Dinghua Zhang · Yunyong Cheng
Ruisong Jiang · Neng Wan

Turbine Blade Investment Casting Die Technology

Translated by Kuidong Huang, Wenhu Wang and Kun Bu

国防工業出版社
National Defense Industry Press

Springer

Turbine Blade Investment Casting Die Technology

Dinghua Zhang · Yunyong Cheng
Ruisong Jiang · Neng Wan

Turbine Blade Investment Casting Die Technology

国防工業出版社
National Defense Industry Press

Springer

Authors
Dinghua Zhang
Northwestern Polytechnical University
Xi'an
China

Yunyong Cheng
Northwestern Polytechnical University
Xi'an
China

Ruisong Jiang
Northwestern Polytechnical University
Xi'an
China

Neng Wan
Northwestern Polytechnical University
Xi'an
China

Translated by
Kuidong Huang
Northwestern Polytechnical University
Xi'an
China

Wenhu Wang
Northwestern Polytechnical University
Xi'an
China

Kun Bu
Northwestern Polytechnical University
Xi'an
China

ISBN 978-3-662-54186-9 ISBN 978-3-662-54188-3 (eBook)
DOI 10.1007/978-3-662-54188-3

Jointly published with National Defense Industry Press, Beijing, China

The print edition is not for sale in China Mainland. Customers from China Mainland please order the print book from: National Defense Industry Press.

Library of Congress Control Number: 2017930271

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer-Verlag GmbH Germany
The registered company address is: Heidelberger Platz 3, 14197 Berlin, Germany

Preface

As the key component of aero-engine, turbine blades determine the performance, reliability and security of the aero-engine. Due to the high external dimensional accuracy, and complicated internal cooling channels of turbine blades, which make the fabrication of such blades more difficult. Hollow turbine blade manufacturing technology has become a major issue during the development of aero-engine. Currently, turbine blades are fabricated by using investment casting process and then supplement the necessary machining process. Among those processes, die cavity optimization, precision manufacturing, and rapid leading are the key points to ensure the accuracy, and shorten the manufacturing period for turbine blades.

The Key Laboratory of Contemporary Design and Integrated Manufacturing Technology, Ministry of Education in Northwestern Polytechnical University has carried out research on the design, analysis, and manufacturing technologies of investment casting die for complex hollow turbine blades. Funded by National High-tech R&D Program, National Key Technologies R&D Program, Aero-Science Foundation of China, the integrated design and manufacturing technologies of investment casting die were widely studied, and over 100 academic papers were published. Independently developed "turbine blade casting die CAD/CAM system" won the 1999 annual ministerial level scientific and technological progress award.

The theory and application achievements in the field of turbine blade casting die were summarized systematically in this book. The related materials have been mainly from the group of "Advanced manufacturing technologies for aero-engine" led by Prof. Dinghua Zhang since 1990s, including academic research papers, technical reports, and patent literature. The main contents include digital modeling of turbine blades, casting die design, cavity optimization, precision manufacturing of die and rapid leading, and detection and evaluation technology for turbine blade. This book aims to provide advanced digital casting die design theory, method and practical technical reference for engineering practice.

The current Ph.D. and graduated students in our group has provided a large number of pictures and materials. In addition, Xi'an Aero Engine Co., Ltd., China Gas Turbine Establishment, Beijing Institute of Aeronautical Materials, and other structures also provide a lot of support. The book was funded by the National Defense Science and Technology published Fund. The authors sincerely appreciate the support mentioned above.

This book was conceived by Prof. Dinghua Zhang, and checked by Prof. Wenhu Wang. This book consists of seven chapters, Chaps. 1 and 6 were written by Dinghua Zhang; Chap. 2 was written by Neng Wan; Chaps. 3 and 4 were written by Wenhu Wang and Ruisong Jiang; Chap. 5 was written by Kun Bu and Yunyong Cheng; and Chap. 7 was written by Yunyong Cheng and Kuidong Huang.

Because of the our limited knowledge, mistakes cannot be avoided in the book. Please feel free to contact us and point out the mistakes.

Xi'an, China

Dinghua Zhang
Yunyong Cheng
Ruisong Jiang
Neng Wan

Contents

Introduction

This book systematically summarizes the theory and application achievements in the field of turbine blade investment casting die technology of China. It is designed to provide advanced design theories, methods and practical technical references for the engineering practice of investment casting die design and manufacturing. The main contents of this book include turbine blade digital modeling, investment casting die design, die cavity optimization, die precision manufacturing and rapid finalization, as well as blade measurement and evaluation. Related materials of this book have been mainly from the research achievements of the authors' group since 1990s, including academic papers, technical reports, and patents.

This book may be suitable for professional researchers, graduates, and senior undergraduates who are engaged in the fields of investment casting, die technology, and digital measurement technology.

