores the application of QR codes as a robust, low-cost and digitally integrable traceability mechanism for foundry molds and sand cores. By embedding or printing QR codes directly on mold surfaces, each mold or core can be digitally linked to its production data, enabling end-to-end visibility, enhanced quality assurance and data-driven process control. The proposed framework contributes to the broader vision of achieving intelligent, interconnected and sustainable foundries through integrated digital traceability.

2. Literature Review

The literature on industrial traceability highlights its increasing relevance in manufacturing systems, particularly within the context of Industry 4.0. The concept of digital traceability involves the ability to track the history, application or location of an item through recorded data, thus enabling transparency and accountability across the value chain. Next-generation Industrial IoT (IIoT) solutions, incorporating sensors, cloud platforms and data analytics within the Industry 4.0 framework, facilitate real-time monitoring of materials, processes and products. Such systems enhance production transparency, quality assurance and data-driven decision-making, demonstrating how digitalization enables intelligent manufacturing and comprehensive lifecycle traceability [9]. Additively manufactured tags embedded with two-dimensional (2D) digital codes have been proposed as a direct part marking (DPM) method for enhancing traceability in sand casting. In this approach, the tags are integrated into the mold or core, enabling each casting to possess a unique and scannable identifier. This technique provides durable, high-temperature-resistant and easily readable identification, thereby improving process traceability, quality monitoring and data linkage throughout the casting production cycle [10].

In a luxury metal parts manufacturing company, an integrated barcode and database system was implemented to monitor components across all production stages, ensuring product authenticity and quality assurance. The deployment of this industrial traceability framework enhanced process visibility, defect tracking and overall production efficiency, illustrating the tangible benefits of digital traceability adoption in high-value manufacturing environments [11]. The integration of IoT devices, databases, and automation systems within the metal-mechanical sector under the Industry 4.0 framework enables real-time monitoring of components and processes. This integration enhances production visibility, quality control and data-driven decision-making, thereby supporting the sector's transition toward smart and connected manufacturing [5]. The effective deployment of digital technologies such as RFID, barcodes, IoT and blockchain has been recognized for their significant roles in data acquisition, tracking and process integration. These technologies contribute to improved quality assurance, supply chain transparency and regulatory compliance [8, 11]

Overall, the literature reveals a clear research gap; while several studies have investigated barcode and RFID applications in manufacturing, systematic frameworks for QR code–based traceability in foundry mold production remain limited. Nevertheless, challenges related to interoperability, efficient data management and cost-effective implementation continue to persist, as highlighted by [12]. Moreover, most prior studies have primarily concentrated on printed tag applications rather than the direct integration of traceability features into molds. This research builds upon these studies by embedding QR codes directly into the pattern surface and validating the approach through mathematical and experimental methods. Existing approaches often focus on isolated identification without full integration into a digital data management system. This paper aims to address that gap by proposing and validating a comprehensive QR code–based traceability framework specifically designed for foundry environments [13].

3. Background and Motivation

Recent developments in digital manufacturing emphasize smart identification systems using barcodes, RFID and image-based tracking. Among these, 2D QR codes offer several advantages:

- **High data capacity**: Can store hundreds of alphanumeric characters.
- **Error correction**: Built-in redundancy allows decoding even with partial damage.
- **Low cost**: Requires only a printer and optical reader.
- **Scalability**: Easily implemented across all production stages.

In foundries, environmental factors such as heat, vibration and dust present unique challenges for identification technologies. QR codes, when printed or embedded on suitable surfaces, can withstand moderate foundry conditions and provide reliable identification during production and inspection stages.

4. Proposed Framework

The proposed QR code–based traceability framework comprises three major subsystems

