International Journal of Precision Engineering and Manufacturing-Green Technology (2022) 9:305–322
https://doi.org/10.1007/s40684-021-00323-w

Online ISSN 2198-0810
Print ISSN 2288-6206

REVIEW PAPER

Integration of Additive Manufacturing in Casting: Advances, Challenges, and Prospects

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Received: 1 November 2020 / Revised: 28 January 2021 / Accepted: 9 February 2021 / Published online: 15 March 2021

Abstract

Additive manufacturing (AM) is a novel manufacturing technology that can create highly customized products with more complex geometries than traditional techniques. Despite its significant advantages, including the freedom of design, mass customization, and ability to produce complex structures, AM consumes a large amount of energy and incurs high costs. In addition, AM suffers from long production cycles and low production efficiency in the large-scale manufacturing of metal structures. This study offers a review of the existing literature focused on metal AM technology. To avoid the shortcomings of AM and highlight its benefits, which are widely used for manufacturing in combination with casting. The current combination application of AM and casting is reviewed to provide solutions to the problem of manufacturing large metal components from the perspective of the use of different AM technology and quality control in casting. However, such integration is insufficient for producing large castings with complex shapes, structures, or multiple features. Therefore, a novel method for integrating AM into casting to enable the manufacture of large scale metal parts with complex shapes is introduced as a topic for possible future research. This method divides complex castings with multiple features into an AM processing part and the casting substrate. The complex features were processed by AM on the fabricated casting substrate. This study provides a review of the application of AM into casting and presents a novel idea for the integration application of AM and other processes. This promising method has significant value for future study.

Keywords Additive manufacturing · Casting · Process integration · Multi-feature structure · Heavy castings

1 Introduction

Additive manufacturing (AM) is a 3D printing technology based on the discrete stacking principle that can be used to form complex structural parts owing to its flexible manufacturing features. According to the characteristics of AM, any complex digital model can theoretically be produced using AM [1]. This technology does not require auxiliary tools such as cutting tools or clamps, or the multiple processing procedures applied in traditional manufacturing. AM can be described as a "near net shape forming" process where most of the materials are used to form parts without utilizing any other auxiliary consumables. AM meets the development needs of green manufacturing [2]. Compared with traditional subtractive manufacturing processes, such as cutting and milling, AM has a high utilization rate and can achieve the purpose of saving resources that is one of the most important goals of green manufacturing [3, 4]. AM has worldwide industrial application including transportation, aerospace, industrial equipment, consumer electronics, medical treatments and construction [5–10].

Given these benefits, the rapid development of AM has received much attention. For instance, the "Made in China 2025" strategic plan highlights the importance of accelerating the development of AM and its related equipment. This technology has also been included in the "Classification of Strategic Emerging Industries 2018". A 2019 study on the 3D printing industry revealed that the 3D printing market scale of China reached 2.36 billion RMB in 2018, which has increased by approximately 42% since 2014, as shown in Fig. 1 [11]. The Wohlers report shows that the application of AM in the automobile, aerospace, and industrial machinery industries is increasing annually [12].

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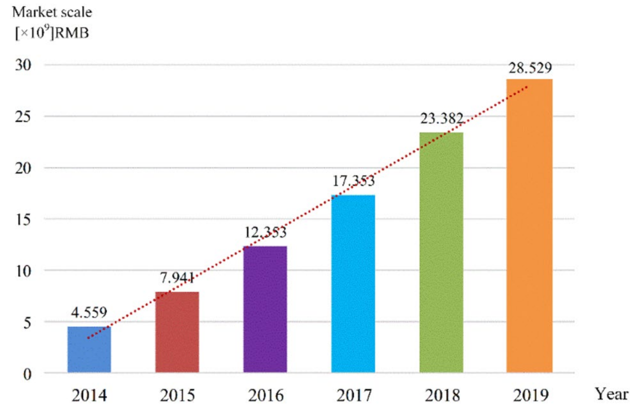


Fig. 1 Market scale and growth of AM in China from 2014 to 2019

Although AM can be used to produce large and complex parts, this technology uses a layering process which results in both high material consumption and high costs. In addition, AM suffers from a long production cycle in the large-scale manufacturing of metal structural parts. For instance, using AM to manufacture a central flange strip takes approximately one month, which is more than twice the manufacturing cycle of traditional technology [13]. AM also consumes a large amount of energy owing to its use of high-energy beams (e.g., laser, electron, and plasma beams). These shortcomings limit the application of AM in manufacturing large metal components [14].

Casting is generally applied in the large-scale manufacturing of metal components. The complexity and precision of the castings are determined by the mold. AM has also been widely used in casting processes, including sand, investment, and precision casting, given its ability to quickly fabricate molds that satisfy casting process requirements [15]. Accordingly, AM can improve the production flexibility, efficiency, product quality, and precision of the casting. This technology can also be used to rapidly produce small batches of single-piece casting [16].

To produce complex casting products with multiple features, the casting mold should be decomposed, as shown in Fig. 2. This decomposition process extends the duration of the manufacturing procedure and increases production costs. The accuracy of the mold and casting product are affected by the accuracy of the mold produced and the casting product is affected by the assembly of the multiple sections of the mold [17, 18]. Powder bed fusion is a kind of metal forming AM process that can be used to directly fabricate metal components with complex structures. Despite its many benefits, AM faces several shortcomings in the large-scale manufacturing of metal components such as long manufacturing cycles, large equipment size requirements, the problems of consistency in AM organization structure, and quality assurance problems in the manufacturing integration area [7, 19]. This paper attempts to address such limitations by integrating AM into the casting process.

2 Scope and Framework

2.1 Scope of the Review

AM technology is widely used in various fields as shown in Fig. 3 [20]. However, large-scale industrial 3D printing has been primarily focused on the processing and manufacturing of injection molds. In other areas, more samples are trial-produced using 3D printing in the research and development (R&D) stage. AM is a powerful and convenient means to convert ideas into real products quickly. When appropriate materials and technologies are selected, AM can produce complex structures (dot matrix, topology, creative design, etc.), which are impossible using traditional processing.

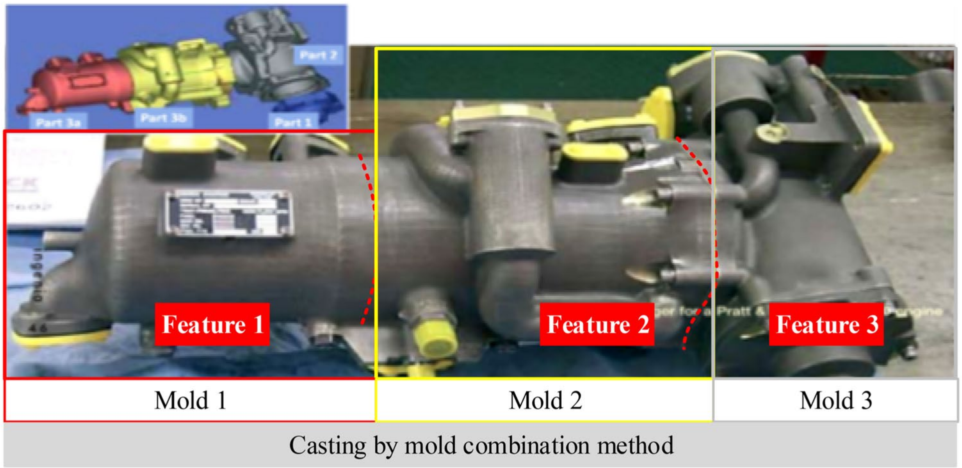


Fig. 2 Application of selective laser sintering (SLS) in engine casting process

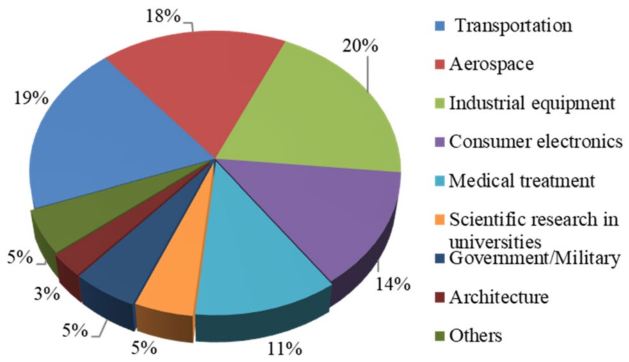


Fig. 3 Proportional distribution of 3D printing in various fields

Furthermore, AM is the optimum approach for producing small batches of flexible manufacturing scenarios.