Chapter 1
Introduction

1.1 Turbine Blade of Aero-Engine

1.1.1 Introduction of Aero-Engine

Aero-engine, as the component of the propulsion system for an aircraft that generates mechanical power, is regarded as the heart of an aircraft [1]. With the development of aircraft power technology and the demands for national defense, the aero-engine has to meet the requirements of the new generation of aircraft, such as high speed, high altitude, long flight time, long distance, and high thrust-to-weight ratio. As a result, there will be increasingly complex structures and high precision of aero-engine, and the number of sophisticated components will also increase substantially [1, 2]. Jet engine with high integrated performance is the trend in the development of aircraft power equipment. A typical jet engine is shown in Fig. 1.1.

Generally, a jet engine is composed of air inlet, compressor, combustor, turbine, and nozzle. Among them, the compressor, the combustor, and the turbine compose the core engine. The major working procedures of a jet engine, including the compression of air, the combustion and the propulsion generated by the turbine, are finished in the core engine. After entering the engine through the inlet, the air is compressed by the compressor and then gets into the combustor. There, the mixture of the compressed air and the fuel is burnt and thus produces high-temperature gas that drives the turbine through expansion. After the gas passes the turbine, the exhaust discharges through the nozzle, producing reaction thrust. The schematic of a jet engine is shown in Fig. 1.2.

The compressor is used to increase the pressure of the air that enters the combustor. Its major performance indices include the pressure ratio and the efficiency of the compressor. The former refers to the ratio of the air pressure at the inlet to that at the outlet, and the latter is the ratio of the compression work required theoretically to the mechanical work consumed practically. Typically, there are two types of compressor, namely the centrifugal compressor and the axial flow compressor. The

D. Zhang et al., *Turbine Blade Investment Casting Die Technology*,
DOI 10.1007/978-3-662-54188-3_1

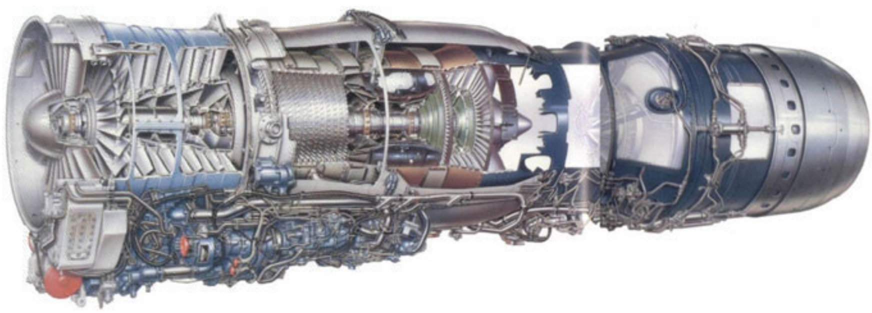


Fig. 1.1 A typical jet engine

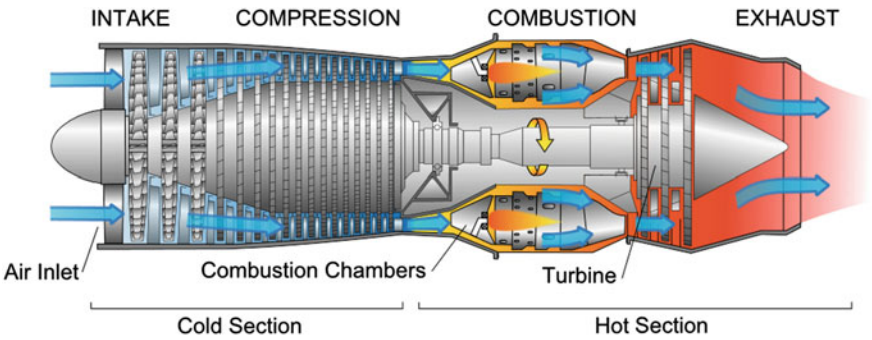


Fig. 1.2 The schematic of jet engine

latter is more widely applied, because the pressure ratio and the efficiency of the axial flow compressor are higher than those of the centrifugal compressor.

The combustor is composed of the fuel injector, the swirler, the liner, and the case. The mixture of compressed air and fuel is burnt in the combustor, which transforms the chemical energy into thermal energy. The main design considerations of the combustor include reliable ignition, stable combustion, and complete combustion.