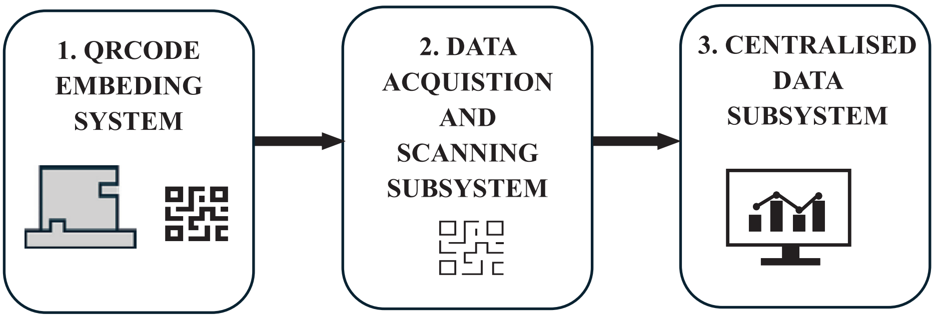

Fig. 1. Conceptual framework of the proposed system

The QR code embedding subsystem generates and applies QR codes onto molds, cores, or pattern surfaces using laser engraving or embossing during pattern making. Each code contains unique identifiers such as batch number, pattern ID, operator ID and timestamp.

Fig. 2. Traceability chain linking Pattern ID, Mold ID, Pouring Batch and Casting ID

Surface preparation and protective coatings are applied to ensure readability after core baking or handling. During core making, mold assembly, pouring and inspection, the data acquisition subsystem captures the QR codes using fixed scanners installed along the mold line or handheld scanners operated by personnel. The scanned information automatically updates the production database and links each physical mold to its digital record. All traceability information is stored and managed by a centralized data management subsystem. The process parameters including temperature, sand moisture, and compaction pressure are linked to their respective mold identifiers within the system. Analytics tools support the visualization of defect trends, process deviations and quality performance. The subsystem is also interoperable with MES and SCADA systems. The QR code serves as the primary digital key within this architecture. It is scanned before pouring to associate melt data such as composition and temperature. It is scanned again after casting to correlate quality results and defects. This process creates a closed-loop traceability system in which each casting's lifecycle is recorded end-to-end.

5. Mathematical Model for QR Code Readability Validation

To evaluate QR code performance in foundry environments, a mathematical readability model is developed. The model relates read success probability (P_s) to key physical and optical parameters affecting QR code detection.

5.1 Variables and Assumptions

Let:
P_s = Probability of successful QR code read
C = Contrast ratio between light and dark modules
σ = Surface roughness (μm)
θ = Deviation angle between scanner and QR code plane (°)
T = Surface temperature (°C)
R_q = Reflection coefficient of surface (0–1)
ε = Random measurement error

The QR readability index R_i can be expressed as:

$$R_i = \frac{C \times R_q}{1 + k_1\sigma + k_2|\theta| + k_3 T} \quad (1)$$

Where (k_1, k_2, k_3) are sensitivity constants derived experimentally.
The read success probability is modeled using a logistic function:

$$P_s = \frac{1}{1 + e^{-(a_0 + a_1 R_i)}} \quad (2)$$

where a_0 and a_1 are calibration coefficients.

5.2 Case Study: QR Code–Enabled Traceability Using 3D-Printed Patterns

5.2.1 Pattern Design and Fabrication

A sand-casting pattern incorporating a 2D QR code was designed using CAD software. The QR code encoded the Pattern ID, Mold ID, Pouring Batch, and Casting ID in a structured key–value format. The pattern was fabricated using fused deposition modeling (FDM) based 3D printing with a heat-resistant polymer material. The QR code was integrated as a recessed feature on the pattern surface with an engraving depth of approximately 1.5 mm, ensuring adequate imprint clarity on the sand mold and resistance to surface abrasion.

5.2.2 Mold Preparation and Casting Process

Green sand molds were prepared using the 3D-printed pattern under standard foundry conditions. A total of 10 aluminum casting samples were produced using commercially pure aluminum, poured at a temperature of approximately 720 ± 10 °C. Each mold carried a unique QR code imprint corresponding to the specific casting sample. After solidification and shakeout, the QR code remained visibly identifiable on the mold surface and was also transferred to the casting identification workflow.

5.2.3 QR Code Scanning and Data Acquisition

QR codes were scanned using an industrial 2D barcode scanner at multiple stages:

1. Post-molding stage
2. Post-pouring and cooling stage
3. Post-shakeout stage

For each casting, multiple scan attempts were recorded to evaluate readability. The decoded information was automatically linked to a digital log containing casting metadata such as pouring temperature, batch number, and timestamp. Successful decoding was achieved for 9 out of 10 castings, corresponding to a 90% scan success rate, with minor degradation observed in one sample due to localized sand erosion.

