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Intelligent casting: Empowering the future foundry industry

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Abstract: Emerging technological advances are reshaping the casting sector in latest decades. Casting technology is evolving towards intelligent casting paradigm that involves automation, greenization and intelligentization, which attracts more and more attention from the academic and industry communities. In this paper, the main features of casting technology were briefly summarized and forecasted, and the recent developments of key technologies and the innovative efforts made in promoting intelligent casting process were discussed. Moreover, the technical visions of intelligent casting process were also put forward. The key technologies for intelligent casting process comprise 3D printing technologies, intelligent mold technologies and intelligent process control technologies. In future, the intelligent mold that derived from mold with sensors, control devices and actuators will probably incorporate the Internet of Things, online inspection, embedded simulation, decision-making and control system, and other technologies to form intelligent cyber-physical casting system, which may pave the way to realize intelligent casting. It is promising that the intelligent casting process will eventually achieve the goal of real-time process optimization and full-scale control, with the defects, microstructure, performance, and service life of the fabricated castings can be accurately predicted and tailored.

Keywords: intelligent casting; 3D printing; intelligent mold; process control; cyber-physical casting system; embedded simulation

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1 Casting and its features

Casting is an essential manufacturing technology with a history of thousands of years [1,2]. During this process, the molten material such as liquid metal or alloy is poured into a mold with the designed cavity, as the liquid material cools and solidifies within the mold, a casting is obtained [3,4]. It has been one of the most widely used forming techniques to fabricate metal parts in the manufacturing industry. It is widely applied in most industrial sectors like aerospace, automobile, defense, railways, construction, mining, chemical engineering, etc [5,6]. The typical features of casting technology can be briefly described as follows:

Feature 1, the ability to fabricate complex-shaped products. It can produce parts with complicated shapes owing to the excellent mold filling ability of molten metals or alloys, especially those structures with intricate inner cavities such as engine cylinder blocks and heads, as shown in Figs. 1(a) and (b) [7,8].

Feature 2, complex process, multiple sources of tolerance. Basically speaking, the casting process is the relative conversions of model and mold, such as from pattern or model to mold and then from mold to casting, from core box to core and then from mold and core to casting, from a pattern to mold, then from mold to an intermediate model, and then from model to mold, finally from mold to casting, as shown in Fig. 1(c). Therefore, the casting process is long and complicated, consisting of many procedures such as

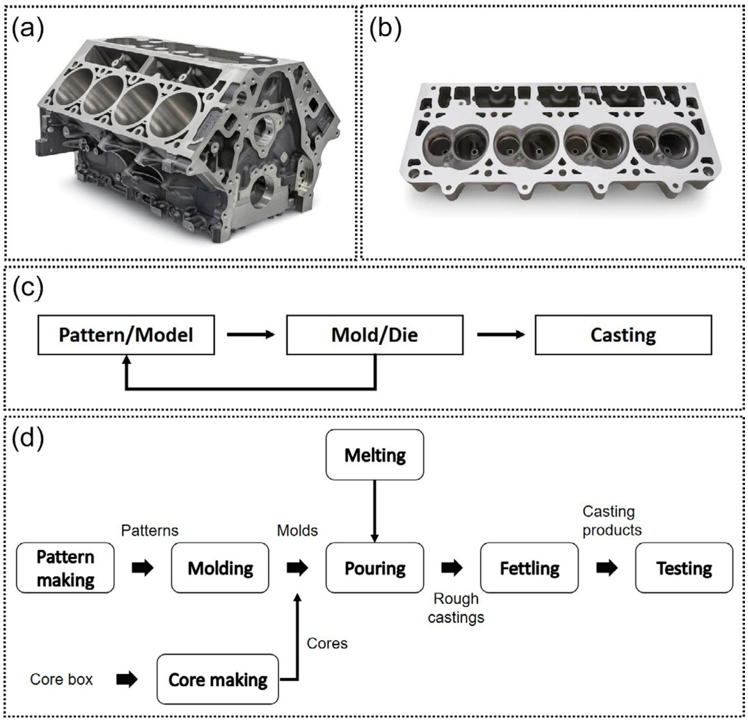


Fig. 1: Cylinder block casting [7] (a), cylinder head casting [8] (b), the conversion of pattern to mold to casting (c), schematic diagram of the whole casting process (d)

pattern making, molding, core making, melting, pouring, fettling, testing and heat treatment, etc., which lead to rather time-consuming and a series of tolerance sources, as shown in Fig. 1(d). Thus, it is very difficult to control the precision and quality of castings [9,10].

Feature 3, strong adaptability and relatively cost-effective. In actual, the most remarkable advantage of the casting technology lies in that it can provide upstream industrial products with almost unlimited alloy types and unlimited casting size in a relatively cost-effective way, i.e., wide source of casting materials can be used, flexible sizes of castings that are suitable for many applications, large amounts of waste can be reused, and low equipment investment.

Feature 4, poor labor conditions, relatively large source consumption and high scrap rate. The casting production have several disadvantages such as the poor labor conditions (e.g., dust, heat and noise pollution) and large consumption of sources that is inconsistent with the concept of green manufacturing, as well as the unstable process control that usually leads to high scrap rate, low dimensional accuracy and quality of products, and the inevitable process induced defects.

Feature 5, multiple physical processes involved, difficult to control the microstructure and properties of castings. The casting process mainly includes the stages of melt flow and mold-filling, solidification, cooling after solidification. It is a multi-physics coupling process, the combination of fluid flow, heat and mass transfer, and phase transition, which is accounting for several intrinsic casting defects including shrinkage porosities, oxidation and slag inclusion, cracks, residual stresses and distortions, etc. Consequently, it is difficult to obtain ideal solidification microstructure and excellent performance of castings.

All in all, it has always been the main goal for foundrymen to utilize high efficiency, high accuracy, green and environmentally friendly, automatic even intelligent casting process to produce high quality castings with controllable and refinable performance. With competitions in aspects of quality, cost and efficiency are becoming increasingly fierce, the traditional foundry enterprises and traditional modes of production are seriously challenged. To be a well-adapted processing technology sequentially, casting technology urgently requires the integration of the cutting-edge quality and process control techniques, as well as advancements in molds, cores, patterns preparation and artificial intelligence (AI) technology to meet the critical demands and maintain technical vitality.

2 History and trends of casting technology

Although it has a long history of development, the basic principles of casting technology have remained unchanged up till now. Casting technology has evolved from a craft into an art [11], and currently it has become an interdisciplinary domain of science and engineering based on solidification principles, control theory, automatics and robotics, etc. As one of the oldest material forming technology, casting is still a sustained and standout manufacturing process with strong vitality, which mainly owing to its constantly innovating and evolving in the developing history – patterning, molding and core making from manual making to machine making, to the wide integration of automation technologies such as molding lines, core shooting machines, robots, etc., and from trial and error method to numerical simulation and information technology, and to the wide application of AI technology, as shown in Fig. 2. As expected, casting technology is developing towards the objectives of high quality, low cost, short cycle, low consumption and no pollution. At present, driven by the greatly promoted development strategies such as “Intelligent Manufacturing”, “Industry 4.0” and others, the concept of “green and intelligent casting” has become a common consensus in the academic field and foundry industry, and it mainly involves the greenization, automation and even intelligentization of the process. It can be forecasted that in the future the casting technology will eventually realize digitalization and intelligentization, which is benefiting from a series of technological advances and various emerging technologies that allow the autonomous even intelligent running of the facilities and processes.

In fact, automation, digitalization and intelligentization are essential methods to improve the level of casting technology. For instance, the robotic systems used in most stages of casting

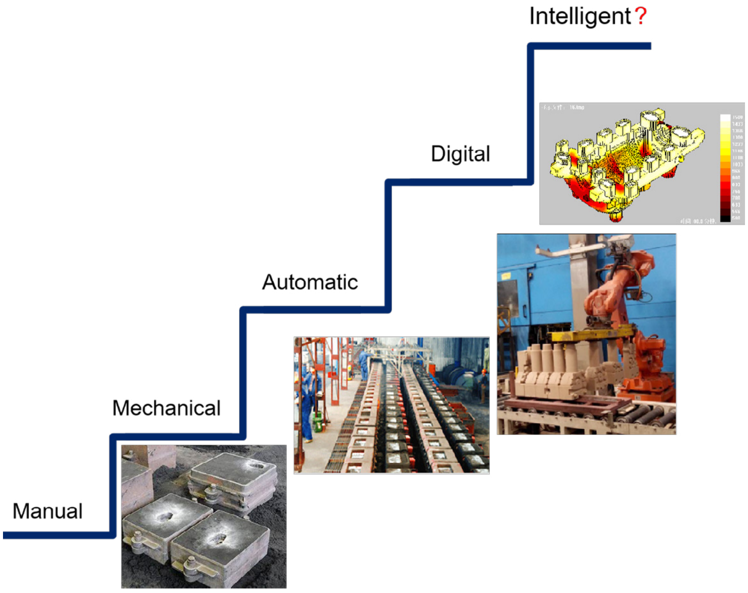


Fig. 2: Evolution history and developing trends of casting technology

process observably reduce the risk of damage or defects and improve the efficiency of the process. Over the last decades, many innovative efforts have been made to realize high precision, high flexibility and high efficiency intelligent casting, e.g. the integration and fusion of additive manufacturing technology with the casting process, the intelligent mold technology developed for casting, the advancements in automation technology, information technology and AI technology that can be applied for real-time monitoring, online decision-making and controlling of key process parameters and casting quality, the development of simulation software or expert systems used for casting defects analysis, performance prediction and process optimization. As speculated, the technical vision of intelligent casting process is to achieve self-sensing, autonomous decision-making and autonomous execution in every stage of the process, which aims at dramatically shortening the leading time, significantly improving the performances of the obtained castings, obviously decreasing the resource and energy consumption, and greatly reducing the production costs. To achieve this goal, there is an urgent need to reshape the existing casting sector via the wide application of sensors, flexible robotics, digital manufacturing technology, AI technology, and other emerging technologies.

