Wang et al.
Chinese Journal of Mechanical Engineering (2022) 35:97
https://doi.org/10.1186/s10033-022-00780-7

Chinese Journal of Mechanical Engineering

REVIEW

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Grinding/Cutting Technology and Equipment of Multi-scale Casting Parts

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Abstract

Multi-scale casting parts are important components of high-end equipment used in the aerospace, automobile manufacturing, shipbuilding, and other industries. Residual features such as parting lines and pouring risers that inevitably appear during the casting process are random in size, morphology, and distribution. The traditional manual processing method has disadvantages such as low efficiency, high labor intensity, and harsh working environment. Existing machine tool and serial robot grinding/cutting equipment do not easily achieve high-quality and high-efficiency removal of residual features due to poor dexterity and low stiffness, respectively. To address these problems, a five-degree-of-freedom (5-DoF) hybrid grinding/cutting robot with high dexterity and high stiffness is proposed. Based on it, three types of grinding/cutting equipment combined with offline programming, master-slave control, and other technologies are developed to remove the residual features of small, medium, and large casting parts. Finally, the advantages of teleoperation processing and other solutions are elaborated, and the difficulties and challenges are discussed. This paper reviews the grinding/cutting technology and equipment of casting parts and provides a reference for the research on the processing of multi-scale casting parts.

Keywords: Multi-scale casting parts, Residual features, 5-DoF hybrid grinding/cutting robot, Teleoperation processing

1 Introduction

The foundry industry is a pillar industry of aerospace, automobile, shipbuilding, construction machinery, and equipment manufacturing. The casting process has the characteristics of low cost, one-time molding, and strong flexibility [1]. It has unique advantages in manufacturing important functional parts, especially those with complex shapes and internal cavity structures [2–4]. Since 2011, the global production capacity of casting parts has exceeded 100 million tons, and it has a trend of continuous growth, as shown in Figure 1. With the increasing requirements for product quality and performance, and the continuous improvement of the quality and standards of casting parts, casting technology is gradually developing toward the high quality, high efficiency, and low-carbon footprint. To achieve these goals, China Foundry Association issued the 14th Five-Year Development Plan for the Foundry Industry in 2021 and highlighted that it is the way to accelerate the transformation and upgrading of the foundry industry. The plan presents a priority development theme that develops intelligent technology and equipment for the grinding and cutting of casting parts.

Affected by the casting process, residual features such as pouring risers and parting lines of casting blanks that will inevitably appear are random in size, morphology, and distribution [5], as shown in Figure 2. To obtain the final casting parts, they must be removed by grinding/cutting, finishing, polishing, spraying, and other processes [6]. The grinding/cutting of residual features is the indispensable primary process in producing casting parts. The treatment of this process directly determines the quality and cost of the product. However, the

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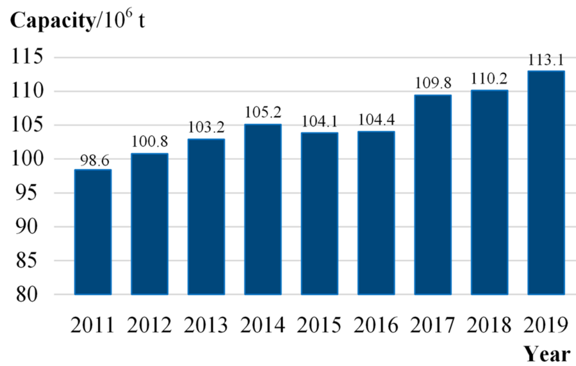