AM technologies can be classified into seven categories according to their different forming methods and material types: (1) material extrusion, (2) powder bed fusion, (3) vat photopolymerization, (4) material jetting, (5) binder jetting, (6) sheet lamination, and (7) directed energy deposition [21]. Powder bed fusion is the primary AM technology for metal parts. It can be divided into direct metal laser sintering (DMLS), electron beam melting (EBM) and selective laser melting (SLM) according to the heat sources used in the processing. Metal AM is the focus of this study, and more attention is paid to the application of other AM methods in casting.

In this study, we review the latest research progress of metal AM technologies and the disadvantages of current metal AM in processing large structural parts. AM supports large metal parts casting by rapidly printing complex shape molds. The current major issues and challenges associated with the adoption of the AM mechanism in casting and forming quality controlled parts are discussed. Although the casting process has the advantage of manufacturing large parts, the manufacturing of large-scale parts with complex structure remains a challenge. To solve the problems associated with manufacturing large metal castings with complex structure characteristics, based on the previous research, this study proposes the corresponding fusion method of AM and casting process.

2.2 Framework and Methodology

To identify the advantages and shortcomings of AM in the manufacture of large-scale metal parts, AM is addressed from the perspective of AM in structure design, manufacturing advances of metal AM technology, quality control of AM in manufacturing metal parts. Since casting is known to be efficient for manufacturing large metal components, we reviewed the combination of AM and casting to provide solutions to problems found in casting alone. The research on the AM and casting application method, manufacturing process and quality control is discussed. We then provide future research suggestions for the challenges of integrating AM into the casting process.

In the production of castings with multiple features, defects are more likely to appear in the multi-feature structures. In addition to quality issues, the large-scale manufacturing process of metal casting using AM is slow and thus has low production efficiency, high energy consumption, and high costs. To solve these problems, a novel idea for the fabrication of large-scale metal components with multiple features is proposed in this paper. This methodological framework is shown in Fig. 4, which also provides an outline for this study.

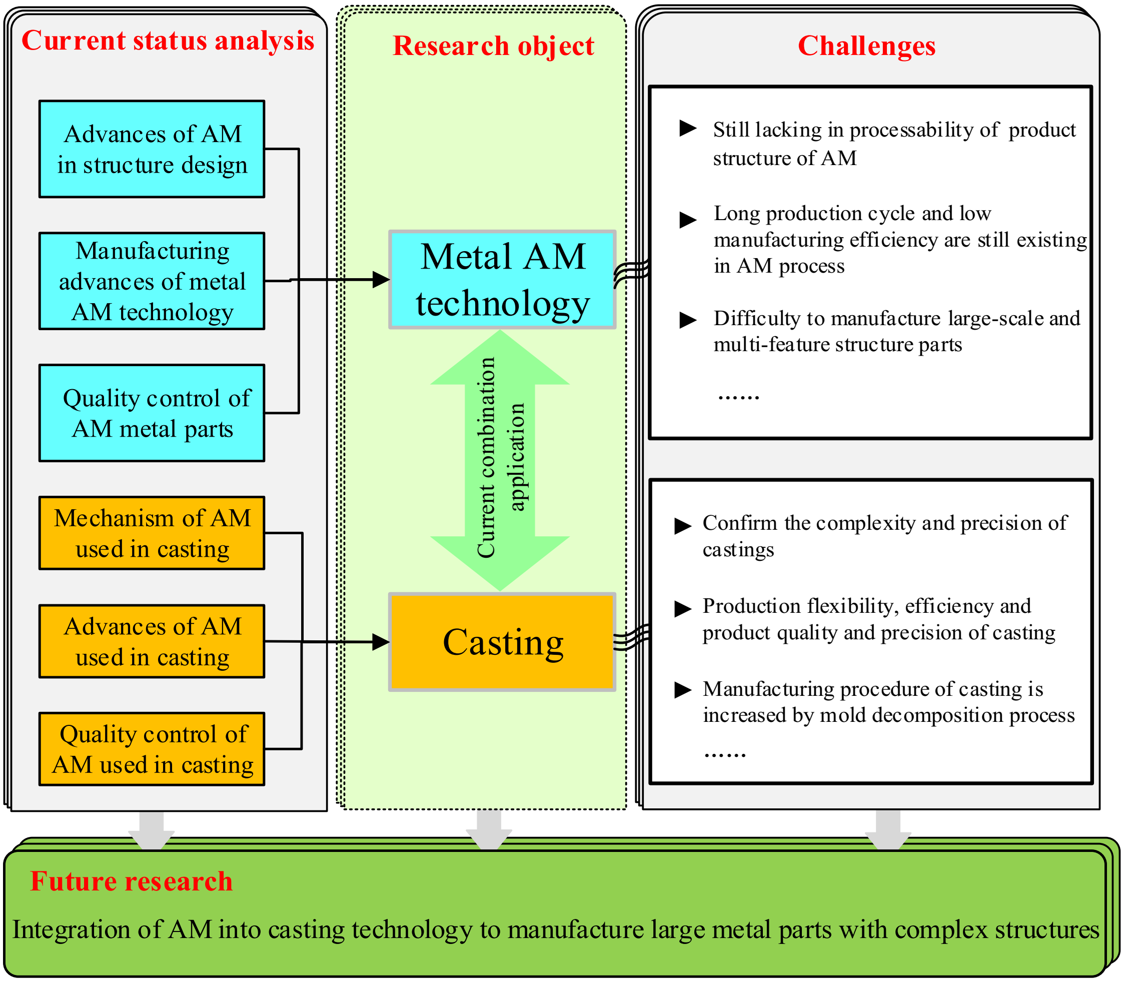
Recommendations for future research are proposed based on the findings related to the challenges in the application of AM in the casting process. The proposed research focuses on the forming mechanism and process control for the large-scale processing of multi-feature casting structures by the integration of AM into traditional casting process. To improve the production efficiency of large-scale multi-feature castings, the AM method is proposed to manufacture the complex manufacturing features of castings. The structural design method, the fusion mechanism, quality analysis, and the process control of integrating the AM into casting process are addressed in detail to show the feasibility of the proposed method. This work provides a reference for future studies on the integration application of AM and other processes.

3 Advances of AM in Manufacturing

Unlike traditional reducing, forging, and casting processes, AM can produce parts with complex shapes and improve the machinability of materials, thereby greatly expanding engineering applications. Given the layered stacking characteristics of AM, there is a significant difference in product design, manufacturing, and forming quality control when compared to traditional manufacturing methods. This section discusses the superiorities and drawbacks of AM in structure design, the advances of AM are addresses from metal parts manufacturing and quality control. The disadvantages of AM in manufacturing large-scale metal structural parts are also elaborated.

