Digital Manufacturing for Foundries 4.0

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Abstract

The concept of smart foundries aims at integrating and enabling smart technologies for digitalization of manufacturing operations. Foundries 4.0 refer to the inclusion of Industry 4.0 principles in traditional foundries. The casting process is known to be one of the most energy-intensive processes. Enabling sensor-based technologies, such as the Internet of Things (IoTs) for condition monitoring, can be an efficient means to bring down the energy costs. IoTs can also be implemented for real-time waste-monitoring. Embedded sensors can be utilized in determining excessive loads during the casting operation. This is very useful to identify overloading and in avoiding potential damage to the castings. Introduction of Additive Manufacturing can reduce cycle time and material consumption. This paper aims to introduce the concept of Foundries 4.0. The key focus is to highlight the integration of digital technologies in establishing foundries of the future. Challenges involved in the establishment of smart foundries are also discussed. A case-study discussing establishment of energy-efficient smart foundries is also presented in this work.

Keywords

Industry 4.0 • Smart foundries • CRIMSON • Castings • Additive manufacturing

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Introduction

Technological advancements in the last few decades have led to the foundation of the fourth industrial revolution, also referred to as Industry 4.0. With the advent of Industry 4.0, manufacturing industries are impacted mainly, leading to an establishment of smart factories, products and services [1]. This is widely supported by internet technologies and is expected to improve industrial production [2]. The nine pillars enabling the future of industries are: The Industrial Internet of Things (IIoT), Additive manufacturing, The cloud, Cybersecurity, Horizontal and Vertical system integration, Augmented reality, Autonomous robots, Simulation, and Big data and analytics [3]. The prime focus of all these technologies is to enable design and intelligence not only in the products but also the manufacturing processes [4].

Castings operations find their use, especially for the manufacturing of complex shapes and while dealing with hard-to-machine materials [5]. Metal casting is one of the critical manufacturing processes which is utilized for various applications. The process involves pouring in hot liquid metal in a mould cavity. The molten metal is left to solidify, and the finished product (also called the Casting form) is obtained towards the end. Digitization, together with other factors such as high production costs, challenges in part quality and a skilled labour shortage, has contributed to the establishment of smart foundries (also referred to as Foundries 4.0 (F4.0)). Smart foundries involve automatization of processes reducing human intervention at the same time enhancing the process throughput and part quality. This involves integration of parts, processes, machines, manufacturing systems and businesses as a whole, enabling intelligent manufacturing at each level of the value chain network. Automation in foundries makes use of big data not only to take care of condition monitoring of the machines but also to take corrective actions by itself when needed [6].

The work carried out in this paper focuses on highlighting the principles and methods in establishing foundries of the

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future. The impact of Industry 4.0 on foundries and challenges involved in its gradual adoption in casting operations is discussed. Furthermore, a case study involving energy-efficient casting processes is also presented in this work.

Smart Foundries

Integration of Industry 4.0 in foundries has recently started, and it has not been well explored yet. Primitive concepts such as remote maintenance using Virtual Private Networks (VPN) or other wireless features such as Machine to Machine (M2M) communication are already in use as of today, and there has been a growing interest to enable more of such techniques in the next generation of foundries [7]. At first, it is very crucial to understand the need for establishing smart foundries and what can be their impact on casting operations. As a generalized rule, F4.0 provides effective, Man, Material, and Machine integration at all levels in the value chain network.

This can be understood with an example. In a sand casting foundry, tons of silica sand is utilized on an everyday basis. On a particular manufacturing system, when the amount of silica sand drops down below a certain level, a smart foundry should not only be able to raise the alarm by itself but also should be able to send an order to the supplier automatically. The impact can be understood more clearly at the factory level. A smart foundry can monitor resource consumption within various levels. Whenever the stock falls below a certain level, a notification is generated and sent to the concerned department. At the same time, a purchase order is generated and sent to the supplier automatically. Such a system can ensure minimal downtime in production runs due to shortage of material supply. And with the integration of IIoT, foundries placed in multiple locations can be remotely monitored by a team which can be made responsible for ensuring adequate material supply at all locations at all times. This is one of the many examples to realize the potential of smart foundries.