Figure 1 Global capacity of casting parts

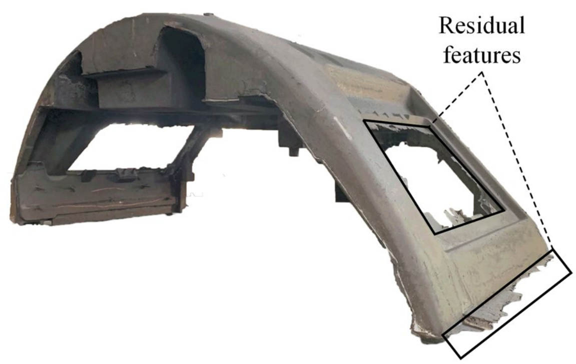

Figure 2 Residual features of casting part

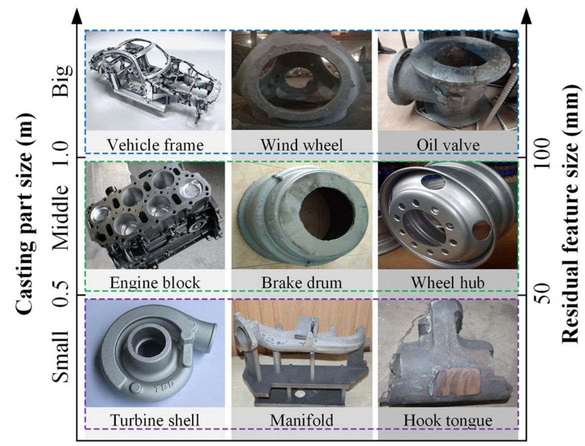

Figure 3 Multi-scale casting parts

Figure 4 Manual processing

grinding/cutting of casting parts involves many problems such as hazardous working conditions and serious environmental pollution. Thus, it has become a bottleneck that restricts the development of the foundry industry [7]. Meanwhile, to meet the function and performance requirements of various types of equipment, casting parts present multi-scale characteristics. The size of residual features increases with the size of casting parts, as shown in Figure 3, which brings great difficulties and challenges to the grinding/cutting process.

At present, the grinding/cutting process of casting parts is mainly completed by the manual processing method. One of the basic forms is that the worker holds the angle grinder, cutting machine, or other tools to process the workpiece. Another way is for the worker to hold the workpiece to operate on the grinding/cutting equipment. The proportion of this method adopted by enterprises has exceeded 95% [8], as shown in Figure 4. However, manual processing easily leads to safety hazards such as pneumoconiosis and work-related injuries [9]. In addition, realizing the quality and consistency of casting parts is difficult. In recent years, find workers for manual processing has been difficult because of the rapid increase in labor costs [10, 11]. Thus, using automatic equipment instead of employing laborers to achieve high-efficiency and high-quality grinding/cutting of casting parts has become an urgent requirement in the foundry industry. The design, measurement, process, control, and other key technologies of automatic equipment are the core of promoting the rapid development of the grinding/cutting field of the foundry industry.

2 Current Solutions

As shown by the development status in the world in recent decades, the rise and application of automation equipment and technology have changed the production methods of many industries [12–15]. The automation equipment for the grinding/cutting of casting parts has been greatly developed. The equipment can be divided into two categories in terms of topological structure: machine tool and serial robot [16, 17].

Figure 5 Maus grinding/cutting equipment

Figure 6 Xinjingjie grinding/cutting equipment

2.1 Machine Tool Grinding/Cutting Equipment

This type of automatic grinding/cutting equipment is often modified from traditional machine tools. Maus, an Italian company, is the first to develop such equipment globally. It has developed a benchmark in the field of automatic grinding/cutting of casting parts. As shown in Figure 5, its product has been applied to many casting enterprises. Chinese enterprises, such as Anhui Xinjingjie Automation, have conducted research, but their products are similar to Maus products, as shown in Figure 6. This type of equipment is mostly 3-DoF or 5-DoF and has the merits of high stiffness (>10 N/μm) and high accuracy (<0.05 mm) [18–21]. It is also equipped with auxiliary functions, such as laser detection, to realize high-efficiency and high-quality grinding/cutting removal of the residual features of small and medium (<1 m) casting parts [22].

Although machine tool grinding/cutting equipment has effectively improved the processing efficiency and quality of casting parts, it still involves many challenges and limitations in practical applications. The machine tool body adopts a serial topology and takes high stiffness as the design goal, reducing its dynamic performance and increasing energy consumption. The volume of the machine tool and its working mode bring some constraints in its flexibility. In summary, this type of equipment can only complete the removal of residual features on flat or small curved surfaces, and cannot easily deal with complex shapes and large casting parts. In addition, the transmission system is very sensitive to metal dust [23]. The component loss and maintenance costs are extremely high, and the grinding/cutting processing environment is harsh, which presents more stringent requirements for its application [24, 25]. Hence, the cost performance of this type of automation equipment is very low, and it is still far from the phase of large-scale promotion and application.