3.1 Advances of AM in Structure Design

AM is a "free manufacturing" technology that is not constrained by the structural complexity of products. Given the anisotropic material of AM parts [22], the influence of the manufacturing process on product structure design and



- Still lacking in processability of product structure of AM
- Long production cycle and low manufacturing efficiency are still existing in AM process
- Difficulty to manufacture large-scale and multi-feature structure parts

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- Confirm the complexity and precision of castings
- Production flexibility, efficiency and product quality and precision of casting
- Manufacturing procedure of casting is increased by mold decomposition process

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Integration of AM into casting technology to manufacture large metal parts with complex structures

Fig. 4 Methodological framework

forming quality should be examined [23]. In large-scale equipment manufacturing, a slide-in large-scale hydraulic press is manufactured by welding a steel plate component or casting. A lightweight design can be achieved using the complex layout of internal stiffeners in the slide that is redesigned via topology optimization, as shown in Fig. 5 [24]. This redesigned structure, which has poor manufacturability, can only be manufactured using AM.

The design of AM is more complex than that of traditional manufacturing, and the shape, material, level, and function of AM products must be considered in the manufacturing process [25]. Product design requirements and manufacturing characteristics should be considered in AM [26]. And the relationship between the complexity and efficiency of innovative products in AM design should also be analyzed [27]. Compared manufacturing- and function-driven design strategies for AM, the results show that the function-driven design is more suitable for the AM design process than the former [28]. Konstantinos et al. proposed combining product function with traditional design methods and combining manufacturing design guidance, AM manufacturing process capability and the topology optimization principle. A multi-criteria decision optimization design method is then applied to select the optimal design [29]. And AM design feature database to support AM design and meet the product design and manufacturing requirements is seriously needed [30, 31].

To slim the amount of material consumed and improve AM product quality, the structural optimization design method for AM can be used to optimize the internal pattern and support of cast products [32, 33]. By using a self-supported AM material in the topological optimization design (Fig. 6b) [34, 35], the topological optimization structure of unsupported AM can be realized [36]. The optimal printing direction can be identified by evaluating the manufacturing time and the materials consumed in each feasible geometric building direction [37, 38]. When deemed necessary, support can be used as a constraint in the topology optimization process to optimize the internal pattern and support of products, as shown in Fig. 6a. By supporting the same part

Fig. 5 Topological optimization for the slide in hydraulic press under different manufacturing requirements

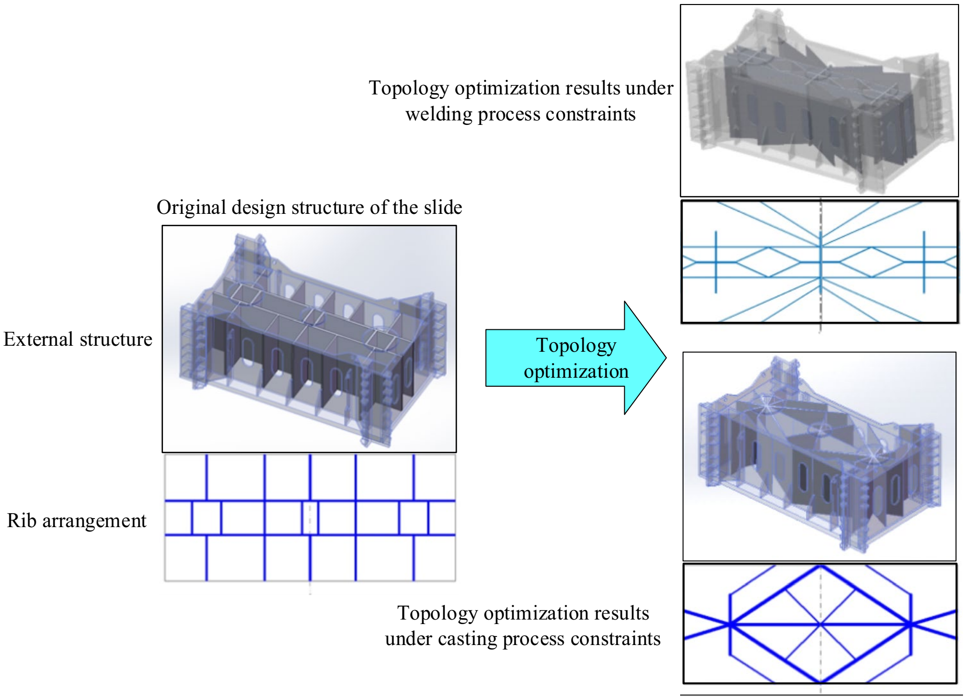
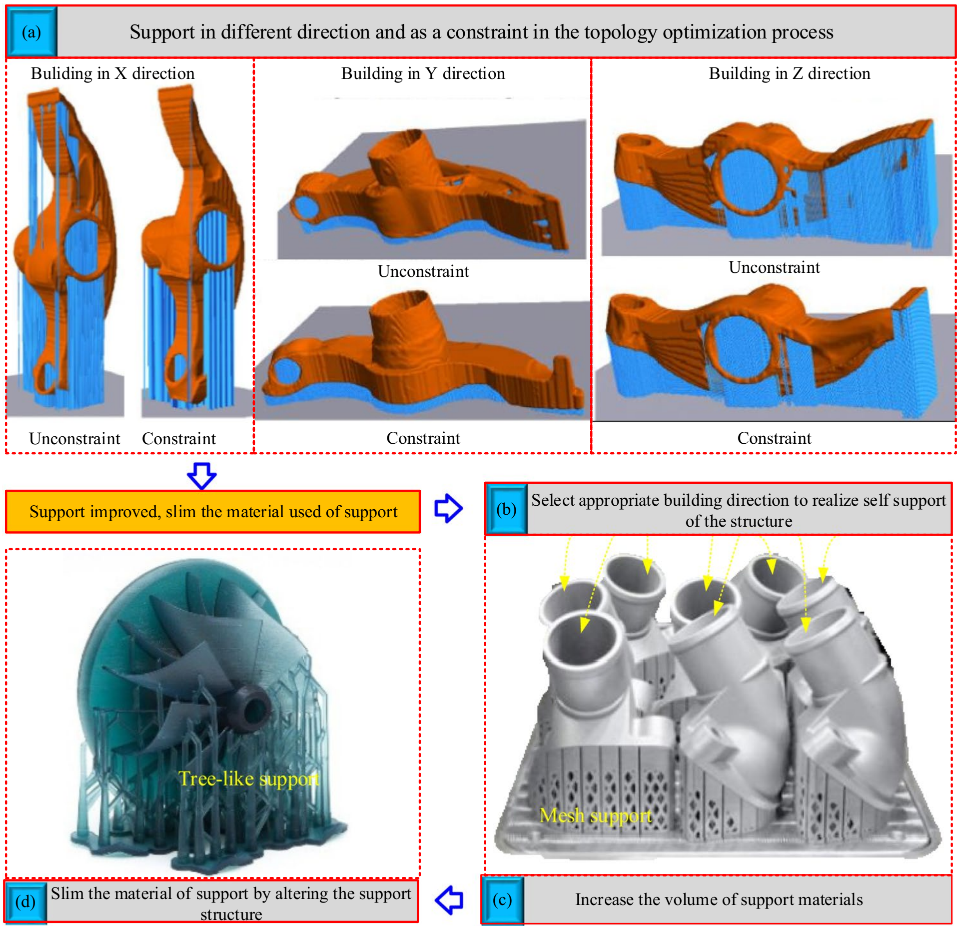


Fig. 6 Support optimization in AM



in different building directions under constrained and non-constrained conditions, the volume of support materials can be increased to improve the quality of products, as shown in Fig. 6c, d [39]. The external suspension structure of the AM part can also be optimized by adopting a topology design [40]. Previous studies have shown that the manufacturing friendliness of topology optimization can be improved by applying a smooth approximation method to constrain the surface of the external suspension structure [41]. Xu et al. proposed a topology optimization algorithm that determines the 3D printing minimum volume based on the progressive structure optimization method and von Mises stress calculations [42, 43].