3 Key technologies for intelligent casting

As well-known, intelligent casting is an important aspect of intelligent manufacturing paradigm [12], which is focused on improving the efficiency, quality, and accuracy, reducing waste and costs, and increasing the flexibility to accommodate for a wide range of materials and designs. In narrow sense, intelligent casting paradigm refers to the applications of advanced technologies to optimize the casting process and improve the quality of casting components. Intelligent casting process does not only encompass a single technology, but also a wide range of technologies that enable autonomous casting production. The current technological clusters of informatization, digitization and automation have paved the way to realize the objective functions of autonomous perception, intelligent analyzing and decision-making, and automatically executive in intelligent casting system. Thus, it would not be wrong to say that “intelligent casting” generally refers to the concept of the highly and deeply integration of digitalization, networking, intelligentization with casting production mode, which strongly depends on the developments of the intelligent casting key technologies [13,14]. Among them, the key technologies in intelligent casting also include a series of advanced manufacturing devices (e.g., the flexible robots and intelligent mold systems) integrated with new generation of information technology, big data processing, and AI technology, and it is developing from the traditional isolated physical unit to smart cyber-physical casting system that combines the virtual information resources with physical casting resources. The key technologies for intelligent casting support the implementation of intelligent casting concept, which will transform the casting production mode from mainly dependent on experiences to theories and prior knowledge. In this section, the main technical progresses involved in promoting the realization of intelligent casting process will be reviewed.

3.1 3D printing technologies

The 3D printing technology, also commonly referred as additive manufacturing (AM), was first invented at MIT as a rapid forming technique to build three-dimensional parts layer by layer directly from computer aided design model [15,16]. Since then, 3D printing methods has been gradually applied to the casting sector for rapid prototyping that comprises rapid tooling (RT) and rapid manufacturing (RM), in which patterns, core boxes, dies, molds for casting and single piece or low-volume castings are made, respectively. Meanwhile, fabricating molds and cores based on 3D printing methods has also aroused concern stage by stage. This is because 3D printing can be utilized to create complex molds, cores and patterns with a high degree of precision, reducing the need for manual labor and improving the accuracy of the casting process. There are several 3D printing technologies that can be innovatively utilized in the casting sector [17], such as fused deposition modelling (FDM), lamination object manufacturing (LOM), stereo lithography (SLA), selective laser sintering (SLS), and three-dimensional printing (3DP), etc., as shown in Fig. 3 [18-27]. Up to now, 3D printing technologies have been mostly implemented for the innovations of rapid casting, which mainly includes direct routes (using 3D printing methods directly) and indirect routes (3D printing methods coupled with secondary or soft-tooling processes). The combination of 3D printing methods and traditional casting technology can breakthrough several constraints of traditional

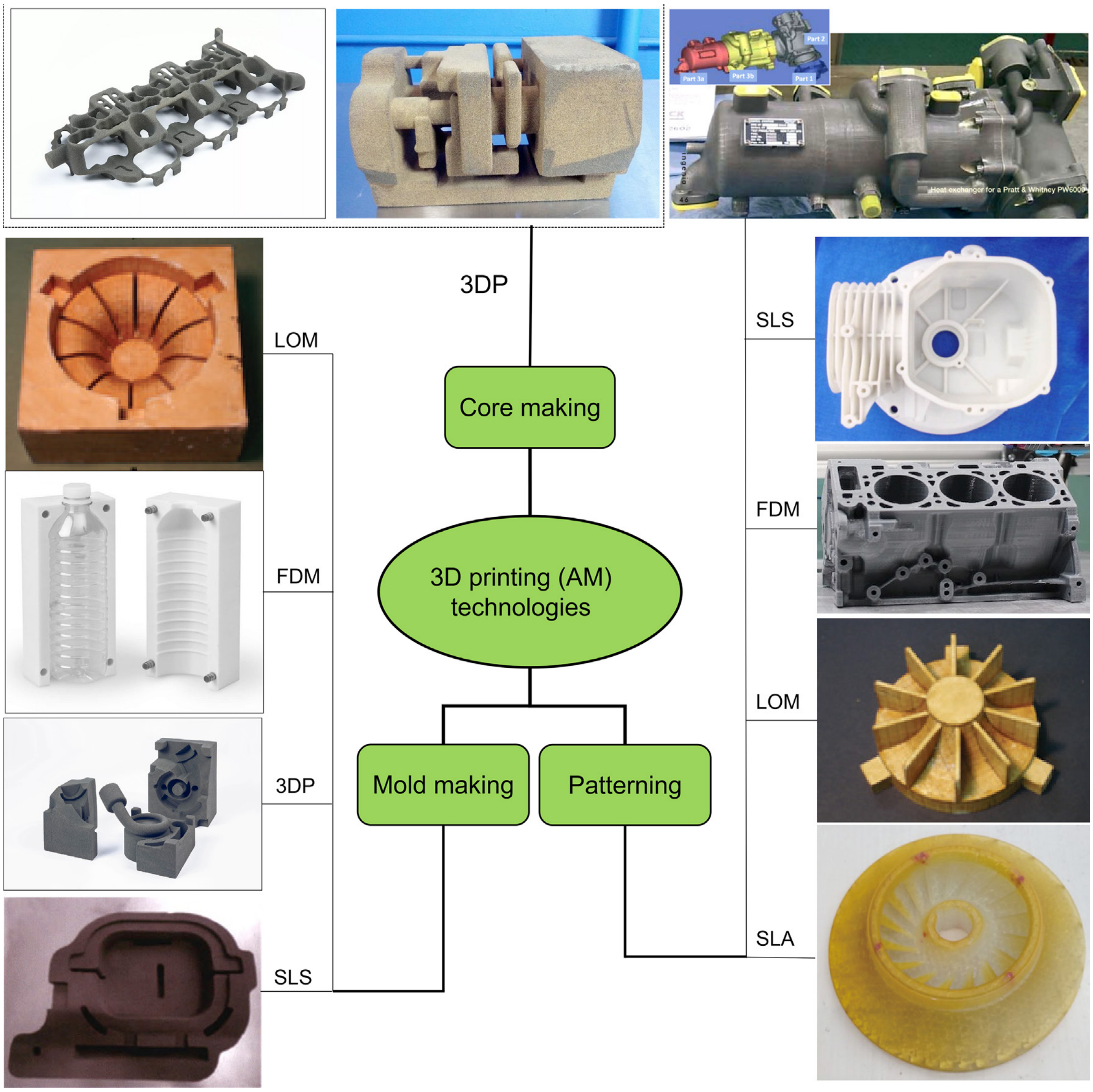


Fig. 3: Applications of 3D printing technologies in casting [18-27]

ways, such as enhance the flexibility in geometry complexity of casting, improve the working environment, simplify the processing procedures and shorten the production research and development cycle.

Nowadays, the innovative integration of 3D printing technology with casting technology has almost revolutionized the foundry industry by offering excellent opportunities to manufacture high quality, complex, accurate prototypes, patterns, molds and cores with dramatically reduced time and cost [28]. The performances of patterns, molds and cores have determining effects on the quality of castings. There is also a growing requirement for the efficient preparation of complex patterns, molds and cores with high quality that can produce high-end, high-performance, large scale and complicated casting components. As they can enable many technical improvements in casting practice, 3D printing technologies have become essential for the production of high-performance patterns, molds and cores owing to the resulting advantages such as less limitations in terms of structure complexity and size, reduced production time and cost that mainly depends on the quantity and the geometry complexity, higher freedom in part design and optimization for any castable alloys [29-31]. Especially in sand casting and investment casting fields, 3D printing is shown to integrate seamlessly with the conventional casting industry as it can produce high quality and complex molds or cores with the required properties for better casting solutions within a short time period, meanwhile without any tooling requirement such as patterns, core boxes, and flasks, etc [32,33]. For instance, Snelling et al. [34] fabricated a functional-designed 3DP sand mold by using an ExOne S-print machine directly from a CAD model, and the printed mold was used as a core to make a specific casting with the complicated cellular structure.

To our best knowledge, several typical features of intelligent casting process are "fast", "flexible", "smart", and "customized". In the future, it is undoubted that the continuous improvements of 3D printing technologies will be helpful in achieving the rapid casting and high-performance customized casting applications. Besides, it is possible to obtain high dimensional accuracy of complicated casting molds or cores in a cost-effective way through 3D printing, which meanwhile provides possibilities to preset various sensors, actuators for actively monitor and control of the smart mold system. Thus, it offers opportunities and challenges for the deep integration of 3D printing technology with intelligent casting practice. It can be expected that in the future the extensive utilization of constantly improved and customized 3D printing technology will shorten the cycle times of casting processes, reduce the various casting defects, lower the production cost, and realize the high-throughput, high-efficiency, and high-flexibility in the design and fabricate of functional, smart, and even intelligent casting molds. These advancements will lay the foundation for the eventual realization of intelligent casting.