2.2 Serial Robot Grinding/Cutting Equipment

In recent years, with the development of robot technology, serial robot grinding/cutting equipment has become an important way to solve processing problems in the foundry industry [26, 27]. This type of equipment has high flexibility and is suitable for processing parts with various morphological characteristics. The efficiency and quality are significantly improved compared with manual operation. Therefore, it is widely used in casting part cutting, grinding, shot blasting, spraying, and other tasks [28–33].

For the grinding/cutting of casting parts, representative enterprises include Koyama (Japan), Kuka (Germany), and ABB (Switzerland), among others. Their serial robotic products have been widely used in casting enterprises worldwide. The grinding/cutting equipment holds a small casting to operate on a grinding belt or a grinding/cutting tool to process casting parts, as shown in Figures 7 and 8.

The serial robot grinding/cutting equipment is favored by industry and academia for its advantages such as high dexterity and large workspace [34]. However, it encounters many limitations when removing the residual features of casting parts. The lack of low stiffness (<1 N/μm) and poor accuracy (>0.2 mm) makes the serial robot unable to withstand large loads, so it is typically used to remove the small residual features [35]. If medium and large casting parts are carried out, only small grinding/cutting depth and feed speed can be applied and the processing efficiency is very low [36]. In addition, the

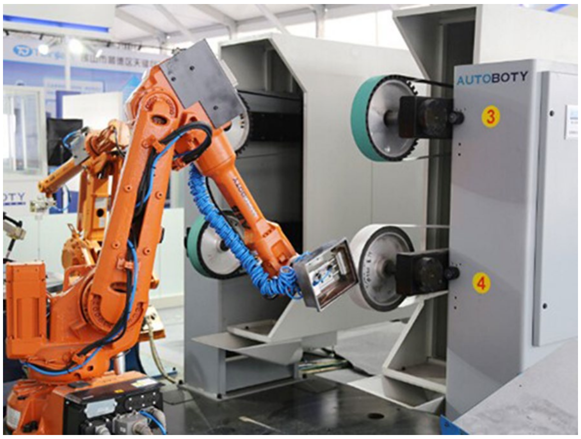

Figure 7 ABB grinding/cutting equipment

Figure 8 KUKA grinding/cutting equipment

stiffness and precision of serial robots vary greatly in the whole workspace. Thus, ensuring the consistency of quality when processing large and complex casting parts is not easy.

In conclusion, the existing machine tool and serial robot grinding/cutting equipment have obvious deficiencies in dexterity and rigidity, respectively. Furthermore, they cannot easily handle the task of processing multi-scale casting parts. Thus, developing automatic grinding/cutting equipment with high dexterity and high stiffness and exploiting corresponding technologies is an urgent need.

3 Proposed Solutions

As the demand for quality increases, the manufacturing industry has drastically shifted its priority from quantity to quality. This condition proposes a higher requirement for the production and processing of core equipment and key components in crucial fields such as aerospace, automobile manufacturing, and shipbuilding. For example, in gas turbines, from shallow-sea short transportation to deep-sea remote detection, the working circumstance continues to change and the difficulty of missions continues to escalate. To adapt to reliable and long-life service under extremely harsh environments, the size and tonnage of gas turbines increase constantly, and the performance demands continue to rise. Therefore, the processing and manufacturing requirements of the engine and other vital components are constantly increasing. In all part manufacturing methods, casting accounts for more than 50%, and the casting blanks have a large size span and a variety of materials. Ship engine chassis, automobile manifolds, truck wheel hubs, steering forks, and others are common casting parts with a size of 0.1–10 m, involving various materials such as cast steel, cast iron, and cast aluminum. In addition, due to the influence of different casting processes, the residual features of the casting parts are random in distribution, morphology, and size. Therefore, removing residual features of casting parts is a bottleneck in the transformation and upgrading of the foundry industry to green development and high-end intelligent manufacturing. The grinding/cutting process with high efficiency and high quality is an urgent problem to be solved.

The serial robot grinding/cutting equipment has low stiffness and poor precision defects, which brings unstable processing and long cycle problems, seriously restricting the precision and quality of production. Thus, achieving efficient manufacturing is not easy. In contrast to the serial robot, machine tool grinding/cutting equipment can rapidly remove the residual features of casting parts, and the processing quality is also guaranteed. However, its poor flexibility causes difficulty in dealing with large or complex casting parts. Its low-cost performance further limits its market promotion and application.