The turbine is used to transform the thermal energy from the combustor into mechanical energy. Driven by the blast of the high-temperature and high-pressure gas, the turbine rotates fast, thus most of the thermal energy is transformed into mechanical energy that is used to drive the compressor, while the rest of the energy produces thrust. The power of turbine is directly proportional to the inlet temperature and the ratio of inlet pressure to outlet pressure [1]. One of the most important parts in the turbine is the turbine blade. Basically, the turbine blade can be divided into rotor blades and guide vanes, which are shown in Fig. 1.3. The high-temperature and high-pressure gas generated in the combustor first passes the guide vanes and is rectified. With part of its pressure head transformed into velocity head through the nozzle, the gas accelerates and lashes against the rotor blades more

(a) Guide vanes **(b)** Rotor blades

Fig. 1.3 Turbine blades of jet engine

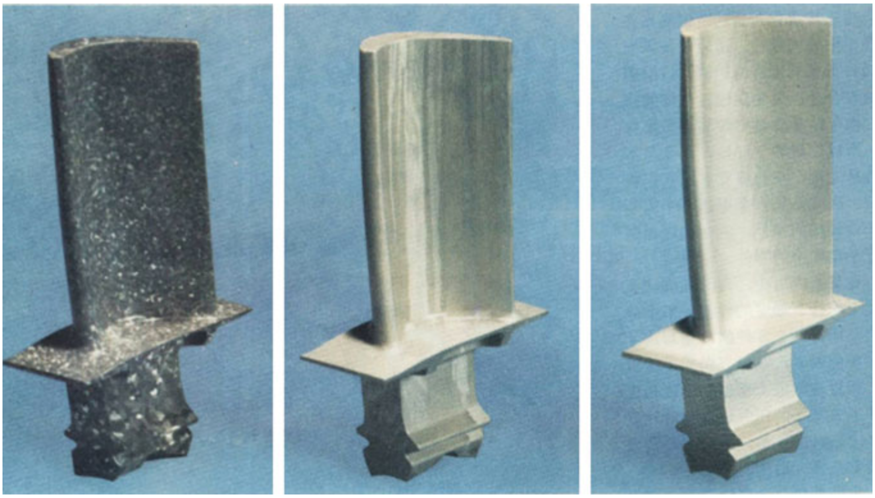
effectively at a certain angle. Then, part of the internal energy expands in the turbine and turns into kinetic energy, driving the turbine to rotate. Since the compressor shares the same axle with the turbine, it is also driven to rotate and compress the air repeatedly. The high-pressure and high-temperature gas from the turbine continues to expand in the nozzle and discharges out of the jet engine at high speed. Because the speed is much higher than that of the air entering the engine, there is reaction force to the jet engine, which enables the aircraft to fly forward. The performance of the turbine determines the overall performance of the jet engine directly.

1.1.2 Turbine Blade of Aero-Engine

1. Performance requirements of turbine blade

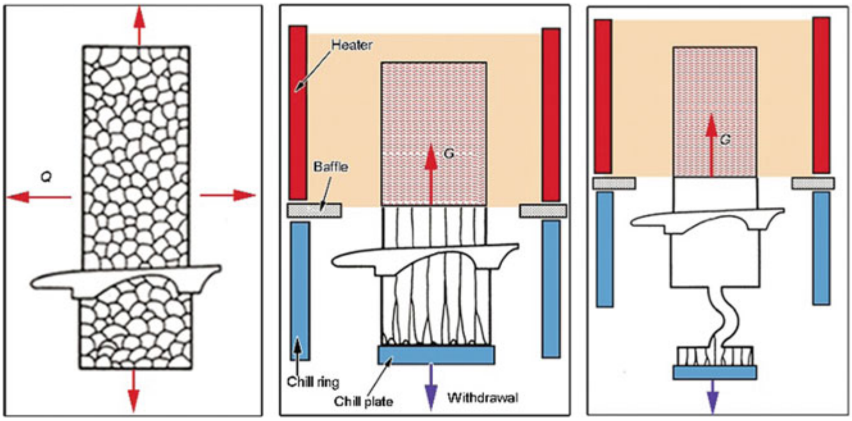
The turbine blade is one of the most critical components of the hot section of aero-engine and gas turbine. Turbine blades are surrounded by high-temperature gas, subject to centrifugal force, aerodynamic force, thermal stress and other complex stresses, and also influenced by high temperature oxidation and hot corrosion. Moreover, when the engine operating conditions change, turbine blades are subject to the thermal fatigue effect. Consequently, as the component of aero-engine and gas turbine working under the harshest condition, turbine blades are required to have some super characters in terms of yield strength, rupture strength, creep strength, and resistance to oxidation and hot corrosion. In order to satisfy the requirements, the design of turbine blades should include a complex internal cooling structure and a high-performance aerodynamic external structure. In addition, better grain structure and high-temperature resistant materials should be adopted to meet the demands of the working condition.