3.2 Intelligent mold technologies

As well known, the core of casting is the procedure of solidification after the liquid material is poured into the mold, which determines the microstructures and performances of the obtained castings. It also influences the formation of various casting defects such as shrinkages and shrinkage porosities, cracks, and distortions. Therefore, the control of solidification process should be the most critical link of casting process. Commonly, the solidification process of the liquid metal inside the mold is dramatically affected by the performance of the molds that related to the molding materials and molding method. Hence, the casting molds (cores) with desired properties are essential for the productions of casting parts and structures with high quality for the reason that the molds play critical roles in removing heat from the molten metal during the filling and solidification stages of casting process. However, owing to the inherent constraints both technical and non-technical, casting molds (cores) are traditionally designed and fabricated to be dense and thick, resulting in disadvantages such as the difficulty in controlling the cooling of castings, large consumption of raw materials and energy, and a long lead time that bring high cost. Moreover, the molds (cores) with a dense structure are unwieldy and inflexible, making it challenging to realize real-time and in-situ monitoring and localized control, not to mention that to realize flexible and controllable intelligent casting process.

As expected, another obvious feature of intelligent casting process is that the performances of the castings, which largely depend on molds, can be flexibly adjusted and optimized according to specific requirements. To achieve the goal of controllable and adjustable casting performances, the first but the most important attempt and effort is the intelligentization of casting mold system. That is to say, the intelligentization of the molds (cores) will lay the foundation for the realization of intelligent casting, but it urgently needs to change the structure of molds (cores) – from dense to hollow, from inflexible to smart. Consequently, designing and building smart and intelligent molds (cores) is also crucial to realize the automatic monitoring and intelligent control of the casting process, which has already become a research hot spot, both now and for the future.

In terms of intelligent casting molds, numerous efforts have been made to design and fabricate smart hollow or functional skeletal molds to replace the traditional dense molds. This can be attributed to the unique opportunities that smart hollow molds provide for embedding various functional components including sensors, controllers, and actuators to realize closed-loop accurate process control. For instance, in order to verify and analyze the heat insulation effect of the air cavity in molds, Deng et al. [35] prepared complex sand molds with and without air cavity surrounding the riser through 3DP method, and confirmed that the specifically designed air cavity surrounding the riser in the mold can lead to a 12.5% increase of the solidification time of the riser, as shown in Fig. 4(a). Besides, Walker et al. [36] designed and prepared instrumented 3D printed sand molds and cores, based on which the in-mold sensing and in-core wireless sensing for casting process could be realized – the unique mold specifically designed for presetting sensors within the mold would enable the collection of a diversity of data at manifold locations: temperature, pressure, moisture, gas contents, motion of the molds and internal cores (shifting or rotation), and magnetic field.

Specially, aiming to promote the realization of intelligent casting process, Kang et al. [37,38] created several intelligent mold structures, such as rib or lattice structure reinforced skeletal casting molds that contained a mold shell and functional structures – a new concept of design to improve the heat transfer and realize controllable cooling. They found that the rapid and uniform cooling derived from the intelligent mold can improve the production efficiency and reduce deformation, residual stress and casting defects, as shown in Figs. 4(b–f). In addition, Deng et al. [39] developed 3DP molds with internal hollow structures to control the local cooling of the castings. They observed that the forcing air through the internal channel around the casting cavity can improve its cooling meanwhile the hollow structure in the feeding system improved the filling. Shangguan et al. [40,41] presented serial hollow mold structures, which significantly improved the casting's cooling rate and greatly reduced the weight of the sand mold, offering the potential to further control the whole cooling process due to the unique feature of hollowness, as shown in Figs. 4(g) and (h). Similarly, Wang et al. [42] proposed a multi-shell mold structure with pre-engineered cooling function, which ensures the directional solidification of a casting.

In order to achieve high-end castings with excellent performance in the future, it is necessary to continuously pay more attention to improve novel molding technology, which aims to efficiently and quickly design and produce high-quality smart molds (cores) integrated with the required and specific properties. For instance, the smart molds can be integrated with the automated even intelligent thermal control subsystem, which mainly plays beneficial roles in mold preheating, compelled heat dissipation, engineering cooling and solidification, real-time temperature monitoring or other functions, aiming to realize rational and efficient thermal control through the casting process. Thus, the

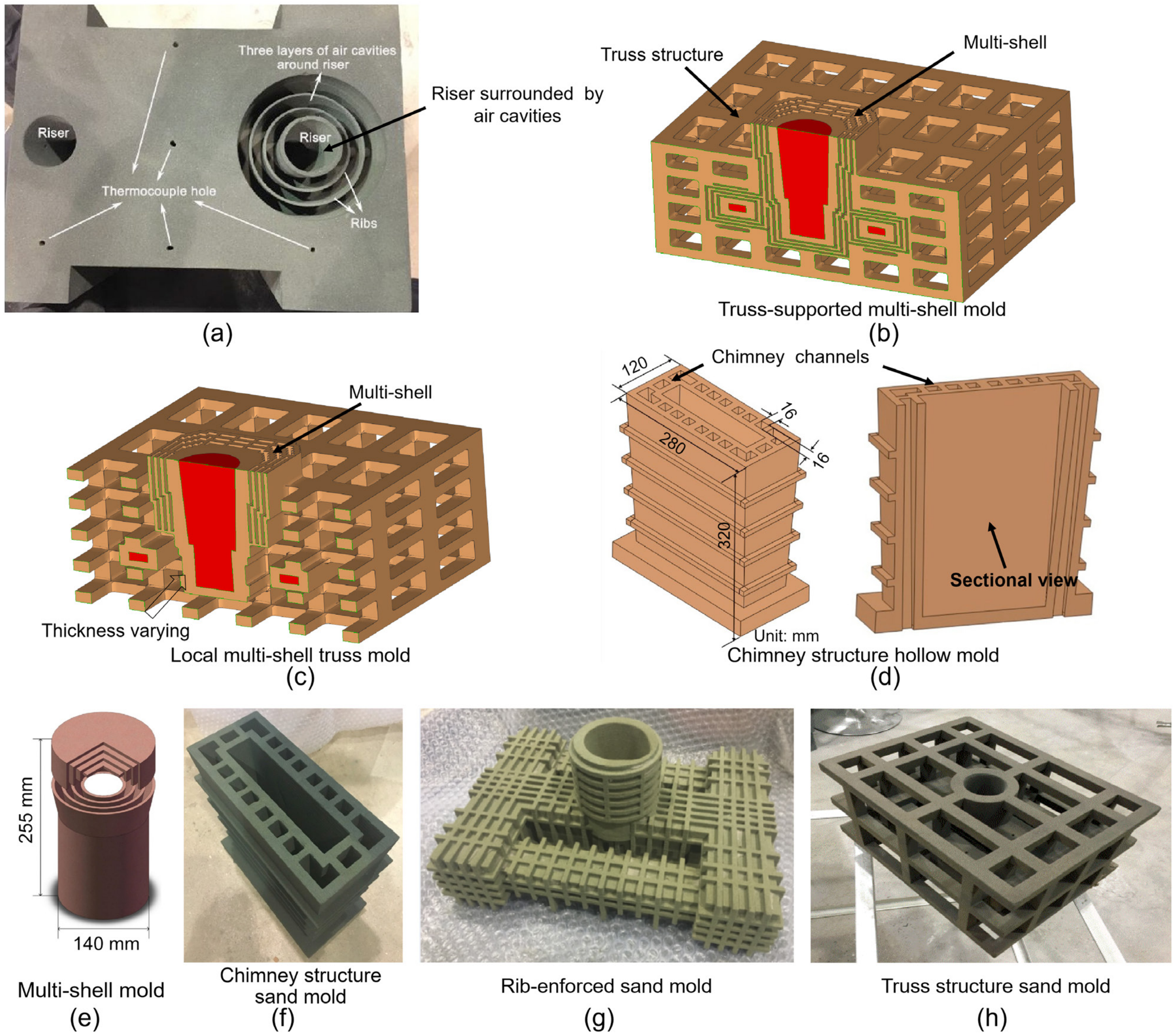


Fig. 4: Intelligent mold structures probably used in future intelligent casting process: (a) sand mold with riser surrounded by air cavities [35]; (b)–(e) CAD model of hollow mold structure [37-39]; (f)–(h) hollow sand mold [39-41]

temperature of molten metal, the mold or the encompassing environment temperature can be precisely regulated on demand. This regulation optimizes the flow and filling, solidification, and cooling processes of the molten metal, aiming to achieve the desired casting microstructure and mechanical properties while minimizing casting defects and enhancing casting quality. Besides, the integration of smart molds with commercial off-the-shelf mechanical control subsystems can optimize the melting, flow and filling, solidification, and cooling processes of the liquid metal. This can refine the microstructure and enhance mechanical properties of castings by selectively utilizing devices such as extrusion, agitation, vibration, and tilting within the mechanical control subsystems [43-49], according to the specific requirements throughout at the casting process, as shown in Figs. 5(a–c). In addition, electromagnetic control subsystems can also be integrated into the smart molds. These subsystems can perform functions such as electromagnetic stirring, pumping, levitation, degassing, deflection and others [50-58], which help to control and optimize the melting, flow and mold filling, and the solidification processes of the molten metal. These in turn improve casting uniformity and reduce casting defects, resulting in better microstructure and mechanical properties of the final product, as shown in Figs. 5(d–f). Another example is the incorporation of ultrasonic control subsystems into smart molds to enhance the quality and integrity of the castings, which is especially beneficial in critical industries such as aerospace, automotive, and energy. The ultrasonic control subsystem can regulate and enhance the melting, flow, solidification and cooling processes of the molten metal by implementing ultrasonic degassing, ultrasonic grain refinement, ultrasonic monitoring and other functions [59-66], leading to reduced casting defects and improved microstructure or mechanical properties of the final product, as shown in Figs. 5(g–k). Future on-going efforts may focus on successfully and economically produce smart or intelligent molds integrated with actively designed or adapted controlling subsystems and equipment for quickly response to specific process control requirements, which will support the implementation of sustainable, green, and intelligent casting.