AM can create more freedom for designers and prioritize the design from the perspective of function, which makes some parts manufacturable that were previously known to be difficult using traditional technology. However, for large parts with hollow structures, the addition of support structure increases the consumption of materials which increases the difficulty of post-processing parts. AM design should include the forming characteristics of AM and incorporate the advantages of manufacturing complex part structure to meet the product functions.

3.2 Manufacturing Advances of Metal AM Technology

For the creation of functional parts, powder bed fusion (PBF) methods use either a laser or electron beam to melt and fuse metals, alloys or material powder together in the presence of a vacuum [6]. To avoid defects, the structure, manufacturability, quality, and precision of products should be evaluated before the manufacturing stage. During the manufacturing process, the formation performance of various materials, the formation mechanism of AM, and the influence of various process parameters on the forming quality must be considered [44]. After the manufacturing process, post-treatment should be implemented to remove the supporting materials and the processed metal parts should be subjected to heat treatment. The following sections describes the advances of metal AM technology during the pre-manufacturing, manufacturing, and post-processing stages.

A virtual design can effectively improve the process efficiency of metal-based AM before the manufacturing stage. Meanwhile, the process parameters can be effectively optimized using the finite element method [45, 46]. The manufacturing direction and path significantly influence the forming quality and support of AM products. Yu et al. proposed a method for automatically generating the printing path, while considering both machining efficiency and manufacturing accuracy [47]. This method aims to solve the problems in generating a parallel direction path that is used to fill internal simple connected areas. Marijn et al. proposed a feature-based design algorithm that selects the printing direction via ray tracing and the convex hull method, based on an automatic recognition of the surface subdivision and detection of the outer surface [48]. Ratnadeep et al. analyzed the influence of printing direction on cylindricity and straightness error and then proposed a multi-objective calculation method to reduce the support structure under the premise of ensuring minimal cylindricity and straightness error of parts [49]. To address the problem where multiple parts (with similar or different geometries) are processed simultaneously, Yicha et al. used the directional optimization method based on AM features to optimize the generation direction of each part under the premise of confirming the quality of products. They also reduced the production time and cost using their own parallel nesting algorithm [50].

Directed energy deposition (DED) uses focused thermal energy (e.g., laser, electron beam, and plasma arc) to melt the material as it is deposited [51]. Similar to DED, SLM is an example of a typical metal AM process that can form nearly full dense metal parts with complex shapes and suitable mechanical properties [52]. Metal AM technology has received significant attention in the manufacturing of precision and complex metal parts [53]. The microstructure and properties of different materials, including their mechanical properties, grain size, and microhardness, have been analyzed in previous research [54–56]. Different processing parameters, including scanning speed [57], laser power [58], scanning path [59, 60], forming direction [61, 62], and temperature [63, 64], have important effects on the microstructure, mechanical shape energy, and material structure of SLM parts [65]. In studying the thermal behavior of SLM, numerous factors were considered, including the temperature evolution behavior at different positions, influence of exposure time on temperature evolution behavior, temperature distribution, and molten pool size at different positions. These aspects were examined via simulation and heat transfer modeling [66–68]. Many other scholars have compared metal AM with casting technology and analyzed the microstructure, residual stress, and various internal defects of samples [69, 70]. Figure 7 demonstrates the metal AM mechanism and contents of related research.

The post-treatment for AM affects the final quality of products, including their surface characteristics, residual stress, and residual porosity [71–73]. The microstructural evolution and mechanical properties of products under different heat treatment conditions can be investigated via optical microscopy, scanning electron microscopy, X-ray diffraction, neutron diffraction, and tensile tests. The residual stress and deformation caused by laser cladding of metal powder can be partially eliminated by machining [74]. The blank density of parts can be increased by implementing a variety of post-treatment processes,

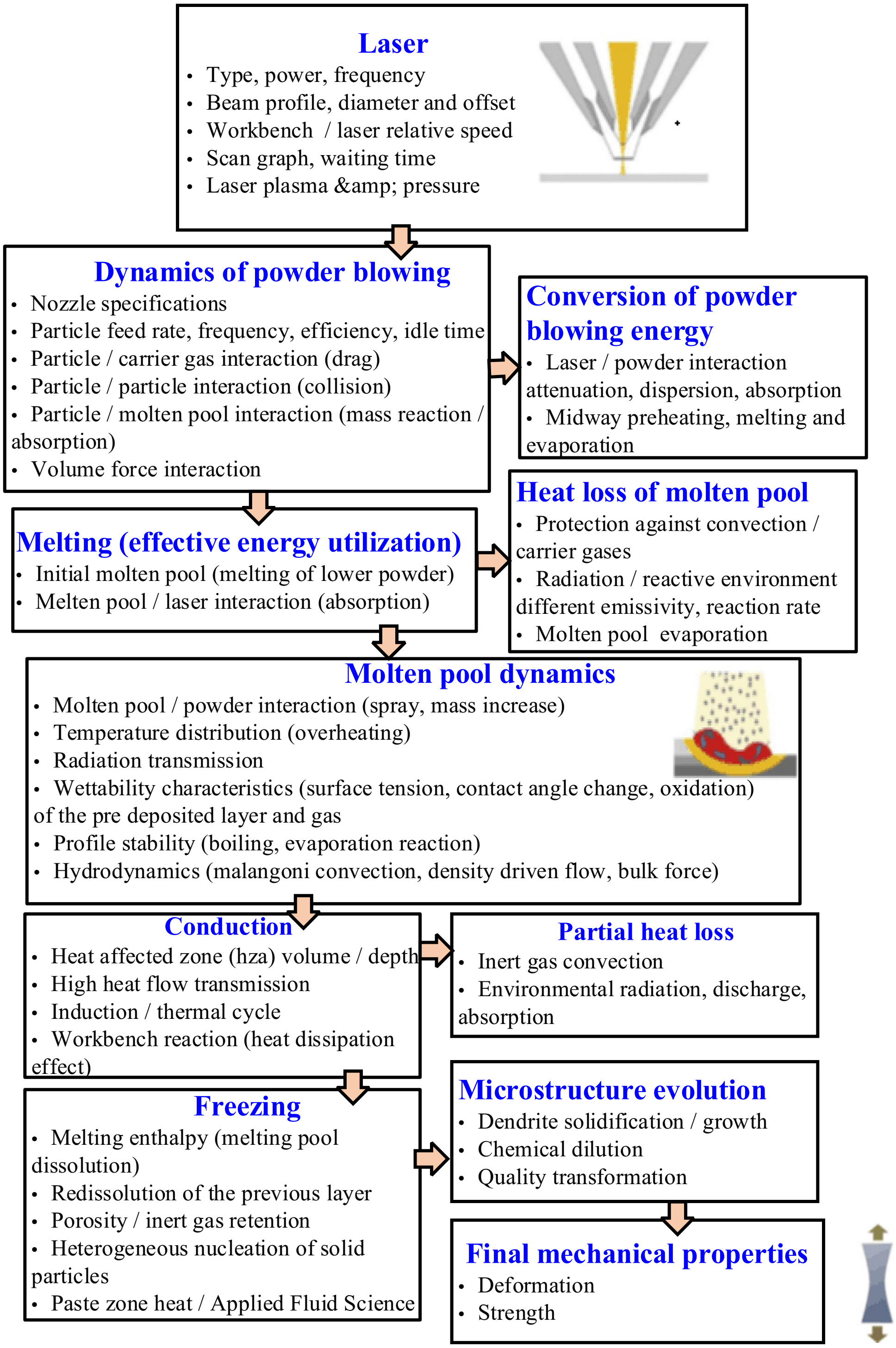


Fig. 7 Main research contents and mechanism of metal AM process

such as pressure infiltration and warm isostatic pressing (whipping) [75]. Additional support structures should be removed during post-processing. Kobryn et al. used multi-axis machining equipment to automatically generate a bracket removal process plan with the goal of disconnecting the contact area between each support component and the parts, and then, eliminating the surrounding support structure in the most economical and effective manner [76].