Quality assurance is another crucial aspect to be considered in casting operations. The manufacturing process itself can be made smarter by enabling automated quality assurance tools. In a given casting operation, the part can be made to go through automated quality checks at each step. The data generated can then be compared with the standards using the software. This Go, No-Go quality procedure helps in fault identification at a very early stage in the production cycle, and the faulty part can be corrected or sent back before it goes through all the stages of the production. This is useful in enhancing resource efficiency and reducing the amount of scrap in smart foundries. Furthermore, this also enables accurate manufacturing of the castings, which is very important from the quality control perspective. The critical elements of F4.0 are discussed in the next section.

Elements of Smart Foundries

There are nine pillars for establishing the Smart foundries (shown in Fig. 1). Each of them is discussed below:

(a) **Industrial Internet of Things (IIoT)**: IIOT refers to the use of internet of things in an industrial environment. IIoT brings together Information Technology (IT) and Operational Technology (OT). OT involves the interaction of control systems, intelligent machines, and humans. The interaction of the two techniques can upscale the data exchange and its analysis that can facilitate faster decision making enabling smart production in the foundries of the future.

(b) **Additive manufacturing (AM)**: AM technologies offer much flexibility to a manufacturer and are much significant in the context of smart foundries. AM provides a capability to manufacture physical prototypes of the product. Integration of AM in the production phase gives a flexibility to manufacture customized parts as per the consumer demands. AM of sand-moulds and patterns has the potential to reduce cycle time and material consumption in sand-castings [8, 9].

(c) **The cloud**: Implementation of IIoT in F4.0 will require big data to be shared and processed in the industry. The cloud acts as a repository for the data which is obtained from machines, robots and production lines. It plays a significant role in facilitating Machine to Machine (M2M) communication in smart foundries. Cloud computing enables the user to extract and analyse the data, improvising both the decision time and the production process.

(d) **Cybersecurity**: With the inclusion of interconnected systems and networks, the future industries have an increased risk of the data breach and cyber-attacks. The existing cybersecurity systems need to be updated and made in-line with the smart industries. Development of high-security cyber-systems is a must to protect critical manufacturing systems from unwanted phishing attacks.

(e) **Vertical and Horizontal system integration**: System integration is another important feature of smart foundries. **Vertical integration** refers to the use of cyber-physical systems in an efficient manner. This allows a smart foundry to react quickly to change in any variable such as consumer demand, inventory, machine downtime and delays in production due to any other