3.1 5-DoF Hybrid Grinding/Cutting Robot

Aiming at the grinding/cutting of the residual features of multi-scale casting parts, a high dexterity and high stiffness 5-DoF hybrid grinding/cutting robot is proposed, as shown in Figure 9. It combines the advantages of the high flexibility of the serial robot and the high stiffness of the machine tool. Different from the existing grinding/cutting equipment, the robot adopts a parallel manipulator with the advantages of high rigidity and compact structure as the main part [37–46].

This 5-DoF hybrid grinding/cutting robot consists of a vertical guide rail, a 2-DoF planar parallel mechanism, and two 1-DoF revolute joints. The planar 2-DoF planar parallel mechanism module is the main part so that the equipment has higher overall stiffness to cope with large cutting tasks and improve production efficiency. The decoupled motion and independent control of these two 1-DoF revolute joints extend the workspace of the robot and make the equipment have high flexibility to

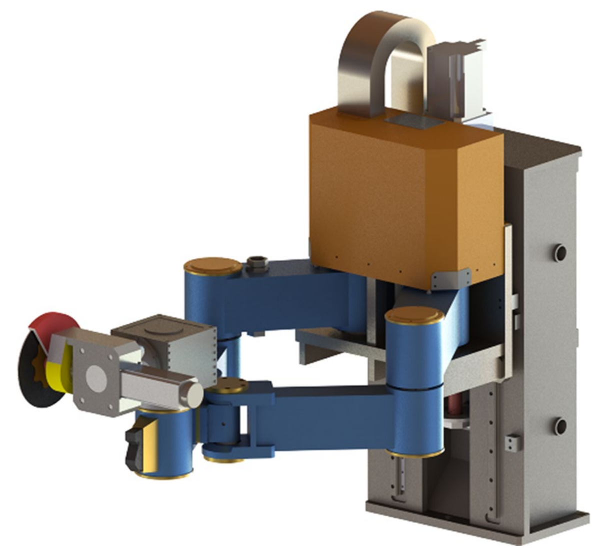

Figure 9 5-DoF hybrid grinding/cutting robot

deal with the grinding/cutting operation of irregular-shaped residual features. The vertical moving guide rail and 2-DoF planar parallel mechanism can realize spatial location positioning, and the orthogonal arrangement of two 1-DoF revolute joints can achieve spatial orientation positioning. Thus, this grinding/cutting equipment has the ability of 5-DoF processing.

Based on the 5-DoF grinding/cutting robot, three types of equipment (workpiece, flow, and tool type) are developed to deal with small, medium, and large casting parts. Master-slave processing and other technologies are proposed. High-efficiency and high-quality processing of casting parts is achieved, and the problem of "small parts can't process fast, middle parts can't process well, and big parts can't be processed" is solved completely.

3.2 Workpiece-type Grinding/Cutting Equipment

Small (<0.5 m) casting parts have the largest quantity and a diversiform category, with the obvious characteristic of large batches. Due to the small size of this casting part, the casting method used is precise, so the size deviation caused by shrinkage and expansion during the casting process is small (±1 mm). Thus, the casting blank is the same as the ideal model and the size deviation distribution is relatively concentrated [47]. In addition, this type of casting part is large in batches. The casting system used is advanced and mature. The residual features, such as pouring risers, generally only exist on flat surfaces, so the obtained casting blanks have good consistency and are easy to process.

To remove the residual features of such casting parts, workpiece-type grinding/cutting equipment has been developed, as shown in Figure 10. The equipment consists of a 4-DoF (three translational and one rotational) hybrid robot and a 2-DoF (two rotational) auxiliary grinding and cutting device. The processing trajectory is completed in advance by manual teaching, and it needs to be programmed once for the same batch of casting parts. Due to the small weight of such parts (<50 kg), the casting blank could be grasped and clamped by the 4-DoF hybrid robot and pneumatic clamp according to the predetermined trajectory. Then, the casting blank is carried to the auxiliary grinding/cutting device for removal of residual features. After completing the step of a single position, the pneumatic clamps are kept, the rotating joints of the robot and the auxiliary device are driven to ensure the movement of the workpiece and machine tool, respectively. In this way, the relative posture of the workpiece and machine tool is changed to perform continuous grinding/cutting.