(1) Complex cooling structure: Cooling structure, aiming at reducing the operating temperature of components, is one of the most crucial measures to improve the reliability of turbine components working at high temperature. Hence, effective and reliable cooling system is an important part of the turbine. Generally, to improve the cooling effect and the high temperature performance, various types of cooling are used in turbine blades, such as convection cooling, impingement cooling and film cooling. As a result, there is an increasingly complex internal structure of the turbine blade.
(2) Advanced grain structure: Thermal stress and strain caused by the uneven internal temperature or constrained expansion of the components under high temperature will have adverse effect on the operation of aero-engine. A rapid increase of thermal stress in a short time can lead the components to crack, and repeated impact of thermal stress and deformation can result in the destruction of components. A typical cyclic loading process is the process of the engine's starting, accelerating, decelerating, and stopping. Hence, the turbine blade working under high temperature should have uniform thermal inertia and good thermal compensation structure. Currently, the grain structure is gradually changing from equiaxed crystal structure to directionally solidified structure and single-crystal structure (shown in Fig. 1.4) in order to deal with the strong centrifugal force and high temperature. The corresponding casting principles are shown in Fig. 1.5.
(3) Superalloys: The material of turbine blade should maintain reliable working under high temperature, which requires enough high temperature strength, good thermal stability, and corrosion resistance of the material. Materials commonly applied to guide vanes include K10, K11, K12, K1, K2, etc. K10 is



(a) Equiaxed crystal **(b)** directionally solidified **(c)** Single crystal

Fig. 1.4 Different kinds of grain structure



(a) Equiaxed crystal Solidification process **(b)** directionally solidified process **(c)** single crystal solidification process

Fig. 1.5 Different solidification process

cobalt-based alloy, and K11 iron-based. When the temperature is below 700–800 °C, nickel-based superalloy GH32 and GH33 can be used on the rotor blade. When the temperature is 800–850 °C, GH37 can be applied. When the temperature is 850–900 °C, forging nickel-based alloy GH49 can be used. Metal matrix composites, ceramic matrix composites, ceramics, and carbon composite material will play an important role in the development of high-performance turbine components.

2. Structure of turbine blade

Generally, the external part of blade in high-performance turbine consists of platform, blade body, and fir tree root. The internal structure consists of pin fin, longitudinal rib, transverse rib, film hole, etc., to enhance the heat transfer and improve the heat-resisting performance of the combustion. The structures of turbine blades are shown in Fig. 1.6.

The detailed internal structure of turbine blade is shown in Fig. 1.7.

The names and functions of each part of the structures in Figs. 1.6 and 1.7 are listed below:

(1) Section height: the distance between the cross section of the blade and the median plane of the engine.
(2) Stacking axis: the set of origins in the local coordinate of cross sections.
(3) External profile of the blade body: the external surface of the blade body, usually divided into suction side and pressure side.
(4) Internal profile of the blade body: the internal surface of the blade body.
(5) Longitudinal rib: the plate that divides the internal profile of the blade body into several cavities.