Table 1. Casting sample Data from QR scan

Sample	Pattern ID	Mold ID	Pouring Batch	Casting ID	QR CODE
1	MS	4950	25-09-01	GB	MS|4950|25-09-01|GB
2	MS	4950	25-09-02	GB	MS|4950|25-09-02|GB
3	MS	4950	25-09-03	GB	MS|4950|25-09-03|GB
4	MS	4950	25-09-04	GB	MS|4950|25-09-04|GB
5	MS	4950	25-09-05	GB	MS|4950|25-09-05|GB
6	MS	4950	25-09-06	GB	MS|4950|25-09-06|GB
7	MS	4950	25-09-07	GB	MS|4950|25-09-07|GB
8	MS	4950	25-09-08	GB	MS|4950|25-09-08|GB
9	MS	4950	25-09-09	GB	MS|4950|25-09-09|GB
10	MS	4950	25-09-10	GB	MS|4950|25-09-10|GB

(a) (b) (c)

Fig. 3. QR code sample (a) 3D printed Heat-resistant Polymer material (b) Aluminium Casting sample (c) QR Code Scanner

5.2.4 Results and Discussion

The case study demonstrates that 3D-printed patterns with integrated QR codes can effectively support traceability in aluminum sand-casting operations. The high scan success rate confirms that the proposed QR code design, combined with recessed pattern features and adequate contrast, is robust under typical foundry conditions. The results also validate the assumptions of the proposed readability model, particularly the influence of surface quality and temperature on scan performance.

This study highlights the feasibility of rapid pattern customization through additive manufacturing, enabling flexible and low-cost deployment of QR-based traceability without the need for permanent tooling modifications. Furthermore, the structured digital linkage established through QR scanning provides a foundation for future integration with manufacturing execution systems and digital twin frameworks.

5.2.5 Key Case Study Parameters

Table 2. Parameters for Casting samples

Parameter	Value
Pattern manufacturing	3D printing (FDM)
Material	Heat-resistant polymer
Casting material	Aluminum
Number of castings	10
QR code depth	~1.5 mm
Pouring temperature	720 ± 10 °C
Scan success rate	90%

6 Discussion

Digital technologies assist to structure, store and access traceability data, the system enhances transparency, reducing errors associated with manual processes, and supports faster retrieval of trace records for auditing, quality assurance and decision-making [14]. Furthermore, enable circular economy strategies by supporting real-time monitoring, logistics optimisation and product lifecycle management, leading to reduced resource use, improved recycling, reuse, and remanufacturing. They enhance material traceability and lower emissions, while also revealing gaps such as limited adoption of product-as-a-service models and insufficient research in certain industries. When applied as an integrated framework, digital tools effectively translate circular economy principles into practical and scalable supply chain solutions [15].

A comparative assessment of identification technologies under foundry operating conditions (dust, heat, vibration and rough handling) underscores the advantages of the proposed QR code approach. From the comparison, QR codes provide the best balance of cost-efficiency, data richness, and robustness for foundry environments, where the conditions often make barcodes unreliable and RFID economically unviable for large-scale mold tracking. RFID enables automated, real-time data capture, while QR codes provide low-cost, accessible identification and information sharing across supply chain actors [16]. Furthermore, QR codes are human-readable, allowing manual fallback verification without specialized hardware, an essential feature for mixed manual–automated operations typical in developing foundries. The results confirm that QR code integration in mold patterns provides a robust and reliable traceability mechanism. The mathematical model effectively predicts code readability under varying physical and optical conditions. The proposed system provides several benefits:

- **Enhanced Traceability:** Every mold or core can be tracked through all production stages.
- **Quality Correlation:** Easy linkage between process parameters and casting defects.
- **Data-Driven Insights:** Enables predictive analysis and continuous improvement.
- **Low Implementation Cost:** Minimal hardware investment compared to RFID systems.