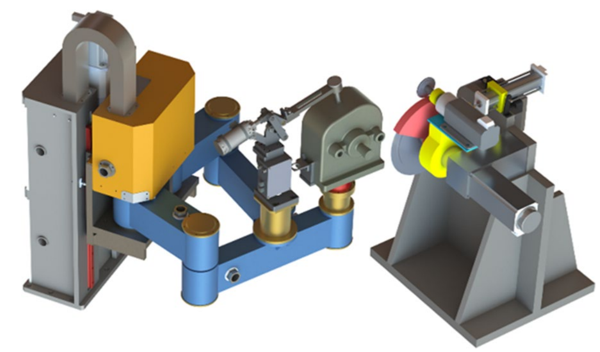

Figure 10 Workpiece-type grinding/cutting equipment

3.3 Flow-type Grinding/Cutting Equipment

Similar to small casting parts, medium-sized (0.5–1.0 m) casting parts also have the characteristics of large batches. However, due to the size and weight (50–200 kg) of this type of casting part, the size deviation led by shrinkage and expansion during casting increases (±3 mm), so more residual features exist that need to be removed for casting blanks. Although most of these casting parts have geometrically symmetrical features, the residual features after casting are not strictly symmetrical [48]. In other words, the relatively random residual features bring about a greater challenge to the grinding/cutting of this type of casting part. If manual teaching is used, we need to extract the trajectory feature points of each casting, which is inefficient and inconsistent.

A flow-type grinding/cutting equipment is developed to address these difficulties, as shown in Figure 11. This equipment consists of a 5-DoF hybrid robot, a 2-DoF push mechanism, a 2-DoF clamping mechanism, a 1-DoF

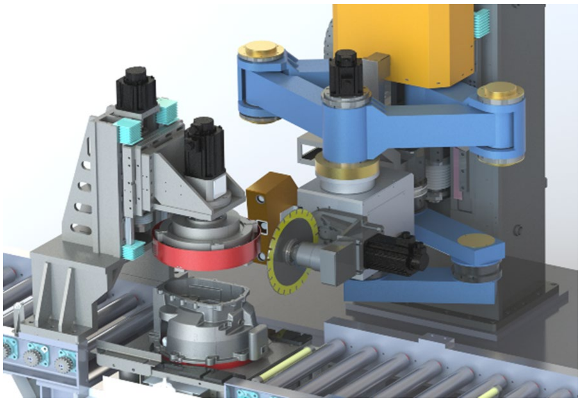

Figure 11 Flow-type grinding/cutting equipment

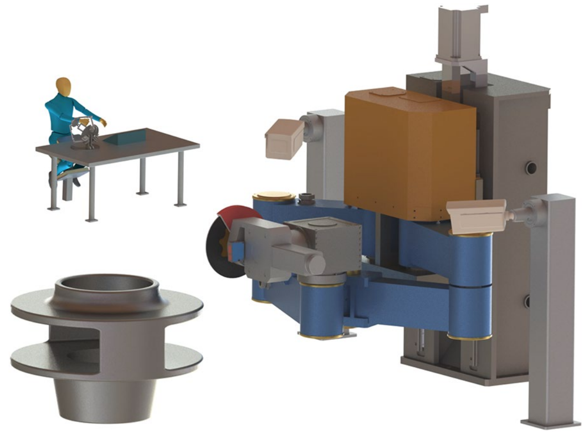

Figure 12 Tool-type grinding/cutting equipment

support mechanism, a roller conveyor line, and a laser scanner. The roller conveyor line is used to convey the casting blanks. When a casting part reaches the specified position, the 2-DoF push mechanism pushes it above the 1-DoF support mechanism. Then, the 2-DoF clamping mechanism and 1-DoF supporting mechanism cooperate to fix the casting part. A laser scanner is used to obtain the morphology of residual features and match the ideal model in the form of point clouds to derive the processing trajectory [49]. According to this process, the 5-DoF hybrid robot performs grinding/cutting on the casting part. After the processing is completed, the 2-DoF push mechanism pushes the current casting part away to process the next casting part. The trajectory acquisition time usually occupies a large amount in the entire cycle. This step can be completed before the casting part is pushed so that the trajectory acquisition and processing procedures of the same part can be completed in different cycles. In this way, the processing cycle time is shortened and the processing efficiency is improved.