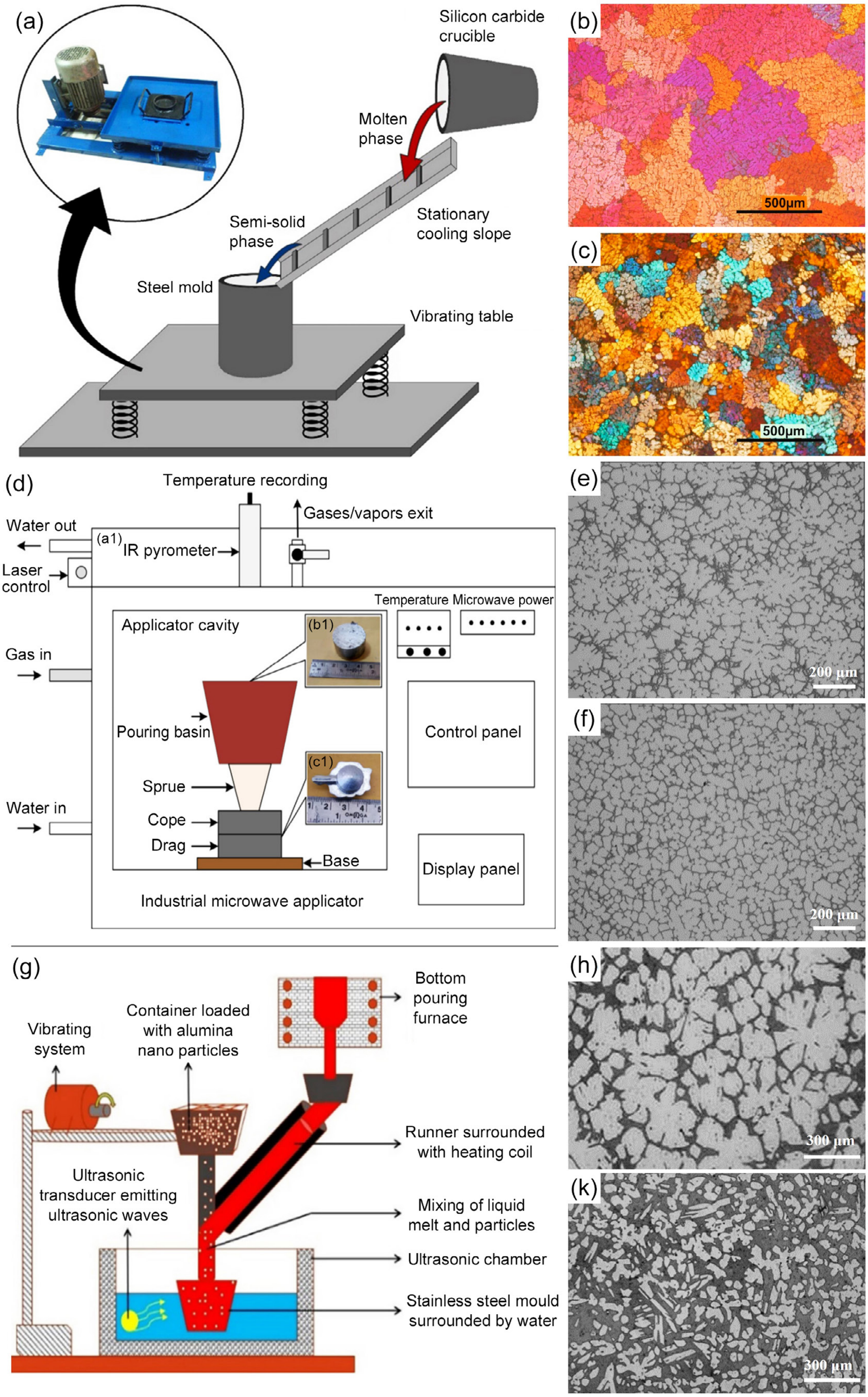


Fig. 5: Schematic diagrams of control subsystems that being integrated into intelligent molds and their effects on microstructure refinement: (a) schematic of mechanical vibrating apparatus for casting [43]; (b) and (c) microstructures of an A356 aluminum alloy without (b) and with (c) vibration during solidification [46]; (d) schematic diagram of microwave assisted in-situ casting [52]; (e) and (f) microstructures of AZ91D alloy solidified at different electromagnetic vibration frequencies of 50 Hz (e) and 900 Hz (f) [50]; (g) schematic of non-contact ultrasonic casting [66]; (h) and (k) microstructures of Mg-8Li-3Al alloy specimens treated without (h) and with (k) ultrasonic vibration [60]

3.3 Intelligent process control technologies

3.3.1 Mold/casting status sensing

The status perception of the whole casting process is the basis for accurate intelligent process control. Currently, the status during casting process can be effectively monitored through the flexible applications of various monitoring devices and sensors including visual sensors, acoustic sensors, touch contact sensors both in no-contacting style and embedded style. It aims to measure or detect various relevant parameters such as temperature, pressure, stress/strain, cracks and flow rate during the casting process, which further lays the foundation of detecting technical problems and adjusting the process parameters in real-time. The key difficulties of status sensing are how to collect critical process parameters that are difficult to see, feel and hear during the casting procedure and find out the mapping formulation between various parameters and castings' performances, which soon afterwards can be integrated into a casting process knowledge base. Many efforts have been made in aspect of attempting to understand the process status automatically or intelligently, as described below:

Example 1, temperature and liquid level monitoring. In terms of getting a deep insight into the process of mold filling, He et al. [67] established a control system based on the programmable logic controller (PLC) to real-time monitor and control the liquid level, temperature, and vibration frequency during the investment casting. The temperature, vibration frequency and liquid level of the investment casting system can be controlled by using laser temperature sensor, vibration sensor and frequency converter, and laser liquid level sensor, respectively.

Example 2, mold filling watching. Based on a contact time method and heat resistant high-speed cameras, Kang et al. [68] developed a wireless monitoring system for the observation of mold filling process, as shown in Fig. 6(a). The system captured the filling process of the steel melt for a 10-ton steel casting, which provided proof for the optimization of the gating system.

Example 3, hearing the occurrence of cracks. The acoustic emission technology was used to accurately detect hot tearing initiation and propagation [69], as shown in Fig. 6(b).

Example 4, stress monitoring. Bian et al. [70] applied the arrays of optical fiber Bragg grating sensors in monitoring the strain evolution and distribution during the casting process of an aluminum alloy, and subsequently a gradient strain distribution after solidification that may be related to the residual stresses was further revealed, as shown in Fig. 6(c). A high degree of correlation was observed between the solidification phases of the aluminum alloy and the strain behavior during casting. Meanwhile, a shrink-fit model was applied to theoretically predict the interaction between the embedded fiber and the cast aluminum after solidification, and showed a good agreement with experimental results.

Example 5, temperature and pressure sensing. Chu and Liang [71] investigated and realized the control on temperature, cooling pressure and ultrasonic wave during the ultrasonic high pressure casting process. Additionally, Shi et al. [72] designed an intelligent control system for the control of temperature and air pressure during the low-pressure casting of aluminum alloy