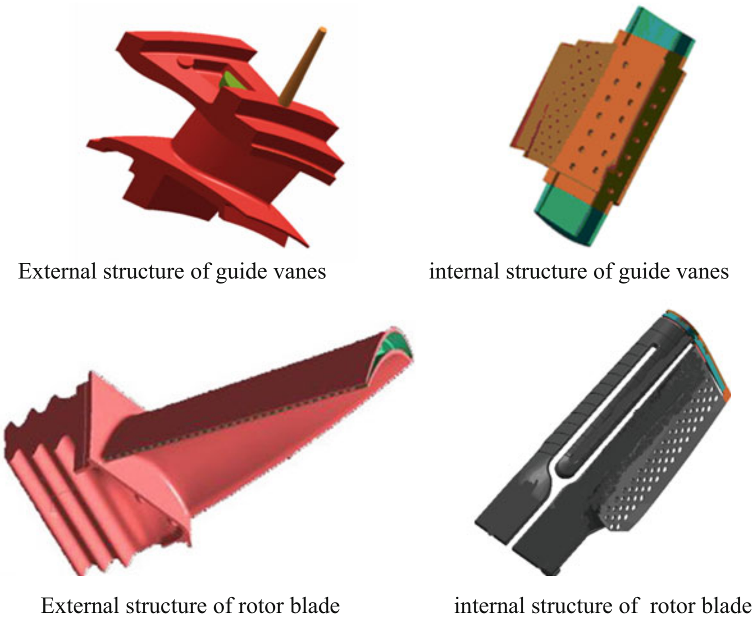


Fig. 1.6 Illustration of turbine blade

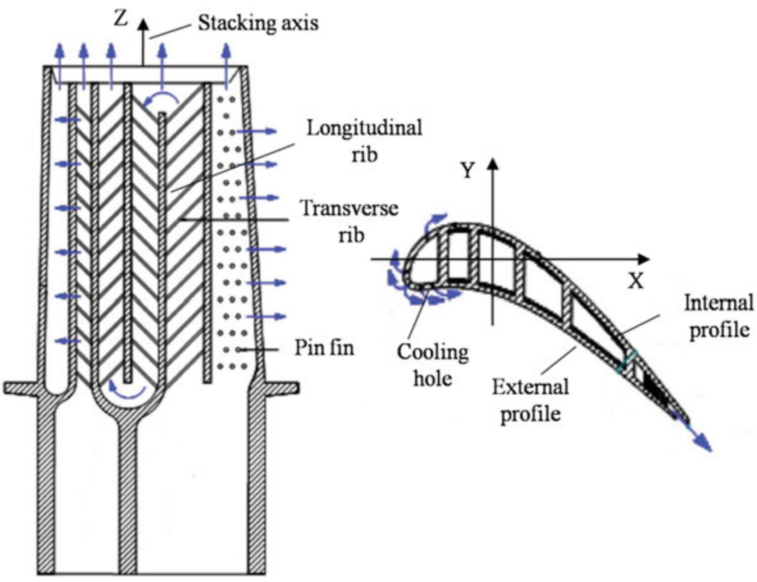


Fig. 1.7 The internal structure of turbine blade

(6) Transverse rib: the ribs positioned at certain intervals to enhance the heat transfer effect in the blade body, usually forming an angle with the direction of the cooling air.
(7) Pin fin: As the coolant flows across the fins with high velocity, the flow separates and wakes are formed to enhance heat transfer.
(8) Film hole: The film hole pumps the cooling air out of the blade, and a thin layer of cooling air is then formed on the external surface of the blade. Film holes are usually positioned at certain intervals and form an angle with the external surface.

1.2 Investment Casting Process of Turbine Blade

1.2.1 The Main Processes of Investment Casting

New design of structure and advanced cooling technologies are adopted in turbine blade. Convection cooling, impingement cooling, and film cooling are achieved through sophisticated cooling structures inside the turbine blade. However, the complexity of structure increases the difficult in fabricating those blades, which becomes a technical challenge confronting the development of aero-engine. Since the conventional machining processes cannot meet the needs of hollow turbine blade manufacturing, investment casting process complemented by machining is employed to obtain the blank of turbine blade [3].

The casting process of turbine blade blank is shown in Fig. 1.8. The manufacturing of the ceramic core is achieved through injecting ceramic materials into the ceramic core die, followed by the sintering process. Then the ceramic core is placed into the wax pattern die where the wax is injected to obtain the wax pattern. After that, ceramic shell building, dewaxing, sintering, metal casting, and knocking out

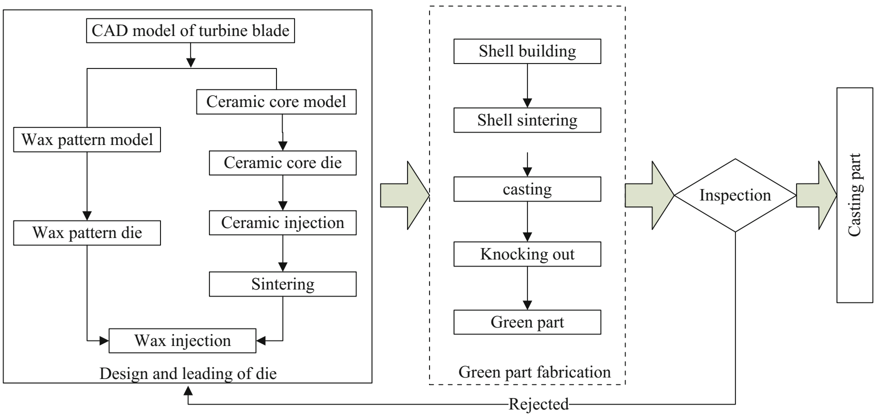


Fig. 1.8 The manufacturing process of turbine blade

are accomplished to get the investment casting blank. Then inspection is carried out. If the profile or wall thickness is unqualified, the wax pattern die will be modified and the above process repeated until the qualified casting is obtained.

1.2.2 Main Issues in Investment Casting of Turbine Blade

Constrained by many factors such as casting process, materials, and inspection measures, there is still a gap between advanced overseas technologies and the investment casting technology of hollow turbine blade in China. The drawbacks mainly include long manufacturing cycle, low precision, instable quality, and high rejection rate. It is found that around 50% of the unqualified blade castings of the same batch result from dimensional deviation. The main problems concerning investment casting of turbine blade are as follows:

(1) Low 3D parametric modeling level: The current CAD software does not provide a specific tool for 3D parametric modeling of turbine blade, which makes it difficult to model the blade and modify it. The reusability or partial reusability of the designed model can hardly be realized. Furthermore, because of the nonstandard design, relatively independent manufacturing process as well as the impact of some manufacturing factors, the design of the turbine blade structure is repeatedly revised, which affects the development cycle of the aero-engine.
(2) Low standardization of investment casting die: Expertise in die design has not been summarized yet, which affects the efficiency of die design and the standardization of the design process. Hence it demands more efforts of design experts and inhibits their creativity. Meanwhile, the lack of design standardization leads to the increase in the manufacturing cost and the extension of the design and manufacturing cycle of dies, thereby affecting the turbine blade production cycle.
(3) Low precision of profile dimensions and wall thickness: Investment castings of turbine blade have a high requirement on the precision of profile dimensions and wall thickness. Currently, there exist bending, deformation and cavity shifting in the investment castings of turbine blade, which results in low passing rate, restriction of production cycle, and high manufacturing cost.
(4) Long finalization time of investment casting die: The manufacturing of investment casting die is customized, and the die cavity is modified through try and error, which results in high cost and long finalization time.
(5) Backward inspection measures of blade castings: The inspection tool for investment castings of turbine blade is complex. Traditional inspection involves a large number of templates. The wall thickness is measured by using less precise ultrasonic tool and destructive sampling inspection. There exists false detection and undetected cases.

(6) Poor collaboration among different specialties: There is no enough collaboration in the current investment casting process. For example, information of materials, processes, tooling and inspection is not effectively integrated and utilized, which seriously affects the quality of turbine blades and the production cycle.

1.3 Literature Review of Investment Casting Die Technology

Throughout the development process of the turbine blade, the precise, agile manufacturing of the ceramic die and the wax pattern die is the key point to ensure precise manufacturing of the blank and short developing cycle. Researches are mainly carried out in the following areas.

1.3.1 Parametric Modeling for Turbine Blade

Developed countries pay much attention to the aero-engine technology. The development of the new generation of aero-engine must rely on new design approaches and advanced technologies. In other words, new design, new materials and new process should be adopted. Digital technology is one of the most effective approaches to the new design of aero-engine. After the digital technology was adopted by the Pratt & Whitney, the marketing time was reduced from 5 to 2.5 years.

BMW, Rolls-Royce and a tech GmbH engineering software technology in Germany jointly developed parametric blade design CAD system. The functions of this system include 2D parametric modeling for cross sections based on design rules, 3D automatic profile modeling, shape fairing, parametric database for blade and integration of CAD and CAE for blade. BR715, HP9, and some other blades were designed based on this system [4]. In Sweden, Volvo Aero Corporation and Luella University of Technology jointly developed a prototype system for 3D modeling of blade based on FEM, and proposed a solution of how to build a 3D model of blade based on FEM optimization when the design parameters are incomplete [5]. NASA Lewis Research Center and Iowa State University in the US jointly developed a parametric modeling CAD system for blade—the BladeCAD. 3D parametric modeling of blade was realized and the output of blade modeling data in IGES format was successfully achieved [6, 7]. Besides, Columbia Laboratory of America, TRW and Deutsche Edelstah Werke also developed CAD/CAM systems for blade independently. By using those systems, the design period was shortened and more importantly the quality of blade was improved [8, 9].

Harbin Institute of Technology and Shenyang Liming Co. developed blade profile modeling system based on AutoCAD through secondary development, achieving the modeling of profile and providing tools for investment casting die design. Yang from Shanghai Jiaotong University developed a CAD/CAM system for turbocharger blade modeling, achieving smooth stitching and solving NC machining problems [10]. Cui et al. from North China Electric Power University developed a blade modeling system based on ARX of AutoCAD [11].

The key laboratory of Contemporary Design and Integrated Manufacturing Technology of Northwestern Polytechnical University researched into the CAD/CAM system of blade since 1996. With the financial support of a number of funding, a series of systems were developed as follows [12–14]:

(1) Rotor blades CAD/CAM system based on UGII and Motif (1997).
(2) CAD/CAM prototype system for investment casting die of turbine blade based on I-DEAS (1996–2000).
(3) CAD system for rotor blade based on UGII (2001–2005).
(4) Parametric modeling system for cathode of investment casting die (2007).

1.3.2 *Intelligent Design for Investment Casting Die*

CAD technology came into being 40 years ago. With the development of computer technology and modeling technology such as curve modeling, surface modeling and solid modeling, domestic and overseas researches on CAD method and system flourish. In the early 1960s, mold CAD research was conducted by some foreign car companies. The rapid development of computer software, hardware, and artificial intelligence allowed the mold CAD applications to develop into higher level.