3.4 Tool-type Grinding/Cutting Equipment

Large casting parts (>1.0 m) are usually key components of high-end equipment, appearing in single pieces or extremely small batches. This type of casting part is large in size and complex in morphology. In general, extensive processes such as lost foam casting are utilized. The shrinkage and expansion are relatively large and change continuously with geometric characteristics such as the appearance and wall thickness of the casting part [50]. Thus, the size deviation between actual casting blanks and the ideal model is very large (3–15 mm). In addition, the residual features of large casting parts increase exponentially with the size of the casting parts, and the distribution and morphology are very random, which inevitably brings many difficulties to the grinding and cutting process. The classic solution uses laser scanning to extract the processing trajectory and then implement automatic removal. However, the problem with this solution is that the amount of point cloud data obtained by scanning is huge, and a very long time is needed to deal with it, even far more than the processing time [51]. Moreover, some phenomena, such as external interference or missing data, during the scanning process causes the processing trajectory obtained by registering to deviate greatly from the ideal trajectory [52].

Tool-type grinding/cutting equipment and teleoperation processing technology based on master-slave control are developed to overcome the aforementioned difficulties, as shown in Figure 12.

This equipment mainly consists of a master control robot, a slave processing robot, and a vision system. The slave processing robot is the 5-DoF hybrid grinding/cutting robot. The master control robot is a 6-DoF manipulator with force feedback. With the help of the vision system, the worker can obtain the relative posture between the residual features of casting parts and the slave processing robot. Then, the movement of the slave robot is controlled by the master control robot to process the residual features. It should be noted that factors such as worker jitter and disordered operation may cause overprocessing. Thus, the forbidden virtual fixture [53] is constructed to limit the processing area of the slave processing robot. The artificial potential field method [54] is used to render the forbidden virtual fixture to realize the restraint and guidance of the master control robot movement. For residual feature removal of large castings, this technical solution can fully combine the wisdom of workers and the excellent performance of slave processing robots. This condition greatly improves the processing efficiency and is expected to change the grinding/cutting processing mold of large castings.

4 Difficulties and Challenges

Three kinds of grinding/cutting equipment formed by the 5-DoF grinding/cutting robot can effectively remove the residual features of small, medium, and large casting parts. However, the high-efficiency and high-quality processing of multi-scale casting parts, especially large casting parts, still faces many difficulties and challenges due to the randomness of residual features in size, morphology, and distribution.

After casting blanks are formed, grinding/cutting of casting parts is the first process. It directly determines the function and performance of parts and affects the following processing costs. The use of high-performance processing robots for operation is the current advantageous solution, but robots with different size parameters are very different. Designing a robot with light weight, high stiffness, and high flexibility to meet certain requirements is necessary to ensure the successful completion of the task. The casting processes of medium and large casting parts are extensive, and the grinding/cutting environment is harsh. As the size of castings increases, the measurement data also increase exponentially. Due to complicated environmental factors, laser scanning faces difficult in obtaining the processing trajectory. For teleoperation processing, the cutting force on the end-effector of the slave robot is difficult to measure directly and feed back to the master control robot, which reduces the transparency of the operation. The haphazard operation of workers in the master-slave control seriously affects the processing efficiency. However, large and irregular residual features have strong time variance during processing, which greatly influences efficiency. Therefore, new grinding/cutting technologies should be developed to shorten the operation cycle. Grinding/cutting is a process of coexistence and fusion of multiple physical environments, which is characterized by strong nonlinear and multi-factor coupling. Making a suitable control strategy is the fundamental way to guarantee the processing quality of casting parts.