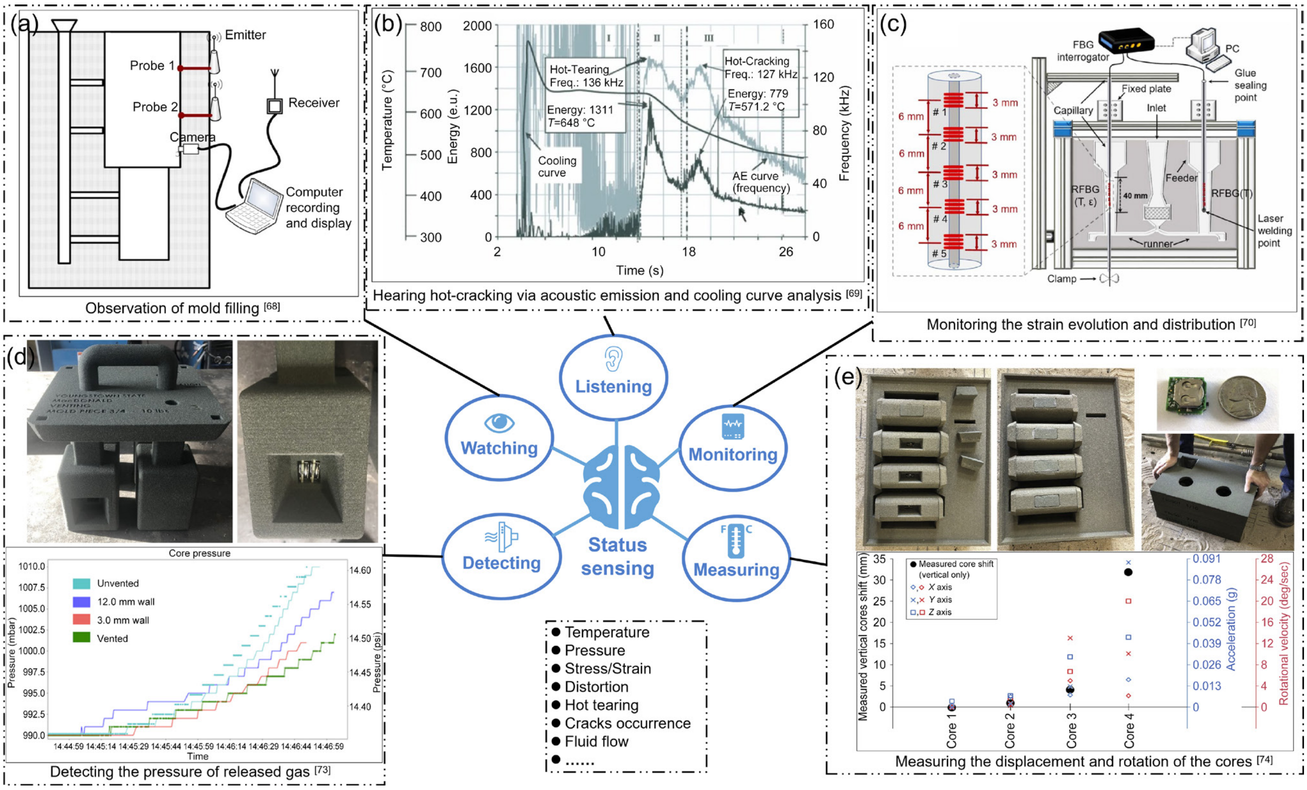


Fig. 6: Status sensing methods applied in casting process (a–e)

hubs. Vuksanovich et al. [73] embedded wireless barometric pressure sensors into 3D printed sand molds and cores to measure the pressures of gases released by the burning and pyrolysis of binders, which provided experimental validation of the software predictions in the cases without ventilation channels. The study demonstrated that wireless disposable sensors can be used to measure pressure at strategic locations, evaluating and optimizing the venting strategies of internal cores. This, in turn, improves the quality of castings by reducing porosity and improving surface finish, as shown in Fig. 6(d).

Example 6, movement and rotation monitoring. Walker et al. [36,74] embedded miniature wireless bluetooth sensors inside the 3D printed cores and obtained the acceleration and rotation of core during the filling process, as shown in Fig. 6(e).

Some common sensing methods that can be utilized in intelligent casting process are listed in Table 1. By utilizing these methods creatively, signals and data related to pressure, displacement, torque, speed, vibration, shock, temperature, and stress-strain during casting process can be collected by corresponding sensors and transmitters. They can then be further processed, stored, analyzed, adjusted and controlled in real-time.

All in all, the objective of status sensing for casting process is to realize online, real-time, all-round measuring and monitoring of process parameters, through which huge amounts of process data can be collected to form multi-source valuable information that can be utilized in the subsequent procedure such as decision-making and cooling process control. As envisioned, the multi-class sensing device will constitute a huge process status perception and detection web in the future. The formative sensing web can be utilized to real-time feedback production data, equipment operation data, energy consumption data, environmental data and other information, showing great importance to achieve the comprehensive insight of the whole process during casting production and improve the production efficiency and quality.

3.3.2 Numerical simulation

Intelligent process control requires a deep insight into the whole process, which likewise relies on the wide usage of advanced algorithms and codes, to simulate the casting process and predict the status of the molten metal during the filling and solidification stages, as well as the potential defects, so as to help designers and engineers to optimize the casting process and minimize defects. Numerical simulations of casting process are extensively utilized for decades, through which the status of process can be predicted and grasped. It has become a useful visualization and digitalization tool for the mold filling, solidification and cooling stages. In the long term, it can also contribute to reducing the cost of laboratory research work, shorten the research and development cycle, and optimize the parameters of casting process. Based on numerical simulation, to control and refine the microstructures and properties of castings has already been one of the hot research topics in foundry sector. Commercially available software packages can now forecast conditions of filling and solidification, residual stresses, distortions, microstructures and mechanical properties of castings, and they also enable predicting the location of possible casting defects including shrinkage porosity, inclusions, and cold shuts before the actual casting is poured.

Over the last decades, important progresses have been made in macro/micro simulation of casting filling and solidification process. As in aspect of casting simulation, it can across the scale of micro, meso and macro, involving various aspects of crystal nucleation and growth, dendritic and columnar crystal transformation and matrix control [75,76]. However, the casting process is strong-nonlinear and time-varying, so the simulation of casting process is closely related to the instantaneous process and parts' status. These characteristics make it quite difficult to realize the accurate prediction of complex process evolution by the traditional offline model. Thus, theoretical analysis model, empirical model, neural network model, etc., have been used jointly to develop online casting process simulation method.

Multi-discipline, multi-scale, high performance, high fidelity and high efficiency have always been the objective of casting simulation. The numerical simulation oriented intelligent casting mainly aims at quantifying the cooling demand of any local area at any time of the casting system through the spatio-temporal discretization of the casting system and the numerical calculation of the virtual heat transfer process, which further provides the basis for applying the intelligent controlled cooling measures during the full range of time periods. For instance, in order to control the cooling of

Table 1: Potential sensing methods for intelligent casting

Items	In-situ sensors can be used
Casting, mold and core temperature monitoring	Thermal couple, thermal resistance sensor, infrared imager
Mold-filling, flume release detection	Camera, contact sensor, pressure transducer, X-ray monitoring system
Melt, air, flume pressure monitoring	Pressure transducer
Defects (porosity, hot tear, crack) formation monitoring	Acoustic sensor, industrial camera
Deformation detection	Stress/strain sensor, displacement sensor, laser or optical scanner and camera

casting at specific local areas and different periods of the casting process, Kang et al. [77] performed a simulation of casting process based on a skeletal sand mold, through which the temperature fields of the casting and skeletal sand mold at a specific time were obtained, as shown in Fig. 7(a). Similarly, Xu et al. [78] simulated a directional solidification process of casting based on a multi-shell mold structure combined with water gradually immersing method, with the temperature fields of casting and mold can be efficiently achieved in advance, as shown in Fig. 7(b). The pre-acquired simulation results can provide a reference for subsequently intelligent process control.

3.3.3 Flexible cooling control

The solidification process and subsequent cooling stage of castings determine the microstructures and mechanical properties of castings. Thus, the control of the cooling process is the core of the quality control for castings. It is proved that improper distribution of mold temperatures may cause many casting defects, i.e., proper cooling control for mold is essential for producing high quality castings with high production rates. The cooling control technologies have gone through three generations. The first is the direct cooling control technologies, such as the forced cooling by chills, water pipes, water cooling plate, and water erosion, etc. The second generation is the cooling of inside-out, such as the post solidification intensive riser cooling. And the third generation is the intelligent cooling control of any interested places at any time. It can be realized by an intelligent cooling system based on hollow molds for castings which adopt shell or multi shells, skeleton- or rib-enforced structures. The hollow mold structure is aimed to be made by additive manufacturing methods.

Nowadays, numerous cooling control methods have already successfully been applied in optimizing and controlling the microstructures and performance of castings. In the same way, the automatic and accurate control of the solidification and cooling process is one of the key points to realize intelligent casting. There are several cooling methods available for controlling the solidification and cooling process of castings, such as the application of a metallic mold to improve the cooling efficiency of castings, the utilization of internal and external chilling blocks in the mold, laying the cooling pipes in the mold to control the cooling of castings by circulating the compressed air, cooling water, liquid nitrogen or other cooling media in the pipes, etc. Several flexible cooling control methods that can be utilized during casting process are illustrated in follows.