Overseas studies on mold CAD technology were carried out earlier. Researchers from the United States, Israel, Singapore and Japan studied the mold CAD technology, method and system in depth, and some intelligent mold design systems were developed. Fuh et al. [15] from Singapore researched the knowledge-based injection mold design technology from the 1990s. In 2002, the IMOLD was developed and then successfully commercialized. Ong et al. [16] constructed the injection mold design system CADFEED through an object-oriented approach. Chin and Wong [17, 18] developed a knowledge-based cost estimation system DTMOULD-1 for injection mold design. Mok et al. [19, 20] from Hong Kong developed an Internet-based and interactive-knowledge-based injection mold CAD system IKMOULD. Bozdana and Eyercioglu [21] developed an expert system for injection process parameter selection. Chan et al. [22] proposed a knowledge-based mold design system IKBMOULD and researched into the management of related design knowledge. Lin et al. [23] developed a knowledge-based parametric drawing mold design system based on Pro-E. In terms of domestic researches, Shanghai Jiaotong University Mold CAD Engineering Center [24–26], Huazhong University of Science and Technology [27, 28], Zhejiang University [29] etc. developed some expert mold design systems, such as DPES and BASECAD. Generally, there is a trend in mold CAD technology toward standardization, intelligence, integration, specialization and cyberization.

Current studies on mold CAD mainly focus on injection mold and stamping dies, but rarely involve investment casting die of turbine blade. The design process of investment casting die is a systematic and tedious work. The major difficult lies in the complex structure of dies and the design process that depends more on experience rather than theory. Focusing on this issue, Wang et al. [30] from the Northwestern Polytechnical University investigated the CAD technology of tribune blade investment casting die, and summarized the characters and design methods of the die. However, there is no design system that supports the whole design process of investment casting die, and the design and optimization of the die cavity still remain to be studied further. In terms of the major issues in casting die design, namely the design of the die cavity and the die base, related studies are listed below:

1. Die cavity design method

The design process of die cavity includes two major issues, the multistate model transformation and cavity parting design.

(1) Multistate model transformation

Multistate model transformation mainly consists of the following steps: (1) Blank model design by adding machining allowance; (2) Process model design by adding process accessories to the blank model; (3) Cavity model design by adding shrinkage factors to the process model.

In terms of model transformation, Wang et al. [31] proposed a DSG-based method for the transformation from the design model to the blank model. Qin et al. [32] researched the inverse transformation method from the blank model to the design model. Zhu and Quan [33], with the idea of parametric design, developed a tool based on Solid works 2001 for blank model design. The 3D blank model can be formed automatically through secondary development and analysis based on the information of model dimension, structure and process requirements. Xu et al. [34] carried out a case study into the MUMPS surface micromachining process and researched into the automatic transformation method from geometric model to process feature model on the ACIS platform. Ma and Wang [35] proposed a new set of feature description methods and systems structures, which achieved the model transformation for sheet bending parts from the design feature model into the process planning model based on feature mapping principles. Liu and Chen [36] proposed the conception of the model of product CAD process information, studied the relationship between the CAD geometric model and the process information model, prompted the feature-based information modeling and transformation method, and realized the transformation from the CAD injection geometric model into the process information model based on the UG NX3.0 platform. However, the studies mentioned above are just adapted to simple and regular components rather than the die cavity of turbine blades with free form surface and complex structures. Moreover, the specific requirements of the casting process for the geometric structure of the model are not taken into consideration. Yang [37] and Liu [38] from the Northwestern Polytechnical University researched into the cavity design processes for rotor blades and guide vanes, respectively, but the researches mainly focused on structure design of specific portions rather than the whole die cavity. Also, the studies were not concerned with the mapping relationship between the investment casting process and the structure of die cavity model, with no enough experience and process knowledge for the design.

(2) Cavity parting

Generally, the parting technique includes the automatic determination of parting direction as well as the automatic generation of the parting line and parting surface. Literatures show that most studies on automatic parting were based on feature recognition and numerical solutions. Tan et al. [39] proposed a parting line determination method based on the premise of a given parting direction. The surface of the casting is divided into visible surface, invisible surface, and degrading surface which were used to determine the parting lines. Ravi and Srinivasan [40] proposed 9 criteria for computer-aided design of parting line and surface to help the user determine a reasonable parting surface. Tu et al. [41] obtained the main contour of the parting lines by projecting the part onto the plate vertical to the parting direction. Zhu et al. [42] proposed the method to determine the parting direction through calculation based on the conception of approximate cone put forward by Antonial, and determined the parting line based on projection. The above approaches attempt to get parting schemes through numerical calculation and geometrical methods, which is effective for simple structures without free surfaces. However, for parts with many free surfaces and complex features, such as the turbine blade, the above approaches are hardly effective.

For the parting of turbine blade investment casting die, Zhang et al. [43] adopted a rule-based approach for the parting design, which to some extent solved the problem of parting. However, the rule base is inflexible and also hard to construct. Meng [44] studied the application of CBR technology in the parting of investment casting die, but there is still drawbacks concerning parting knowledge extraction and case reasoning, which restricts its further application.