Although the AM process generally produces semi-finished products, those products still require additional traditional processing (CNC, grinding and polishing, plating, dyeing, etc.), which diminishes the advantages of AM in earlier designs. This lack of efficiency, as well as other diminishing aspects of AM technology, affects the large-scale implementation of AM in the manufacture of large and complex metal components.

3.3 Quality Control of AM in Manufacturing Metal Parts

Metal AM is similar to welding in that the defects, including pores, inclusions, lack of fusion, and cracks, are almost inevitable [77]. AM parts are stacked layer by layer and a large anisotropy may be observed in the internal materials of these parts. Therefore, appropriate testing and evaluation methods should be devised to prevent defects in the manufacturing and use of AM products.

Nondestructive testing technologies, such as ultrasonic testing and industrial rays, can be applied to detect the internal and service qualities of AM products [78]. Material density, elastic parameters, porosity, residual stress distribution, and various internal discontinuities can also be evaluated via nondestructive testing [79]. However, the current radiographic tests for AM remain insufficient, and AM products are still inspected, following the processes of other similar forgings or castings. In this case, a set of matching detection methods and systems that consider the particularity of AM parts in the detection process must be devised. In terms of use and acceptance level, the acceptance parameters in various aspects should be adjusted by considering the microstructure particularity. Eleven ASTM standards for AM, including specifications for AM document processing, data reporting, and evaluating metal powder performance characteristics, have been formulated and issued by the technical committee of AM, F42. More than 10 new standards are still under development [80–82].

AM technology enables products to meet the maximum functional requirements in the design process. The advantages of AM are only evident in the manufacturing of small and complex structural parts. Manufacturing large mechanical parts consumes a large amount of energy owing to the use of high-energy beams, with long production cycles and low manufacturing efficiency. Although AM has optimized topology for large structural parts, AM technology is being studied for use in direct forming. Traditional forging and casting processes are still used for manufacturing large metallic structural parts in engineering practice. The fabrication of large-scale and multi-feature mechanical parts by AM remains a challenge. The combination of AM with other traditional processes highlights the advantages of this method and addresses its low processing efficiency and high costs [83–86].

4 Application and Challenges of AM in Casting

Casting is an efficient means in manufacturing large metal components. The combination of AM and traditional casting create a new process—rapid casting [87]. Rapid prototyping technology is directly or indirectly used to manufacture molds of different materials, cores or shells for casting, and then used traditional casting process to quickly from cast metal parts [19]. In rapid casting, the difficulties in mold fabrication of traditional casting are solved using AM [88]. The mold fabrication cycle has been shorten, and precision and longer life of molds are improved than traditional casting. Rapid casting technology can improve production efficiency and is suitable for small batch production of various metal parts. This practice has been widely adopted in manufacturing metal castings in the aerospace and automotive industries.

4.1 Mechanism of Different AM Technology Used in Casting

Previous studies have examined three ways of combining AM with casting, namely direct casting, primary conversion casting, and secondary conversion casting methods, as shown in Fig. 8 [89]. These methods are described in detail as follows.

1. Direct casting is primarily used in the manufacturing of single parts. In the casting process, the direct-casting mold shell is directly fabricated and treated by AM. Subsequently, a preheated alloy liquid is poured into the casting shell (Fig. 8). The parts are extracted after solidification and cooling.
2. Primary conversion casting is primarily used in manufacturing single and small batch parts. In this process, a rapid prototyping (RP) prototype is fabricated by AM and applied to all types of traditional castings (Fig. 8). The required parts are obtained via direct casting.
3. Secondary conversion casting is primarily used in manufacturing batch parts. In this casting process, an RP prototype is initially manufactured by AM, and then elastic materials, including wax and silicone rubber, are injected into the RP to obtain a set of deformable molds. Given that the deformable mold is easily removable, complex alloy parts are manufactured by combining the deformable mold with traditional casting (Fig. 8).

Stereolithography apparatus (SLA), selective laser sintering (SLS), fused deposition (FDM), and laminated object manufacturing (LOM) are widely used in the

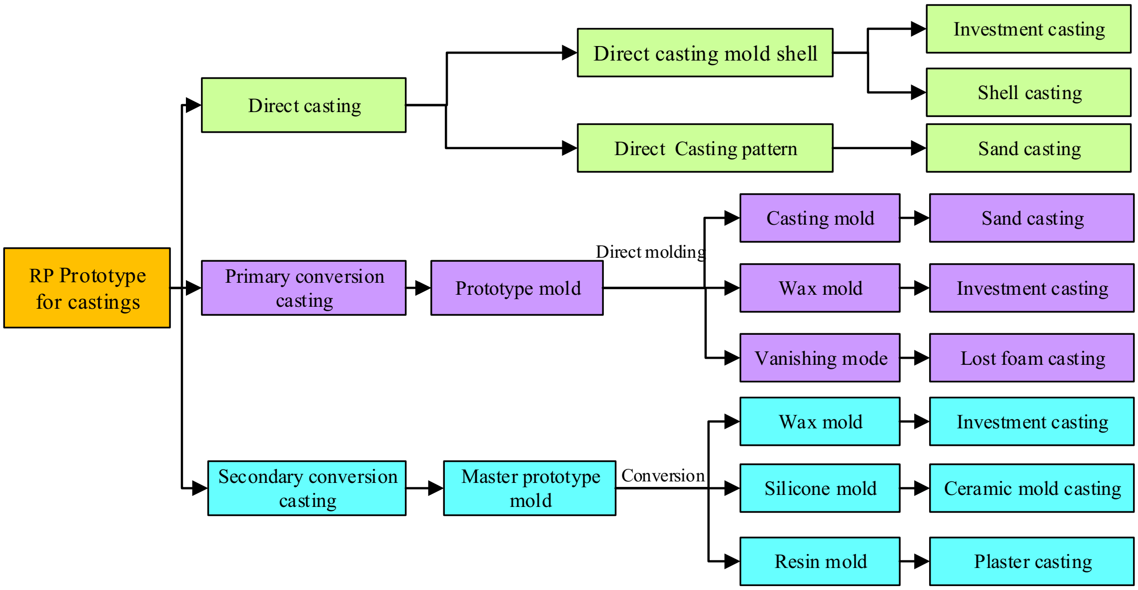


Fig. 8 Rapid casting and its application

Table 1 Performance and characteristics of different AM methods used in casting

AM method	Prototype material	Manufacturing costs	Processing speed	Prototype precision (mm)	Metal casting precision	Application in casting
SLA	Photosensitive resin	High	Fast	±0.1	CT4-7	Sand mold, investment mold, plaster mold, ceramic mold
LOM	Paper, plastic, composite materials, etc	Low	Relatively fast	±0.125	CT4-7	Sand mold, plaster mold, ceramic mold
SLS	Coated sand, paraffin, PS powder, ceramic powder, etc	High	Slow	±0.1	CT5-8	Sand mold, investment mold, metal mold, ceramic mold
FDM	Paraffin, nylon, ABS, PLA, low melting point metal, etc	Medium	Slow	±0.128	CT4-8	Sand mold, investment mold, plaster mold

casting process. Table compares the performance and characteristics of the different AM methods used in casting. Among the methods listed in Table 1, SLS and SLA are used to print wax and resin-based molds in investment casting, respectively.