Example 1, inside-mold cooling. Hu et al. [79] investigated the influence of flow rate of the circulated cooling water on the cooling effect of the metallic mold. Yang et al. [80] developed a computerized intelligent real-time monitoring and control system (IRMCS) for die casting process involving cooling the die with multiple channels, demonstrating that the developed

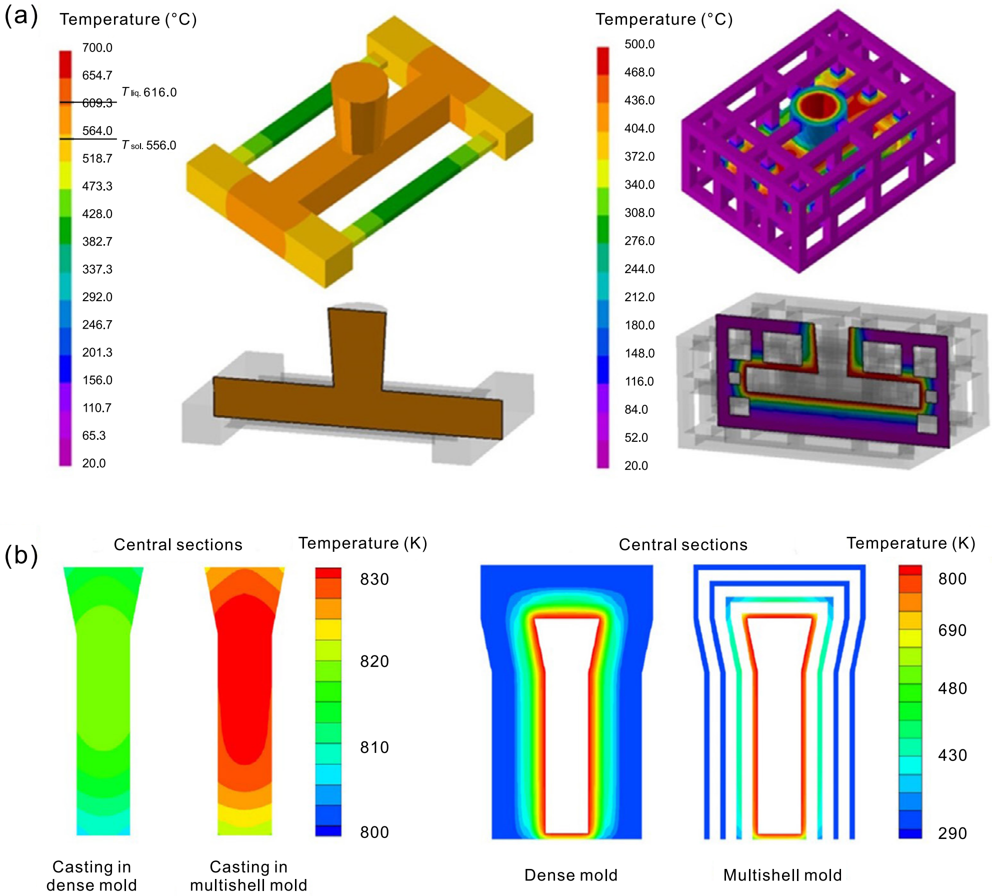
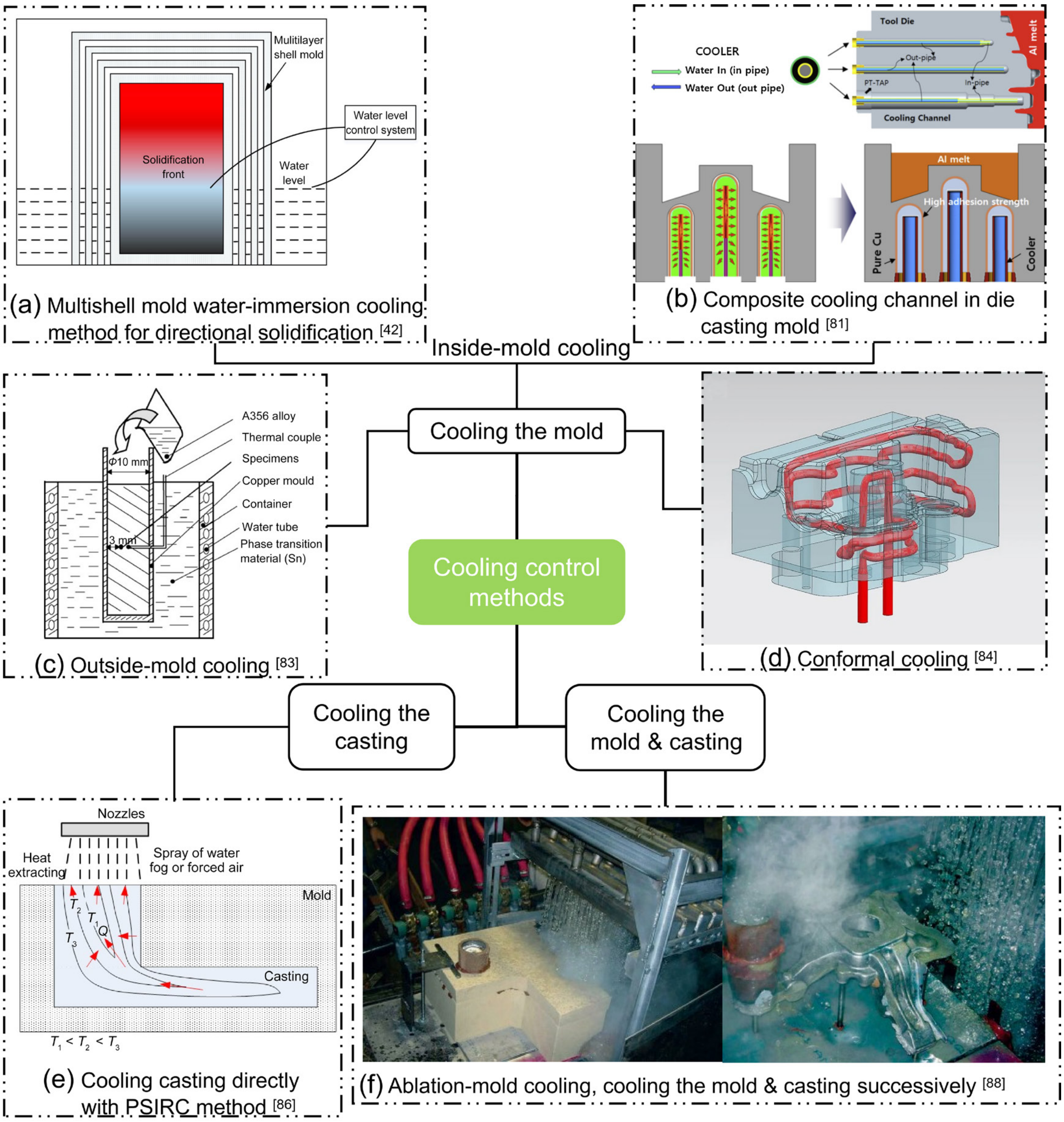


Fig. 7: Simulated temperature fields of casting and hollow molds: (a) stress frame casting and skeletal mold [77]; (b) rodlike casting and multishell mold [78]

control system is capable of adjusting the desired supply of cooling water into multiple cooling channels, which can effectively control the local temperature of the die insert within a given range, and then realize the concept of close-loop cooling control. Similarly, Wang et al. [42] proposed a multishell mold structure and water-immersion cooling method (MSMWI) for the directional solidification of castings, putting forward that this cooling method was helpful in improving the mechanical properties of the castings (such as tensile strength, elongation, and hardness), as shown in Fig. 8(a). Furthermore, Shin et al. [81] successfully improved the cooling performance of high pressure die casting mold through inserting pure Cu bush into the cooling channel of die casting mold to form a copper lining, as shown in Fig. 8(b).

Example 2, outside-mold cooling. By using water spraying method, Stets et al. [82] cooled the upper part of the sand mold to accelerate the cooling of the casting after its solidification, and further studied the influence of water flux, timing on the cooling speed and cooling effect of the casting. However, these cooling methods usually have limited cooling efficiency on the obtained castings, and are difficult to achieve precise and quantified cooling control. Therefore, it is still necessary to develop novel cooling means to improve the cooling process of castings. In addition, Zhang et al. [83] realized fast-cooling of casting through using a copper mold cooled by Sn phase-transition medium, and the method was used to prepare cast A356 aluminium alloy with refined microstructures and mechanical properties, as shown in Fig. 8(c).

Example 3, conformal cooling. Conventionally, cooling channels in casting molds are usually produced linearly in circular profiles that may be ineffective due to the limited geometries rather than conformal style, which is prone to bring about molding defects such as hot spots and distortions forming in the castings. Fortunately, conformal cooling channels can now be produced in any geometry by additive manufacturing, and this technique is widely used in casting practice, as shown in Fig. 8(d) [84]. Based on numerical analyses and experimental methods, Kurtulus et al. [85] comparatively


(a) Multishell mold water-immersion cooling method for directional solidification [42]

(b) Composite cooling channel in die casting mold [81]

(c) Outside-mold cooling [83]

(d) Conformal cooling [84]

(e) Cooling casting directly with PSIRC method [86]

(f) Ablation-mold cooling, cooling the mold & casting successively [88]

Fig. 8: Typical cooling control methods used in casting process (a–f)

investigated the effects of standard and conformal cooling channels on the casting steps and final properties of the products cooling in gravity die casting molds. The mold surface temperature distribution in the conformal cooling mold was more homogeneous, the average grain size of the castings was 13.5% smaller than those castings with standard molds, and the mechanical properties of the castings were improved.

Example 4, direct cooling of casting. Kang et al. [86] proposed a novel cooling method that was named post solidification intensive riser cooling (PSIRC), during which the top of risers can be cooled by forced air or water mist when the solidification of a casting finishes and then the feeding channel is turned into cooling passages during the cooling process of a casting after their functions of feeding have finished, as shown in Fig. 8(e). This method can realize inside-out, fast and even cooling of castings, which may meanwhile improve the production efficiency and reduce residual stress and deformation. The PSIRC method was further applied to the casting process of a stress frame specimen and a hydro turbine blade, and its effect on the cooling of the castings was investigated at the same time. The results demonstrated that the cooling speed of these castings increased apparently with improved temperature distribution uniformity, and the PSIRC method enhanced the strength and hardness of the blade casting meanwhile significantly reduced its residual stress.