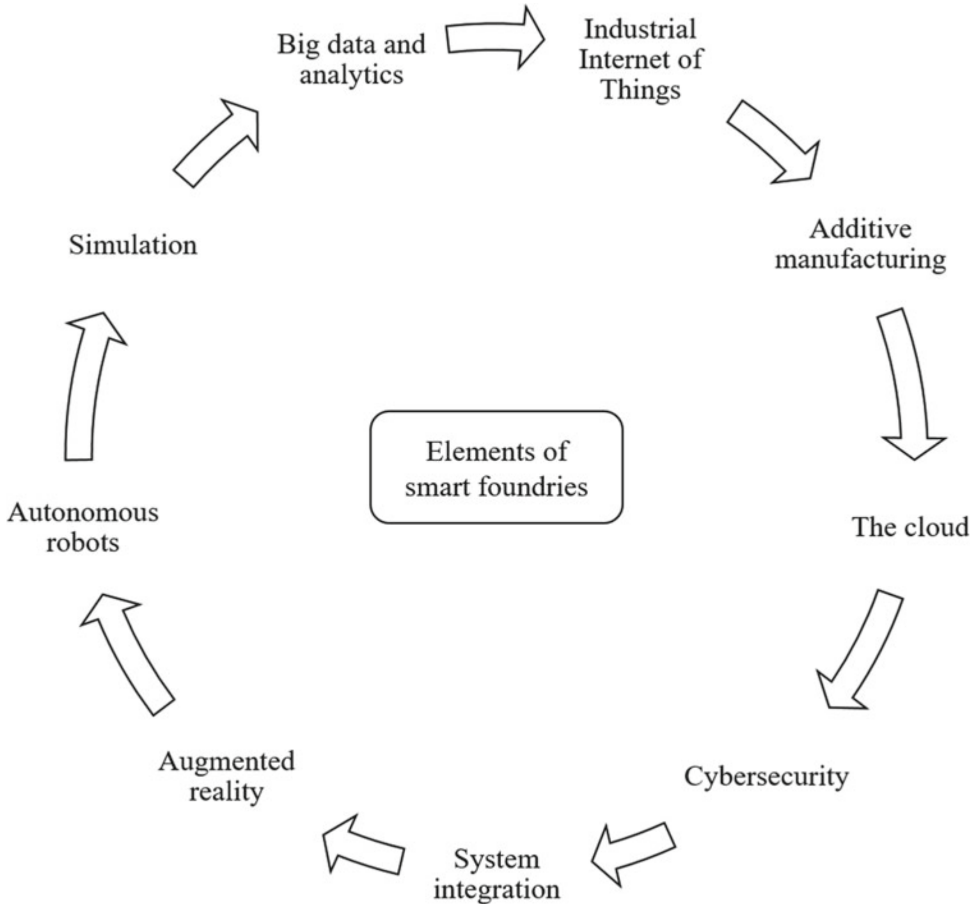


Fig. 1 Elements of smart foundries

reason. **Horizontal integration**, on the other hand, focuses on establishing value-added networks. A network can either be between a supplier and customer, or it can also be an integration of new business models among factories located in multiple countries and across different continents.

(f) **Augmented reality**: With the use of augmented reality, a worker on a particular machine can be trained from a remote location. By making use of 3D augmented reality glasses, a learning seminar offering a realistic hands-on, a virtual machine can be carried out. Also, if there are any known breakdowns in a smart foundry, a skilled technician should be able to rectify and provide support to the local staff from a distant location. This is very useful in reducing machine breakdown time and improving productivity.

(g) **Autonomous robots**: Automation is one of the main principles of F4.0 concept. Use of robots in the manufacturing industry for performing various tasks is not new. In smart foundries, the capabilities of robotics are improved further. Robots can be made more autonomous and can be trained to work alongside humans. With the help of advanced machine learning algorithms, they can be trained to take into account, the effects of time delay on the processing of a particular part on the assembly line. The robots are further made capable enough to take corrective actions and decisions independently in order to make the production process smooth and optimal.

(h) **Simulation**: Enhanced visualization is primarily supported by simulations. A foundry can be modelled much before it is set-up and effects of downtime, scheduling and any change within the operations can be realized a priory. This helps in saving time and resources and can be carried out even in the design phase. Simulations also find their utility in producing a digital twin (or virtual representation) of a physical process. The learnings and analysis can later be transferred to the actual system, thereby forming a closed-loop cyber-physical system.

(i) **Big Data and Analytics**: In the context of Foundries 4.0, collection of data from various manufacturing systems and enterprises will become standard in decision making. The real-time data thus generated need to be carefully evaluated to optimize both, production and process quality.

Advantages

Smart foundries offer the following advantages over conventional foundries:

- Casting simulations can help to improve the quality of castings.
- Optimization processes have the potential to upscale the production process, thereby increasing the yield.
- Virtual casting operations can pre-estimate and identify geometrical changes for better productivity.
- Reduction in shop-floor trials for the development of new castings can be reduced, thereby saving both time and cost of production.
- Smart technologies add more confidence in decision making and are also a valuable addition to the foundry business.
- From a quality and reliability perspective, digitalization provides more documented and scientific evidence to certification of the manufacturing process and techniques.
- The central repository allows the data to be stored and managed for many years. This can further be utilized in several projects and can be shared conveniently between users present at multiple remote locations.