2. Die base design

The base of investment casting die mainly consists of the locking structure, lifting structure, and some standard parts. Rapid construction and modification of the model can be achieved by parametric method because of the similarities in the structure of parts and components of the same type. Since the current parametric design method focuses on low-level sets and topology information such as points, lines, and surface, it cannot express the semantic and functional information or reflect the designer's intention. The template-based design can overcome the shortcomings of the parametric design to some extent. The template is a framework with rules embedded in it. It encapsulates the properties within the object and represents the knowledge in an object-oriented way. Modularization and standardization of the products can be achieved through the combination of the template technology and the engineering design, thus greatly improving the efficiency of product design [45]. So far, there have been more than 3000 templates in the GM's template library. After years of development of design automation, Japan's Toyota eventually chose the template design to achieve a major breakthrough in automatic mold design [46]. Hunter et al. [47] studied the template design process of fixtures, classified the design knowledge, and achieved partial reuse of the design knowledge through constructing the knowledge templates. Shi [48] built the standard parts library, the standard structures library and the drawing die templates library based on template and "toy brick" design principles, and achieved template design of covering part mold based on the KBE technology. Yang et al. [49] developed a template library for CAD covering part mold design on the UG platform and achieved template design of mold structures. The current studies concentrate on the expression and construction of geometric template of a single part or component, but do not support complex assembly design. As for researches on structure design of turbine blade investment casting die, Xin [50] studied selection method for standard parts, external parts, and combination fixture parts, respectively, but they did not discuss the design of correlation between assembly components or the position relationships. Nor did they study the automatic generation of mounting holes in the standard parts library. Since the die is a complex assembly with parameter relevance and dimension constraints among related parts, it is necessary to establish a relevant template for assembly in order to realize template-based design, which is concerned with template defining, constructing and instancing.

1.3.3 Optimization of Investment Casting Die Cavity

The investment casting process of turbine blade blank without machining allowance involves many kinds of shrinkage, namely wax pattern shrinkage, ceramic shrinkage, shell shrinkage, and alloy solidification shrinkage. Those types of shrinkage must be taken into consideration during the design process of internal and external profile of die cavity. Traditionally, a global shrinkage ratio is given for the purpose of compensation. The global shrinkage ratio is determined by several factors. Even for the same casting part, the shrinkage ratio of different portions may be different. Die cavity design is one of the most important steps for the complex investment casting die design of turbine blade. The quality of die cavity directly determines the precision of profile and wall thickness of blade. The principle of cavity optimization is to assign reverse deformation to compensate the shrinkage of solidification and cooling process [51].

Constrained by testing measures, conventionally a single global shrinkage ratio was used to optimize the cavity [52, 53] based on the assumption that every portion of the turbine blade has the same shrinkage ratio. However, the cooling speeds of every portion are not identical because of the complex structure of turbine blade.

Hence, the deformation of each portion of the blade is different. As an improvement, it is proposed to use individual shrinkage ratio along the X, Y, Z coordinate axis, and as a result the accuracy of die cavity was improved [54, 55]. The shrinkage ratio of the two methods mentioned above was determined by simple experiments, or even by experience. In order to get qualified casting parts, the die cavity was modified constantly according to the shape and size of casting parts. Eventually, the production cost will be increased, the production cycle extended and the precision poorly maintained.

With the development of casting process simulation and reverse engineering technology, some numerical methods have been verified and widely used in the production [56, 57]. A more accurate reverse deformation value for different portion can be obtained by using simulation method. Modukuru et al. [58] proposed a displacement field superposition method through reversing grid. The deformation was superposed on the nodes reversely through finite element method. This process was conducted iteratively until the shrinkage shape was very close to the ideal shape.

The Key Laboratory of Contemporary Design and Integrated Manufacturing Technology in Northwestern Polytechnical University [59, 60] studied the virtual cavity modification method for designing turbine blade. Based on the reverse engineering, the simulation displacement field was used to modify the cavity to gain high precision casting part. Besides, a lot of works were carried out in terms of process optimization, using different methods to ensure the precision of casting part design and increase the pass ratio of casting part [61, 62].

1.3.4 NDT of Investment Casting Blade and Rapid Finalization

In order to maintain the quality of turbine blade, a comprehensive inspection and evaluation is needed. Currently, there are many types of inspection methods for aero-engine turbine blade, which are listed below:

(1) Ultrasonic inspection method: The advantages of this technique include good penetrating ability, high sensitivity, localization and quantification of defects, and portability. However, measuring resolution and precision is limited because of blind spots and influence of heterogeneous lattice. American Electric Power Science Research Institute (EPRI) developed a phased-array ultrasonic detection technique and applied it on turbine blade inspection. Italian QI Composites Company has also conducted research on this issue.
(2) X-ray inspection method: The advantages of this technique include high accuracy and high inspection speed. However, it cannot locate the defects because of the one direction projection, which restricts the application of this method.
(3) NDT based on CT: NDT based on CT is developed on the basis of X-ray detection method. As the most advantageous NDT method, it can inspect