Example 5, ablation-mold cooling. Grassi et al. [87, 88] firstly proposed ablation casting method, in which the sand was rinsed off by spraying water after the solidification of the casting and then the sprayed water directly cooled the surface of the casting, as shown in Fig. 8(f). Using this technique, high cooling rates for castings can be achieved, which thereby leading to better properties of the castings such as significantly reduced size of primary aluminum phase, refined eutectic silicon and needle iron phase, and significantly improved the performance of the casting. Taghipourian et al. [89] investigated the effect of delay time after melt pouring on the microstructure and mechanical properties of A356 aluminum alloy during the ablation casting process, concluding that the morphology of eutectic silicon and iron inter-metallic was improved and the dendrite arm spacing was reduced dramatically by applying ablation cooling. Boutorabi et al. [90] compared the microstructure and mechanical properties of plain carbon steel castings produced by conventional casting and ablation casting, finding that ablation cooling increased the ultimate strength from 638 MPa to 1,094 MPa and the tensile elongation from 13% to 16%. Similarily, Acar and Guler [91] applied two direct water-cooling techniques named as “quench casting” and “splash casting” respectively to the lost foam casting process of A356 alloy, and the results indicated that both methods changed the traditional casting microstructure and properties considerably. Wu et al. [92] prepared plate-shaped castings with high internal quality by using a combined ablation cooling and mold heating process, finding that the elongation of castings was about 3–5 times higher than that of the conventional sand castings.

Example 6, closed-loop and intelligent cooling control. However, the existing cooling methods for casting process described above lack the capability of continuously, intelligently and simultaneously controlling the cooling rates in accordance with the fluctuation of the local mold temperatures, and consequently are not able to solve localized thermal management problems which are currently present in most molds used in the industry. Besides, as the location-specific properties of a casting product predicted from its location-specific microstructure models that depending on location-specific cooling conditions, it is impractical to control mold temperature to a specific point due to the temperature fluctuation during cooling stages. Instead, controlling the mold temperature at a desired range is of great interest to the real casting process.

In order to achieve location-specific cooling control according to the differential cooling requirements, Kang et al. [93] proposed a concept of comprehensive closed-loop cooling control system that can be applied in intelligent casting process, as shown in Fig. 9. The system mainly consists of a shell to control the cooling of castings, a series of cooling nozzles or heaters arranged surrounding the shell, and temperature sensors embedded into the shell or attached on the surface. The applied devices can be connected to a control platform such as a programmable logic controller (PLC), with the nozzles serving as the actuator and the sensors serving as the input. In this case, the difference of the measured and set temperatures is used as the feedback to control the action of these cooling nozzles or heaters, which provides the possibilities to function at any required time and by any way according to requirements, such as continuously or intermittently. As for the cooling response, water, compressed air, liquid nitrogen, or other cooling media can be ejaculated from these nozzles to the shell surface. Finally, the comprehensive closed-loop cooling control of a casting can be realized, and its typical application scenarios include chilling the local areas of a casting to facilitate its sequential solidification, rapidly cooling the isolated hot spots to avoid local shrinkage in replacement of chills, heating the risers and thick areas to prolong their solidification, and afterwards fast cooling them to realize uniform cooling for less residual stress.

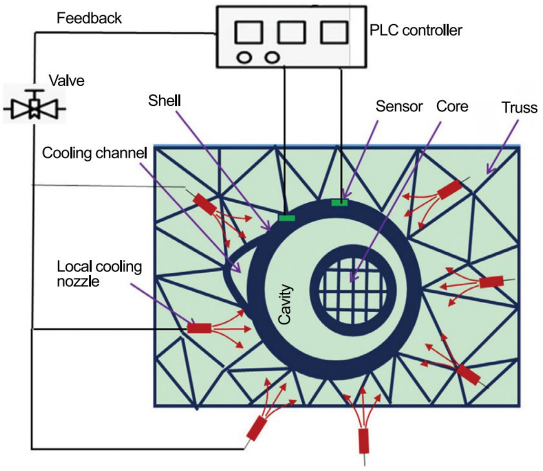


Fig. 9: Schematic diagram of comprehensive closed-loop cooling control system based on skeletal sand mold design [93]

4 Prospects of intelligent casting process

In the future, the intelligent casting process may primarily achieve three functions such as real-time status perception based on ubiquitous sensors with greater connectivity, intelligent process reasoning and decision based on AI enabled simulation or casting knowledge expert system, and intelligent process control based on smart actuators, as shown in Fig. 10. Take intelligent process control as an example, the intelligent control subsystems exchange information with actuators (including thermal, ultrasonic, electromagnetic, optical, mechanical, etc.) through communicating network, and drive the actuators to perform according to planned path. The coordinate matching and navigation system is used to monitor the feedback information of the navigation rod of actuators in real time, ensuring that the actuator operates correctly according to the optimal planning. Simultaneously, the actuators can be automatically charged when their power is lower than the set value. Particularly, it is worthy to mention that the intelligent mold systems are physical basis and carrier for realizing these functions. Thus, the intelligent mold systems, which can be integrated with various of sensors, control systems and actuators, may become one of the research frontiers and hotspots in the casting sector.

4.1 Intelligent status perception

The intelligent casting process relies on comprehensive process status perception. This will be achieved by configuring various sensors to acquire and analyze multi-source information, allowing for real-time understanding of the evolution process of key control variables during casting. Currently, several sensing systems can be deployed to collect information on environmental parameters, key process parameters, and equipment operating parameters in the casting process. For instance, data on temperature, air pressure, mold displacement, and liquid level in specific areas of the casting system can be collected. This information can provide valuable insights into the process status, serving as a reference and basis for optimizing the follow-up process parameters. However, there are challenges in achieving non-destructive comprehensive status sensing due to the high cost of sensors, the limited availability of sensors that can withstand severe working conditions such as high temperature and pressure, and the delayed response and low accuracy of sensors. For example, current parameters sensing in the casting process often lacks real-time responsiveness and accuracy, leaving many key processing information un-acquirable, such as microstructure, micro-crack, flow rate, parts thickness, strain, stress, and so on. Therefore, it is still necessary to develop advanced sensing devices and data analysis technology to collect and achieve

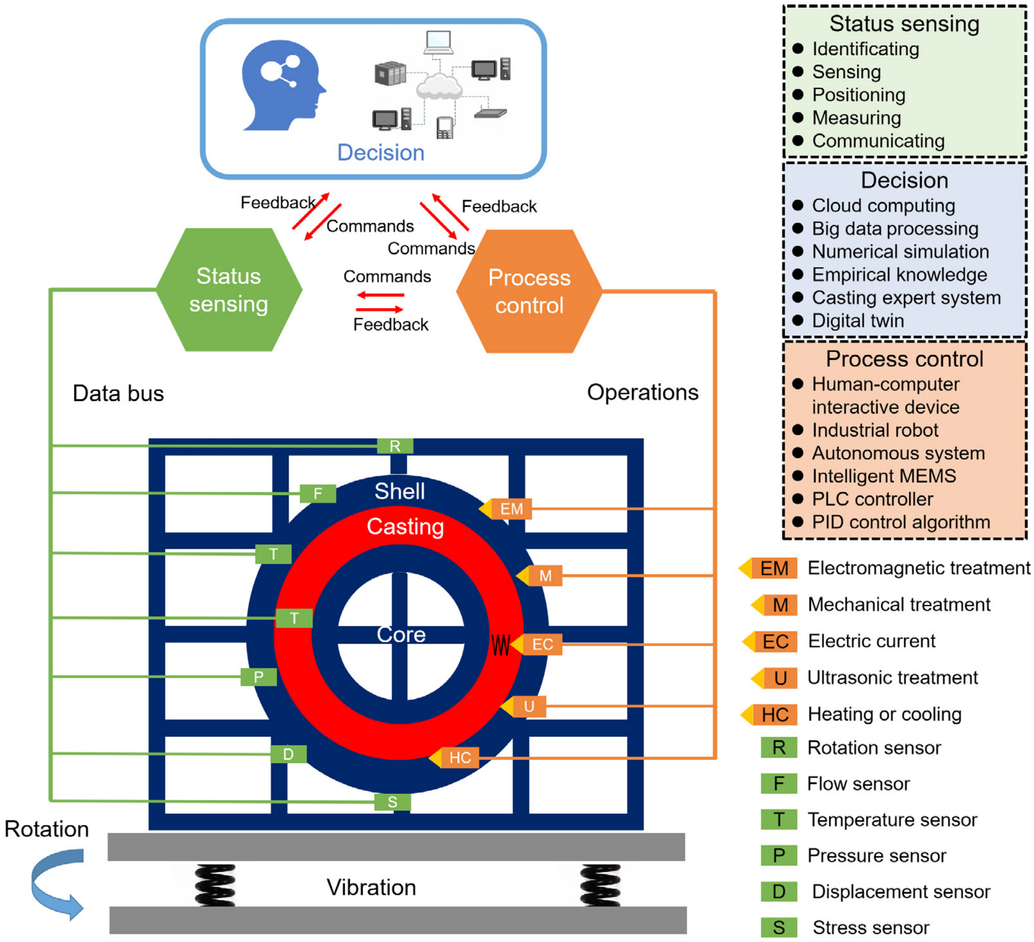


Fig. 10: Intelligent casting process based on intelligent mold system

more accurate and timely process information during casting practice. In the future, a vast sensing network with greater connectivity will be formed by the widespread utilization of high-temperature and high-pressure resistant sensors, both active and passive, contact and non-contact, wired and wireless, as well as devices of the industrial Internet of Things. The wide application of fast response, high data flux communication technology allows for online, in-situ, real-time measurement and monitoring of multiple physical parameters during the casting process. This technology may also enable autonomous intelligent perception and interaction based on smart devices that can communicate with each other and the outside world.