Energy-Efficient Smart Foundries—A Case Study

A traditional foundry is driven by energy-intensive processes. A large amount of energy is spent in melting metal alloy for the casting process. In this case study, the comparison is made with foundries utilizing sand casting and investment casting process. For either of these two processes, batch melting is used, where a particular batch of metal alloy is melted and held at high temperatures ($\sim$700 °C) in the furnace for a long time. Any left-over molten material is sent to reuse or scrapped [10]. Typically, if the molten material is an aluminium alloy, it reacts with the surrounding air and forms an oxide layer on the surface. When such a material is filled in the mould, the gravity facilitates the turbulent behaviour of the liquid during filling, and the oxide film gets broken and thus trapped in the bulk material. This cracked oxide layer further compromises upon the quality of the castings produced, thereby producing defected castings with low mechanical properties [11, 12].

To address this issue, an anti-gravity sand casting process is developed by researchers from the University of Birmingham and N-Tec Ltd. The process is called as CRIMSON (Constrained Rapid Induction Melting Single Shot Up-Casting) process. The process is suitable to reduce energy consumption and produce defect-free casting [13, 14]. A schematic of the CRIMSON facility is shown in Fig. 2. The CRIMSON process, instead of batch melting, emphasizes on melting only the required amount of metal alloy using an induction furnace. A counter-gravity filling is then applied to fill-up the mould cavity. This ensures a smooth flow of the molten material at the same time avoiding over-energy consumption. The CRIMSON process if upscaled to a factory level, has the potential to bring down the energy consumption rates in foundries substantially. With the implementation of the principles of Industry 4.0, the process can be a milestone in establishing energy-efficient smart foundries in the next industrial revolution. One or more techniques can be incorporated within a foundry incorporating CRIMSON process.

(a) **Use of AM for CRIMSON process**: AM can be utilized to produce rapid sand castings. It is a direct tooling technique which can manufacture both the sand moulds and patterns for the CRIMSON process. Furthermore, complex shapes can also be produced with ease and at a much faster pace using a commercial 3D printer. The AM process utilized for this is the 'Binder jetting process'. In this process, a desirable CAD model of the mould is imported from CAD software to the 3D printer. At first, a layer of powder (sand) is spread on the platform. The print head then sprays a binding agent in the form of micro-droplets, forming the first layer of the part. The platform is then lowered down, and the same process is repeated for every layer until the whole 3D part is produced. The printed part is freed from the unsolidified powder by using a brush or pressurized air. In some cases, the part can be post-cured to enhance strength properties. The process schematic is shown in Fig. 3. The 3D printing process can save up to 75% of the manufacturing costs [15]. Similarly, for producing patterns for CRIMSON, Fused Deposition Modelling (FDM) can be deployed. FDM is a material extrusion AM process, where the desired pattern is produced by melting and depositing the material, layer by layer which is then solidified and removed.

(b) **RFIDs for automation**: Radio Frequency Identification (RFIDs) can be used to define a sequence and automate the control at various levels. In a sand mixing machine, with the use of RFIDs, a pre-mixing sequence can be defined. This is not only able to utilize the exact amount of material but at the same time, this information on material consumption and usage is stored on a remote PC. This can reduce unwanted material wastage and optimize the process.