Meanwhile, FDM and LOM are often used to print plastic ink and paper-based molds in sand casting and directly manufacture sand molds in casting. The manufacturing of the casting mold can be simplified using AM. Accordingly, the four processes of pattern manufacturing, molding, core making, and molding in traditional casting can be skipped, thereby significantly improving production efficiency. The characteristics of rapid and traditional casting have been analyzed and compared in many studies. Nishant et al. found that AM outperforms traditional sand mold casting in terms of material consumption, freedom of design, cleaning of castings, and mechanical properties of products [90]. Chen et al. used a porous alumina ceramic of alumina fiber as raw material for direct solidification and injection molding and then addressed the problems related to the manufacturing and composition uniformity of multi-empty ceramic components with complex shapes via a joint application of AM and casting [91].

The previous applications of 3D printing in casting have mainly focused on the rapid manufacturing of molds, direct printing of metal products, and reparation of defects. From the analysis of the AM application mechanism with casting, it can be determined that the current method of AM enables the manufacture of quick-processing molds that improve the productivity of castings and reduce costs. However, AM may supplement or partially replace casting methods, whereas some castings may be printed directly with titanium, nickel, and steel metal powders. In the future, the entity structure of castings and molds will be redesigned as open truss or space frame structures by AM [92, 93].

4.2 Advances of AM Used in Casting

3DSP is a relatively new AM technology that can directly fabricate complex sand molds and sand cores without any tooling requirement for sand casting. 3DSP has many advantages including: the ability to reduce shrinkage by allowing casting in the appropriate direction without requiring a hard mold, ability to shorten the delivery cycles by making it easier to nest multiple parts into one mold, ability for hybrid molding by integrating 3DSP with traditional mold manufacturing, and ability to manufacture complex mold-free castings separately [94]. Sama has developed non-conventional design rules for gates and feeding (also known as rigging) to improve casting performance (i.e., filling, feeding, and solidification). The improved casting performance is illustrated by systematically redesigning each element of the rigging system. The melt flow was numerically simulated to assess the effectiveness of the redesigned rigging system. The results show that the 3DSP can impact part performance, i.e., optimize metal casting designs via 3DSP, and drastically improve the casting performance, which could potentially transform the industry of sand casting to produce high quality castings [95]. Real-time on-line monitoring of core movement in metal castings is realized by using direct digital manufacturing. 3DSP reduces the complexity of mold and core design. Using 3DSP, precisely sized and located pockets were manufactured inside of cores [96].

Conventional AM can be applied to all stages of the casting process, including printing the wax mold, the ceramic shell, the sand core, and the sand mold [92]. Laser AM can produce high-density metal parts and can be used in manufacturing molds and models. For those parts with cavities, Bassoli et al. applied 3D printing and casting technologies to form their outline structure and inner cavities, respectively [97]. Mohammeddeng et al. fabricated thin-walled parts and complex shapes using casting and AM [98]. Froes applied AM and casting to reduce the weight and material density of aircraft parts [99]. A new type of nano MgO reinforced alumina based ceramic core was prepared by direct application of AM technology, which shows that AM is effective in rapidly manufacturing alumina-based ceramics with high strength, low shrinkage, and high quality [100]. Rogov et al. used plasma electrolytic oxidation technology to improve the properties of 3D printing and casting AlSi12 alloy substrate [101]. Balyakin introduced the process of accelerating the investment casting process by determining the optimal temperature conditions and cooling time by comprehensively applying AM technology and thermal image analysis technology. Ultimately, it reduces the duration of the production cycle and the cost of the finished product, while retaining quality characteristics [102]. AM technology of high-quality steel can meet the requirements of high-pressure casting and other high-quality die inserts, which can then improve the manufacturability of parts [103]. Therefore, metal AM technologies has a speed advantage in small batch casting productions and has an advantage for the research and development of a certain type of project verification, such as automobile, aerospace, aviation, mechanical equipment industry, etc.

4.3 Quality Control of AM Used in Casting

In establishing quality control for casting parts, the properties of the material (e.g., metal) and the formed castings should be considered. Because the quality of casting molds directly affects the quality of the final castings, the application of AM in casting process focuses on improving the forming quality of casting molds.

With sand mold casting being the most widely used, AM has been widely studied to improve the forming quality of sand molds. Sand molds can be manufactured by binder jetting process with complex metal geometry. However, different 3D printing material media affect the quality of casting products. Snelling et al. studied the potential difference of two different 3D printing media on material properties (microstructure, porosity, mechanical strength) of A356-T6 casting [104]. Combining AM and lightweight technology with integrated computing material engineering (ICME) tools and the latest strain-life fatigue data, the casting process can be optimized. Shah et al. discussed this technology applied to the design and optimization of thin-wall ductile iron sand castings with 3D sand printing (3DSP) AM technologies [105]. Upadhyay et al. compared the characteristics of a sand mold printed with inorganic sand with those of a model printed with organic powder and found that some printing parameters significantly influence the characteristics of trial samples [70]. Hodder et al. used traditional and nonstandard casting sand for 3D printing materials, but their models were suboptimal owing to limited compaction [106].

To improve the precision and quality of the casting mold, Bryant studied the influence of machine settings on the physical properties of 3D-printed sand [107]. Two factor matrixes were constructed to directly measure the effects of six settings on resin content and compaction characteristics of bonded sand. The factors include: X-resolution, printhead voltage, layer thickness, and the frequency, speed, and angle of the recoater blade. The responses included density, permeability, strength, scratch hardness, loss on ignition, and print resolution. Several relationships between the machine settings and the physical properties of the product were proposed, providing inputs for mold manufacturing. Sapkal et al.

used a pneumatic impact test to analyze the size change, the abrasive wear pattern of FDM printing and the resultant strength for sand casting. To improve the service life of the 3DSP casting mold, two different post-treatment methods, electroplating and wear-resistant coating, were also investigated by Sapkal [108].

The optimization of process parameters can effectively improve the mold performance. Through a case study, Kafara discussed the influence of the amount of adhesive used in 3D printing on the dimensional accuracy and resilience of manufacturing samples and used optical metrology methods based on fringe light projection to analyze the dimensional accuracy [109]. It is crucial to determine the relationship between process parameters and sand mold performance to produce molds where there are numerous requirements, such as strength, permeability, stiffness, reduction of gas emission during casting process, and minimization of combustible material quality in mold. Therefore, an excellent casting can be produced by improving the process of liquid alloy filling and solidification and is therefore a suitable tool for foundry workers. The relationship between printing parameters and mold performance is used to optimize the strength and permeability of these molds to provide accurate boundary conditions for solidification simulation before casting a test article [110]. Wang et al. used SLS and SLA to print impeller wax molds with complex structures to shorten the production cycle and prevent surface shrinkage and internal defects by optimizing the pouring system in the casting process [111]. Le et al. combined AM technology and proposed a new method for optimizing sand mold design which responds to a shell. Since the cooling rate is related to the dendrite arm spacing, they parameterized the shell to have a specific cooling rate configurable by changing the thermal conductivity and shell thickness to control the ultimate tensile strength and hardness. Their cooling simulation provides a new method for mold design [112, 113]. Garzón et al. studied the possibility of reducing the cost of AM metal products using binder jetting to form a gypsum mold of metal casting parts. The structure and temperature strength of their model were improved using different infiltration and post-treatment parameters [17].