4.2 AI enabled simulation

For an intelligent casting process, the numerical simulation is expected to be highly accurate, fast, efficient, and capable of intelligent parameter setting and rapid analysis of results. With the increasing availability of computing power and off-the-shelf AI models for casting simulation, intelligent numerical simulation is becoming a reality as more AI models are incorporated in this field. More precise solving parameters, including fine boundary conditions, can be preset and controlled for every interested point at any required time. This allows for an independent understanding of the mapping relationship between input processing parameters and output simulated results. An example of intelligent simulation is the AI enabled numerical simulation. In traditional numerical simulation of the casting process, initial and boundary conditions typically remain constant or change minimally. However, this approach is time-consuming. Agile response to discrepant, quantitative, and customized controlling requirements of castings is often achieved by constantly adjusting the boundary conditions of the casting system, making them dynamic. Therefore, the numerical simulation must be embedded online and adaptable to meet the need for a quick response. The AI enabled numerical simulation aims to fast provide the simulated theoretical reference through dynamically predicting the temperature distribution, residual stress distribution of the casting-mold system. In order to avoid the disadvantages of time-consuming and inflexibility in numerical simulation, Han et al. [94] created a rapid predicting model for temperature fields in the solidification process of sand castings using U-Net network structure. The AI model they developed can realize rapid prediction of temperature field during the solidification process of sand castings with different shapes, as shown in Fig. 11. Furthermore, the advancement of virtual reality, augmented reality, and other digital technologies has led to stronger visualization capabilities in the numerical simulation of the casting process. This, in turn, enables intelligent decision-making and control during casting.

4.3 Knowledge-driven decision-making

Through the utilization of creative AI models and algorithms [95-97], analyzing extensive datasets obtained from the virtual or practical casting process can yield valuable insights that can be used in aspects of the intelligent design of casting system [98-100], the optimization of process parameters, the reliable prediction or improvement of casting quality [101-103], and the predictive maintenance during the life cycle of castings. In a narrow sense, intelligent decision-making in the casting domain is the interdiscipline of turning multi-source information into better

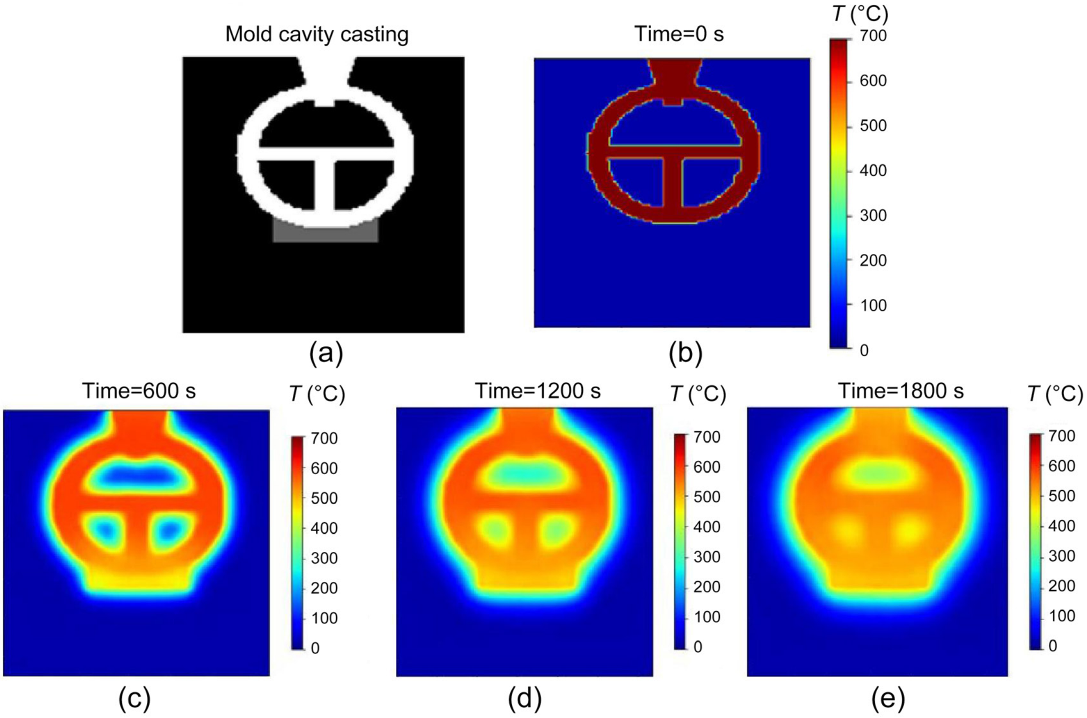


Fig. 11: Continuous prediction results of temperature field during casting process [94]: (a) mold cavity and casting geometry; (b)-(e) predicted temperature field contours of casting system at different times of 0 s, 600 s, 1,200 s, 1,800 s after pouring, respectively. The prediction time of a time step is less than 1 s

controllable actions at any scale. Intelligent decision-making is crucial for a cost-effective casting process. It involves making optimal or satisfactory decisions based on specific models or mapping relationships to improve quality and efficiency. This process relies on AI’s ability to fuse multi-source information and make informed decisions or recommendations for subsequent control actions. It can be widely used to automate and streamline operational tasks, enhancing productivity. Currently, both traditional and novel decision-making methods are used to optimize processing parameters during the casting process. However, most of these methods are conducted offline, resulting in limited efficiency. In the future, decision-making in intelligent casting processes should surpass traditional PLC control methods and be feedback-controlled, adjustable, and optimizable in real-time online. Moreover, the implementation of these functions relies on the advancement of multi-objective high-throughput information collection techniques, high-efficiency big data processing technologies, and other related technologies. Additionally, it requires the integration of online embedded simulation results with the adaptable application of offline casting process knowledge base systems. Finally, future intelligent decision-making should consider real-time status and constraints during the casting process. It should also make full use of offline casting process knowledge base systems and novel machining learning methods to achieve optimized decisions. This may require the development of more efficient and adaptable optimization algorithms and tools. It is hopeful that the current decision-making expert system will evolve into an intelligent casting decision-making system with self-learning, self-evolution, and self-upgrading functions. This system can be widely used in scenarios such as design consultation, material process selection, parameter optimization and setting, control process forecasting, quality prediction, and performance or defect analysis.

4.4 Intelligent process control

Intelligent process control is a critical aspect of casting process, aiming to achieve quick and accurate execution of optimized processing parameters. Automatic control technology has made remarkable progress and is widely used in casting process control, achieving automatic execution to some extent. However, during the casting process, actuators may experience vibration and deflection, which can introduce uncertainty and errors into the casting system. This can cause the implemented processing parameters to deviate from the ideal targets, resulting in a deterioration of the casting quality. In addition, advanced process control technologies, such as intelligent cooling control, are becoming increasingly available. However, the development of multi-axis collaborative actuators and new intelligent control methods, such as fuzzy-PID and fuzzy-neural network control, is still necessary to apply them to advanced equipment for process control. Furthermore, the increasing use of high-efficiency automated equipment, intelligent robots with improved feedback and response sensitivity, and advanced control systems enable fast and near real-time control of the casting process. The intelligent casting process utilizes online measuring and real-time analysis to determine the control mode. This is followed by automatic matching with an ideal simulation model and targeted solutions from a professional casting process knowledge repository. The process parameters are then intelligently implemented according to the post-optimized decision result. For instance, the intelligent cooling control, whose main feature is embodied in the differentiation, quantification, and precision of the cooling according to specific demand throughout the entire casting process, will realize the agile cooling control such as adjusting and controlling the cooling of the castings at anywhere, anytime through the utilization of all kinds of sensors and actuators.

5 Summary

Casting technology remains a prominent manufacturing process due to its technical vitality, social demand, and continuous innovation. With the increasingly fierce competitions in aspects of quality, cost and efficiency, the concept of green and intelligent casting has become a common consensus in academic and industrial communities. This concept mainly involves the greenization, automation, and intelligentization of the entire process. Intelligentization appears to be an inevitable course towards upgrading and innovating the foundry sector. Achieving an intelligent casting process is heavily dependent on the continuous advancements in 3D printing technologies, intelligent mold technologies, and process control technologies based on automatic systems and robotics. The intelligent mold system is the physical pillar of intelligent casting process. It provides opportunities for closed-loop, accurate cooling control in any interested areas of the casting at any specific time, resulting in improved cooling strategies, controlled stress and deformation, and reduced usage of molding materials. Although it may take many years before intelligent casting process becomes commonplace, it is hopeful that the smart hollow mold will be integrated with the Internet of Things, intelligent equipment and devices, intelligent decision-making and control subsystems, and other advanced technologies to form an intelligent cyber-physical casting system. It will play a key role in fulfilling the goal of real-time process optimization and control during casting process, and the microstructure, performance and service life of the fabricated castings can be predicted and prominently improved according to specific requirements.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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