(c) **QR codes for smart castings**: A QR code can be embedded in a casting part and is scanned at each

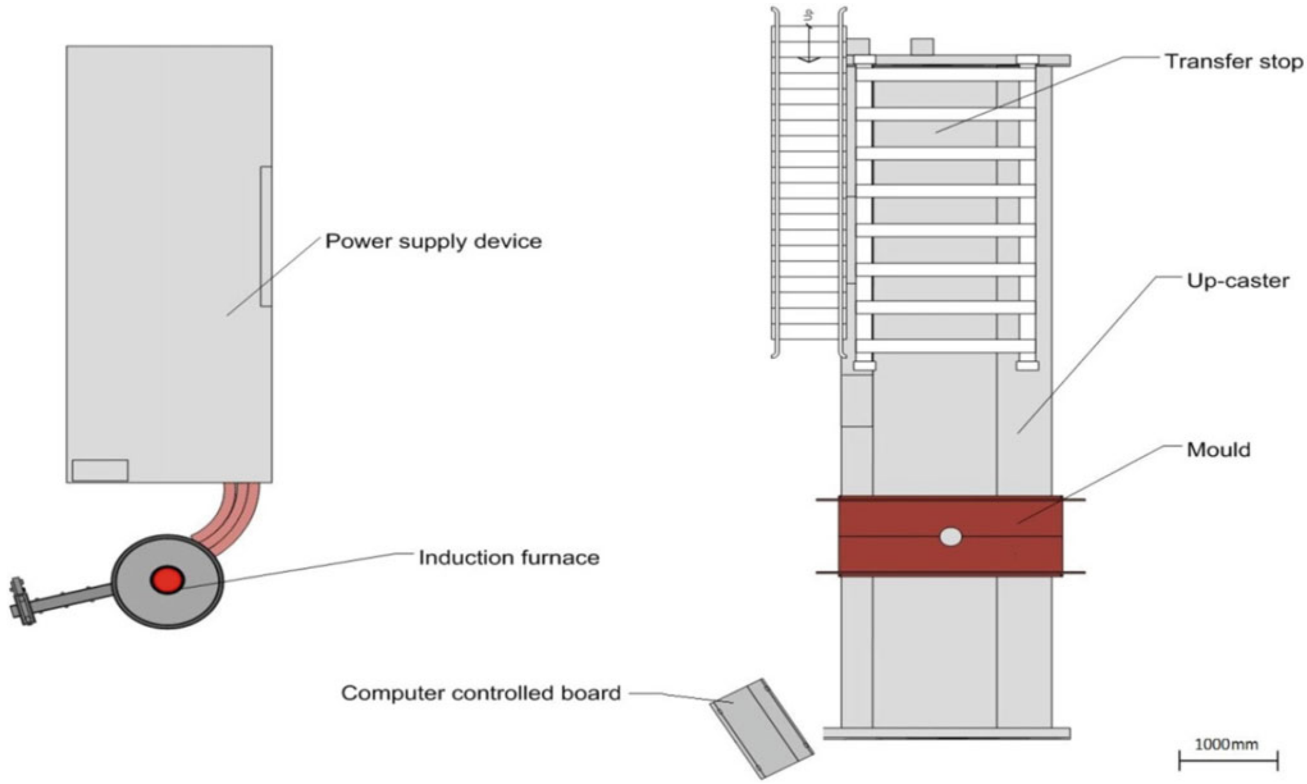
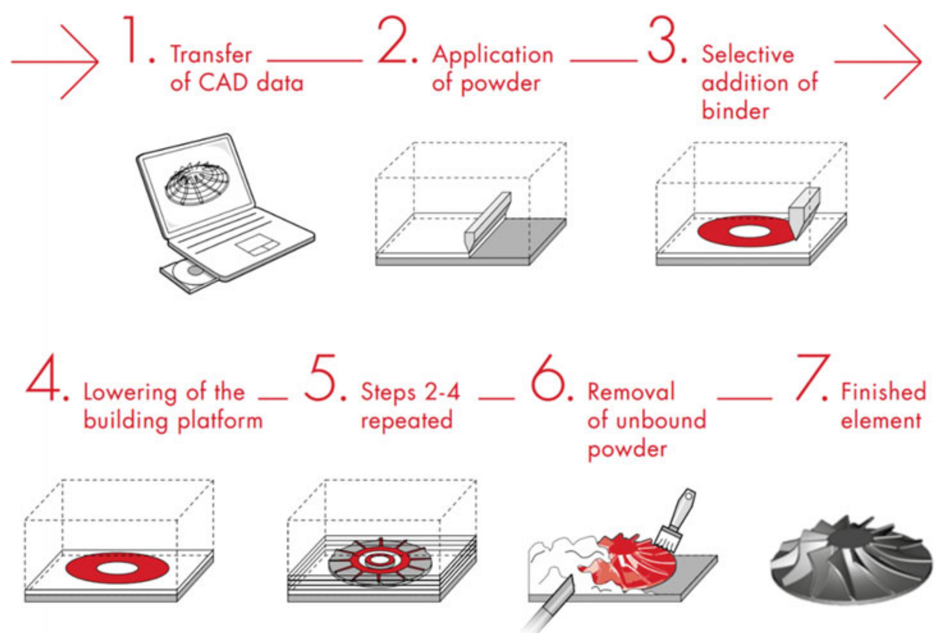