The review of research demonstrates that the primary method to improve the formation of quality of castings is by combining AM with casting to improve the quality of AM manufactured molds. For complex multi-feature casting structures, deficiencies remain in the research methods for producing large castings with complex shapes and structures or having multi-features. Therefore, the rapid manufacturing of large multi-feature casting remains an important research topic which needs to be solved urgently.

4.4 Challenges of the Combination of AM in Casting

As mentioned above, combining AM with casting can improve the production efficiency and reduce the cost of castings. However, using this combination in manufacturing large-scale castings with complex shapes, structures, and other features remains largely unexplored.

Previous studies on the combination of AM and casting have primarily focused on how AM can be used to fabricate casting molds to improve casting flexibility and shorten the mold preparation cycle. However, these studies only applied AM to form the casting mold. To produce large castings with complex shapes and structures or with multi characteristics, using the current AM or casting process alone still has some shortcomings, including long production cycles and the likelihood of forming defects. If the casting parts are divided into complex structures and casting substrate, which are fabricated by AM and casting processes respectively, the problem can be solved. However, there are few scholars involved in researching the integration manufacturing method of the same part processed by two manufacturing processes simultaneously.

One of the challenges faced by AM in casting include the use of the powder feeding laser for direct deposition on metal components. Although there are many research results on the forming modes and mechanisms, the research still lacks focus on the material fusion mechanism, deformation behavior, forming law of multi-feature large metal components as processed by the integration of laser AM and casting, and the influence of thermal / mechanical coupling mechanisms on forming quality.

The structural characteristics and design methods of the multi-characteristic structure processed in the junction of the two processes are yet to be determined. Currently, although there has been research into the structural technological characteristics of AM and the casting processes, more research into the structural design methods for the integration of the two processes is necessary.

The forming quality analysis and evaluation mechanism of the integration of AM and casting process is unspecified. At present, the research on the forming quality analysis and characterization methods of AM in casting parts is difficult to effectively support the evaluation and characterization of the forming quality of the two process integration parts.

5 Future Research of Integrating AM into Casting Process

In the manufacturing of large and complex castings, if the substrate casting matrix is manufactured via traditional casting, then complex casting features may appear on the casting substrate when the laser AM method is applied.

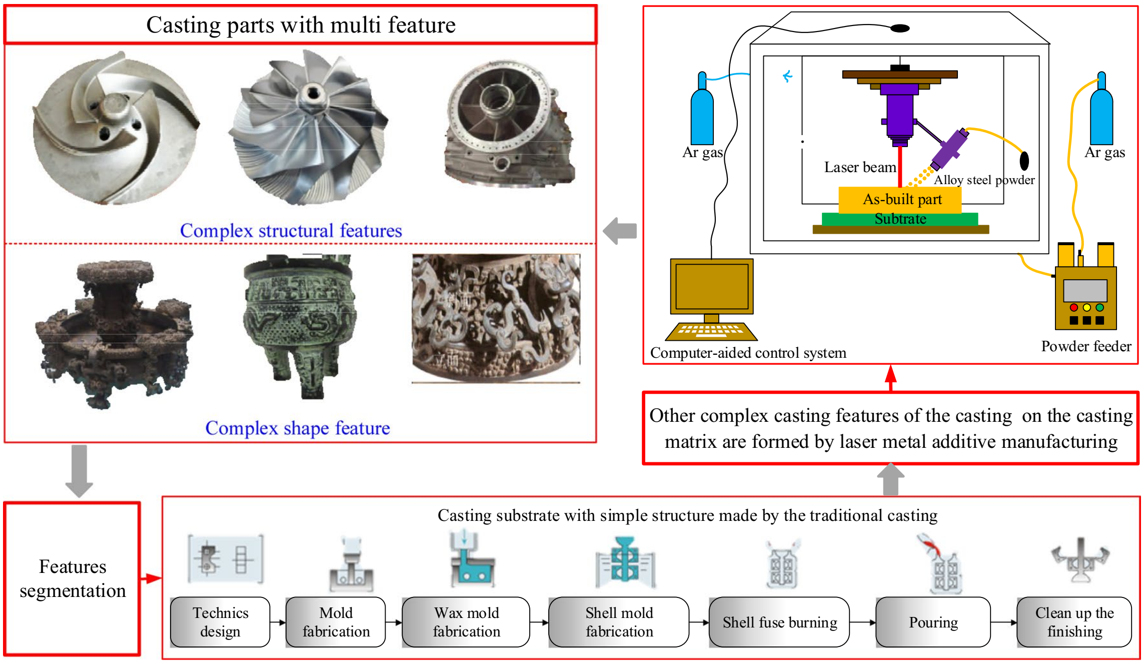


Fig. 9 Complex casting parts manufactured by integrating AM into the casting process

The practical methods and manufacturing processes are illustrated in Fig. 9. Accordingly, the preparation cycle of a multi-feature casting mold can be diminished, the manufacturing accuracy of complex structural features can be improved, and some defects in the key casting features can be avoided.

When integrating AM into the casting process, the feature segmentation of casting parts with multiple features should be considered. The division of the entire casting part into casting substrates and AM features is a design problem that needs to be addressed before the manufacturing process. The process fusion mechanism of AM and casting is another issue that needs to be considered when using AM to form complex features on the casting substrate. The product quality should be evaluated after the manufacturing of all parts by detecting the formation of defects and controlling the forming quality.

Based on the findings of previous research, several recommendations for future study on the integration of AM into the casting process are proposed. The overall research route is shown in Fig. 10. The challenges related to the integration of AM in casting processes are considered and possible solutions to address them are provided in the following recommendations.

1. *Structural design method for the location of the fusion of AM and casting substrate* By considering the structural and processing characteristics of the original castings, the casting feature segmentation can be separated into AM features and casting substrate. The parameters of various features on the casting substrate, including their positions, sizes, shapes, and cross-linking structures, should be analyzed to address the influence on forming quality. The structural parameters affecting the material mechanical properties at the location of the fusion between the AM and casting substrate can be analyzed via correlation, dimensional, similarity, and sensitivity analyses.
2. *Fusion mechanism of the multi-feature casting structure and AM process* To study the fusion mechanism of the two processes, an experimental platform of laser AM for multi-feature casting structures should be built. The casting substrate is fabricated based on the structural parameters obtained via the structural design method for the two processes. The constraint effect of the casting substrate on the AM process should be explored. Subsequently, the processing and forming methods of the AM and casting process integrated method can be analyzed. To reveal the molten pool and metal crystal forming mechanism at the fusion zone, the effects of AM methods on the molten pool, crystal morphology, and deformation behavior of the molten pool metal materials can be explored. To explore the distribution law of the temperature and stress fields in the forming process of the fusion part, the thermal and stress behaviors of the AM manufacturing of the multi-feature casting structure should be analyzed.