Table 3. Comparative Analysis: QR Code vs RFID and Barcode Systems

Parameter	QR Code	RFID	Barcode
Implementation Cost	Very low (printing /engraving only)	High (tag + reader infrastructure)	Low
Read Range	Line-of-sight (up to 1 m with scanner)	Up to 10 m (no line-of-sight)	Line-of-sight (≤ 0.5 m)
Read Speed	Moderate (0.4 – 0.6 s per mold)	High (simultaneous multiple tag reads)	Moderate
Durability in Heat & Dust	Good with refractory ink or engraving; resistant up to 300°C	Excellent (encapsulated tags up to 600°C)	Poor; easily degraded or obscured
Data Capacity	High (up to 3 KB including error correction)	Medium (unique ID + external database link)	Very low (<100 bytes)
Interference with Metal	None	Significant (requires isolation or ferrite backing)	None
Ease of Integration	Very easy (camera or scanner-based)	Complex (RF reader setup, shielding)	Easy
Maintenance Requirement	Minimal (visual inspection, reprint if damaged)	Moderate (tag calibration, firmware updates)	Moderate
Environmental Suitability for Foundries	High	High (but costly)	Low

However, certain challenges still persist in the implementation of QR-based traceability systems. High temperatures and surface abrasion can damage or partially degrade printed codes, reducing their readability. Environmental factors such as dust buildup and glare further affect scanning accuracy, often making code recognition inconsistent. Effective deployment also requires strict process standardization, including consistent code placement and a uniform encoding format across production lines. Although RFID and QR solutions are relatively simple and cost-effective, printed codes frequently face issues such as heat degradation, detachment and poor readability in dusty foundry environments [4].

6.1 Technical Limitations: Scanner Calibration and QR Code Usage

Although the proposed system demonstrates significant potential, its real-world implementation is subject to several technical limitations that influence data reliability and operational performance.

6.1.1 Scanner Calibration:

The accuracy and efficiency of QR code reading depend heavily on proper scanner calibration. Industrial environments create challenges such as fluctuating lighting, reflections from metallic surfaces, dust accumulation, and vibration, which all interfere with image acquisition. Optical scanners require periodic calibration to maintain accuracy, especially when they operate near heat sources or under changing illumination. Incorrect scanner orientation or an inconsistent focal distance can lead to partial decoding or false reads, so stable mounting fixtures and automatic focus adjustment are necessary. Firmware settings, including contrast thresholds and refresh rates, must be tuned to account for variations in QR code print quality and surface texture.

6.1.2 QR Code Usage and Durability:

The usability of QR codes in foundry operations depends on their material compatibility and printing durability. Exposure to high temperatures, abrasion during mold handling and contact with parting sand can degrade printed QR patterns, so protective coatings and recessed printing methods are necessary to increase longevity. Smaller QR codes or high-density encoding reduce readability in dusty or low-light environments and maintaining an appropriate balance between data volume and physical size is essential for reliable performance. QR codes offer up to 30% data restoration, but prolonged thermal or mechanical stress can exceed this limit, which creates a need for redundancy methods such as dual-code marking. In high-temperature zones, printed codes may fail to survive mold baking or pouring and metallic or ceramic QR plates provide a more durable alternative. These limitations require optimized scanner setup, regular maintenance and materials-specific QR code design to improve the robustness and reliability of the system in industrial conditions.

7. Future Work

The QR codes generated for individual sensors store configuration parameters, network credentials, and metadata, enabling rapid installation and error-free commissioning through mobile devices. QR-assisted configuration reduces manual intervention, improves accuracy, and enhances scalability in IoT deployments [17]. Optimised laser processing enables the fabrication of high-contrast, permanent QR codes without degrading material integrity, while ensuring consistent machine readability at micro-scale dimensions and in harsh operating environments. Laser-marked QR codes on metal components therefore offer a durable and tamper-resistant approach to traceability and identification for industrial and aerospace applications [18]. Future developments in traceability will focus on laser-engraved metal QR tags for high-temperature applications, AI-based image recognition for real-time defect correlation, and digital twins that synchronize physical molds with virtual models to support advanced process simulation and optimization. The digital-twin core rack offers an indirect, sensor-based method for identifying sand cores without physical marking, which makes it suitable for fragile inorganic cores and harsh foundry conditions where heat, dust and vibration can damage labels. This approach requires higher investment and is limited to tracking cores while they remain on the rack[19] .

8. Conclusion

This paper presented a QR code–based traceability framework tailored for foundry mold and core tracking. The approach offers a cost-effective, scalable and digital alternative to traditional identification methods. By linking each mold to its production data, the system enhances quality control, supports root cause analysis and contributes to the realization of smart and sustainable foundries aligned with Industry 4.0 objectives.

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