Fig. 2 Schematic of the CRIMSON casting facility at Cranfield University. Image adapted from [10]

Fig. 3 Additive manufacturing of sand moulds. Image adapted from [15]



step. QR codes can provide an efficient means for tracing the complete life cycle of the casting product from its inception to its delivery to the customer.

(d) **Online monitoring of the process parameters**: In the CRIMSON process, two thermal cameras may be deployed; one at the melting station and other next to the mould cavity. The thermal camera at the melting station can track real-time melting temperature. This information is fed to a computer which is not only able to record the real-time temperature data but also can make a decision to cut off the electric supply automatically, so no excess energy is spent in the melting process. Similarly, the thermal camera monitoring the mould cavity can give real-time data and temperature distribution profile in the mould. The temperature data thus produced can be utilized for improving the simulations and bringing them more closer to reality.

Challenges and Future Prospects

Despite several advantages, there are specific bottlenecks associated with the inception of smart foundries. Some of the challenges associated with smart foundries are discussed below:

(a) The entire concept of Foundries 4.0, is reliant on connectivity. In a situation where a foundry loses its internet connection temporarily, the entire manufacturing process will come to a standstill. Any ongoing tasks within the foundry in that particular instant of time cannot be updated on the server in real-time. This also will result in the loss of data.
(b) Risk of cybersecurity, data-phishing, and hacking is another issue of concern that needs to be addressed while laying down the foundation of smart foundries.
(c) Another aspect that needs attention is the supply chain. The automation process within the foundries will not be of much use if the current supply chain cannot keep up with the concepts of foundries 4.0.
(d) The use of high-end equipment for running simulations might add economic burden on foundries. Furthermore, this will also require advance FEM and CFD training provided to the employees.

One of the most critical challenges that remains to be addressed is to identify the extent of efforts needed to transform an existing foundry into foundry 4.0. Instead of turning the entire manufacturing model, small modules are desirable to incorporate at once. Goals of Foundries 4.0 should be realized in steps. Prospective digitized solutions must be made adaptable with the existing production system, so as to avoid any economic burden. At the same time, the current workforce should be trained to adapt to the desired skill set. A thorough understanding of all the challenges is thus a must to enforce smooth transition of traditional foundries to smart foundries.

Conclusions

With the advent of the next industrial revolution, digitalization is taking over the entire manufacturing industry, and foundries make no exception to it. Metal casting is a critical and energy-intensive process which is utilized for various applications. There remains a need to transform traditional foundries into smart foundries. The concept of Foundries 4.0 is introduced in this work. Critical elements facilitating the shift from traditional to smart foundries are identified and presented. Advantages and challenges associated with establishing foundries of future are also discussed in this work. A case study discussing a non-conventional energy-efficient sand casting process (CRIMSON process) is presented. In the context of Foundries 4.0, such a process can be a milestone in establishing energy-efficient smart foundries in the next industrial revolution.

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