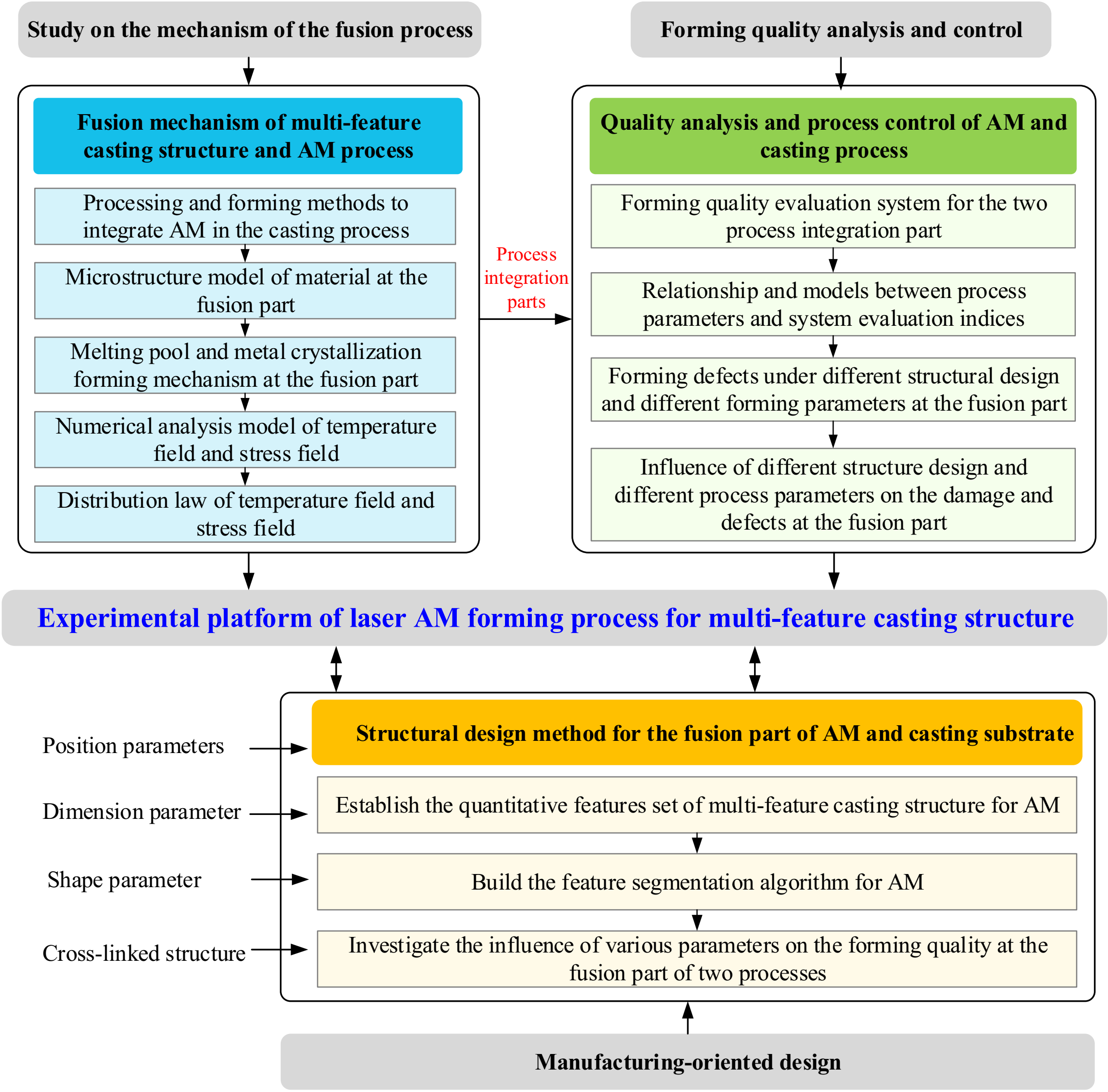


Fig. 10 Research route of integrating AM into casting method

3. *Quality analysis and process control of AM and casting process* Considering the working conditions, stress analysis, and forming quality evaluation criteria of the original castings, the forming quality evaluation system for the parts fabricated by the process integration method can be established. The evaluation indices for the fusion area include combination strength, geometric accuracy, bearing capacity, mechanical properties, thermal deformation, stress distribution, surface roughness, hardness, and density. The mapping relationship and model between the manufacturing process parameters and the system evaluation indices can be established to determine the influence of process parameters (e.g., laser power, layer thickness, processing speed, scanning gap, and scanning path) on the forming quality of the fusion part. To improve the forming quality of the parts manufactured via AM and casting, process parameters optimization method can be proposed.

Casting is a traditional manufacturing technology that has been extensively applied in various fields. In contrast, AM is a new manufacturing technology that has witnessed rapid adoption and development. Previous studies have examined the combination of AM and casting, particularly in mechanical manufacturing. The existing studies on AM have primarily adopted product structure design and metal AM process control methods to provide a foundation for integrating these processes. Based on the characteristics and advantages of these processes, the integration of AM and casting can be examined using the current theory, welding, and remanufacturing experiences as references. Conducting research on the integration of AM and casting offers theoretical and practical significance. The proposed process integration method has proven to be feasible in theory and exhibits great significance and application value.

6 Conclusions

AM, which is a kind of "free manufacturing," changes traditional manufacturing. However, production efficiency, energy consumption, and cost are undesired factors to consider when using AM to manufacture large metal parts. Owing to its ability to rapidly manufacture complex structural shapes, AM can be used in mold fabrication. Integrating this technology into casting can enhance production efficiency and reduce costs. However, such integration is insufficient for producing large castings with complex shapes, structures, or multiple features.

To identify the advances and shortcomings of AM in manufacturing large-scale metal parts, this study offers a review of the existing literature on AM from the perspectives of advances of AM in structure design, manufacturing advances of metal AM technology, quality control of AM in manufacturing metal parts. Casting alone is an efficient means in manufacturing large metal components, however when casting is combined with AM, the benefits are highlighted. The research status of the combination application of AM and casting discusses the combination application method, the manufacturing process and the quality control of AM in casting. However, defects still occur in the large and complex parts manufactured by the combination of AM and casting, the lengthy mold preparation cycle of large castings with multiple features, and the tendency for the formation of defects in key casting features.

This study attempts to address these limitations and introduce a novel process integration method for integrating AM in casting to allow the manufacture of large-scale metal parts with complex structures. AM is proposed for the formation of complex manufacturing features and for improving the production efficiency of multi-feature casting parts. To confirm the forming quality at the fusion part of the two processes, future research on a structural design method for the fusion part of AM and casting substrate is suggested. The fusion mechanism of the use of AM within casting, together with the associated quality analysis and control, is discussed to highlight the feasibility of integrating AM into the casting process. The proposed integration method can provide novel ideas for integrating AM into other processes and shows great significance and application value.

Author Contributions MG contributed to the conception of the study and wrote the manuscript. LL, QW and ZM performed the literature search. XL contributed significantly to analysis and manuscript preparation. ZL helped perform the analysis with constructive discussions.

Funding This work was supported by the National Natural Science Foundation of China (nos. 51775162, 52005146), Natural Science Foundation of Anhui Province (2008085QE265, 2008085QE232, 2008085ME150), Suzhou Engineering Research Center for Collaborative Innovation of Mechanical Equipment (SZ2017ZX07), Anhui Major Science and Technology Project (18030901023), and Opening Project of Suzhou University Research Platform (2019kyf21, 2019ykf26, 2019ykf27).

Availability of Data and Materials All data generated or analysed during this study are included in this published article.

Compliance with Ethical Standards

Conflict of interest The authors have declared that no competing interests exist.

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