In conclusion, to realize high-efficiency and high-quality grinding/cutting of multi-scale casting parts and promote the development and transformation of the foundry industry, we have to urgently solve the following technical problems in design, measurement, process, and control:

(1) Performance design and optimization of robot: Robot performance determines whether it can be competent for grinding/cutting tasks. Even if the robot's configuration is determined, the performance design and optimization with the target of light weight, high stiffness, and high flexibility are also difficult. As the performance design of the robot involves two related and integrated parts of dimension and topology, the optimization problem is multi-objective, multi-parameter, and multi-constrained. Therefore, in-depth research on the coupling effect of dimension and topology on performance is necessary. Then, according to the requirements of the processing equipment in the service environment, the integrated optimization design of the dimension and topology of the robot should be implemented to obtain the optimal performance of the entire domain.

(2) Measurement of casting parts: Measurement is one of the most important steps to ensure the processing effect. The difficulty is how to measure different casting parts quickly and generate accurate processing trajectories. The morphological characteristics of various casting parts are very different. The size deviation caused by shrinkage and expansion enlarges with the size of casting parts. Moreover, the measurement system is susceptible to harsh grinding and cutting environments. Therefore, developing the targeted measurement approach is indispensable, as well as deeply studying the shrinkage and expansion mechanism of the casting process, and establishing the mapping between the deviation and geometrical characteristics of casting parts. Based on this condition, the measurement data processing algorithm with strong anti-interference and high adaptability has to be applied urgently to realize the efficient measurement of casting parts and rapid acquisition of the processing trajectory.

(3) Grinding/cutting process planning: Process planning can effectively improve processing efficiency and quality. Process planning for casting parts with complex shapes in multiple processing stages is difficult. Grinding/cutting of casting parts involves multiple stages, and each stage has different goals and constraints. Therefore, proposing a corresponding grinding/cutting process is necessary according to the characteristics of the residual features to be removed. In addition, the relevant process modeling method and the mechanism models of the indices such as cutting force and material removal rate should be studied. Based on this perspective, the process planning of grinding/cutting can be carried out according to the requirements of processing efficiency and quality.

(4) Processing quality control: Control is the last step to ensure processing quality. The difficulty lies in the force control in teleoperation processing and the trajectory tracking precision control in automatic processing. It is necessary to propose a method of real-time feedback of the grinding/cutting force to the master robot to improve the transparency of operation. Based on this idea, the mappings of the processing force of the slave robot and the master robot should be constructed. The guaranteed grinding/cutting force strategy in the teleoperation processing should also be formulated. For automatic processing, factors such as deformation caused by the processing force will decrease the trajectory tracking accuracy. Therefore, studying the dynamic characteristics of the robot during the processing is a significant task. The grinding/cutting dynamics and trajectory tracking accuracy model will be established to reveal the formation mechanism of the robot trajectory tracking error. Furthermore, it is also essential to propose a corresponding compensation strategy for static and dynamic robot errors to enhance the processing quality by optimizing control parameters.

5 Conclusions

A high dexterity and high stiffness 5-DoF hybrid grinding/cutting robot was proposed to achieve residual feature removal of multi-scale casting parts with random size, random morphology, and random distribution. This robot combines the merits of the high flexibility of a serial robot and the high stiffness of a machine tool. Based on this concept, three types of grinding/cutting equipment are developed to deal with multi-scale casting parts and teleoperation processing, and other technologies are exploited. The characteristics of these solutions are elaborated in detail.

The solutions proposed in this paper provide new ideas for the removal of residual features of casting parts and overcome the limitations of traditional manual operation and current automatic equipment. At the same time, it has promoted the development and transformation of the foundry industry towards automation and intelligence. Given the limited depth of current research, the proposed schemes still face difficulties and challenges in design, measurement, process, and control in application, which need further exploration.

Acknowledgments
Not applicable.

Author Contributions
MW and TS discussed and wrote the manuscript; YS reviewed and revised the manuscript; PW guided the technical schemes; YC provided part of the materials for the manuscript. All authors read and approved the final manuscript.

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Funding
Supported by National Natural Science Foundation of China (Grant Nos. 51875391, 51875392), Tianjin Science and Technology Planning Project (Grant Nos. 18PTLCSY00080, 20YDLZGX00290), State Key Laboratory of Digital Manufacturing Equipment and Technology (Grant No. DMETKF2022007).

Competing Interests
The authors declare no competing interests.

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Received: 7 January 2022 Revised: 18 June 2022 Accepted: 6 July 2022
Published online: 28 July 2022

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