中國機械工程學刊第四十卷第二期第 149~159 頁(民國一百零八年)
Journal of the Chinese Society of Mechanical Engineers, Vol.40, No.2, pp 149~159 (2019)

Establishment and Realization of Intelligent Integrated Grinding and Measuring Workcell for Blade Edges

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Keywords: blade edges, intelligent manufacturing, on-line measuring, flexible grinding, aero engine.

ABSTRACT

In the aeronautical engineering, leading and trailing edges are the most important parts of a blade surface, whose machining accuracy and shape conformity may exert a crucial influence on the aerodynamic property of the whole blade. Therefore, it urgently needs to execute the manufacturing of blade edges in the manner of high precision, efficiency and consistency. The purpose of this research is to study and establish an intelligent integrated grinding and measuring workcell for blade edges, which could be utilized to derive the desired blade edges so as to serve as a major solution for the final process of those precision-forged blade edges. Based on the design concept of intelligent manufacturing, the workcell contains such subsystems as on-line measuring subsystem, industrial robot subsystem, flexible grinding subsystem, loading/unloading subsystem and intelligent expert subsystem *etc*. In the actual application, the blade edges are rapidly measured by the on-line measuring subsystem to establish the removal allowance model firstly. And then, under the coordination and control of the intelligent expert subsystem, the industrial robot subsystem holds the blade and executes the grinding motion and station transfer. Finally, the blade edges are grinded adaptively on the flexible grinding subsystem. As a result, the automatic manufacturing process of “measuring - grinding - measuring” of blade edges is realized, which shows the intelligence of the manufacturing workcell obviously. Also, the grinding and measuring process of blade edges are executed on the system to verify its precision and feasibility. As the experimental results show, the precision and efficiency of the system can meet the requirements of the modern production of blades, which manifests the huge practical significance and application value of the system.

Paper Received October, 2018. Revised March, 2019. Accepted June, 2019. Author for Correspondence: Chao Bi.

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INTRODUCTION

In the field of aviation industry, as the core component of propulsion system, aero engine has been always reputed to be the heart of an aircraft, whose major function is to convert the chemical energy of the fuel into the kinetic energy of the airplane [1]. Therefore, it exerts a really important impact on the flight performance such as security, reliability, mobility and economy *etc*. In an aero engine, there are hundreds of blades of different kinds and functions employed to realize the compression and expansion of the airflow in the channel as well as the change of airflow direction, whose geometries may impose a significant influence on the dynamic performance of the engine [2]. Being the key parts of an aero engine, blades are always characterized with great varieties, large quantities, different shapes and complex structures *etc*, which operate at high speed and in harsh environments characterized by high temperature and huge pressure. As a result, the production of various and numerous blades has occupied a considerable proportion in the whole manufacturing process of an aero engine.

Generally speaking, in order to ensure the excellent dynamic performance of aero engine, blade surfaces are always designed to be free-form surfaces according to the principle of fluid mechanics, which could be principally divided into 4 parts, *i.e.* convex airfoil surface, concave airfoil surface, leading edge and trailing edge (*i.e.* blade edges)[3]. Among them, as the connection parts between the convex and concave airfoil surfaces, the leading and trailing edges prove to be the most important parts of a blade, whose machining accuracy and shape conformity may exert a crucial influence on the aerodynamic property of the whole blade [4].

Currently, in accordance with the development demands of the advanced aero engine of new generation, geometrical dimensions of blade edges are becoming smaller and smaller, while the required accuracy and quality higher and higher, which is in an attempt to satisfy the requirements of the bypass ratio, thrust-weight ratio and service life of the aero engine [5].

In addition, blades must possess precise dimensions, accurate shapes and strict surface integrity so as to improve the efficiency of air compressing, reduce the consumption of secondary flow and increase the stall margin, particularly the leading and trailing edges [6]. At the same time, difficult-to-machine metal materials are gradually adopted as the materials of blades, such as nickel-based superalloys, titanium alloys, heat-resistant alloys and stainless steels *etc*. All of those mentioned above put forward high requirements and huge challenges to the manufacturing and inspecting means of blade edges, as well as the corresponding equipments.

So far, many groups and researchers have carried out the study of grinding and measuring technologies for those conventional workpieces deeply and systematically, leading to the development of so many advanced multi-axis NC machine tools and robotic manufacturing systems of various forms. All of these keep them ahead in the field of manufacturing and inspecting of routine parts. However, as to ones with complicated structures and free-form surfaces such as blades in an aero engine, especially the leading and trailing edges, the multi-axis NC machine tools and robotic manufacturing systems may be not competent due to their complicated geometries and high precision demands.

In the majority of manufacturing and researching establishments of aero engine, the grinding and measuring assignments of blade edges typically require manual intervention, such as the polishing manner of hand grinding and the inspecting manner of template matching, which cannot meet the requirements of modern aeronautical manufacturing in the matter of machining quality and efficiency [7]. Also, being time-consuming and labor-intensive, the manual operation may bring about the problems of instability of accuracy and inconformity of geometry at the regions of blade edges, which might have an adverse impact on the aerodynamic property of the blade. As a result, it urgently needs to carry out the research on advanced manufacturing technologies of blade edges towards the goal of realizing their machining and inspecting manner of high accuracy, efficiency and conformity, which will help to improve the overall performance of the aero engine.

Currently, the world manufacturing field is going through the change of Industry 4.0, bringing about the revolution of production mode and the industrial upgrading from automation and informationization to intelligentization. In particular, the core of Industry 4.0 is intelligence, which has become the mainstream developing direction of the production and operation mode of factories in the future. As to the grinding and measuring task of blade edges, many researchers have attempted to automate the process in the manner of using machine-based or robot-based manufacturing methods and equipments to replace the manual labor and improve the productivity and quality as well. Xiao Guijian *et al* developed the method of equivalent self-adaptive belt grinding, in which a cubic boron nitride belt was used to improve the dimensional accuracy, profile shape errors and surface quality of the real-R edge of the precision-forged blade [8, 9]. Meshreki M *et al* performed the analysis for a robotized grinding process of titanium high pressure compressor blades, in which the major factors that influenced the accuracy of the process and the final part quality was studied by analyzing the dynamic characteristics of the grinding wheel as well as that of the blade [10]. Wang Wei *et al* set up a method to generate the grinding paths including the curve length spacing optimization for the belt grinding robot workcell and off-line simulation platform, which could help to provide theoretical support for the smooth and accuracy path of the robotic surface grinding procedure [11]. Accordingly, there are distinct, practical and urgent demands to realize the development of intelligent integrated grinding and measuring equipments for blade edges at the level of manufacturing workcell.

On the base of this background, for the purpose of completing the manufacturing and inspecting task of blade edges in the manner of high accuracy, efficiency and conformity, an intelligent integrated grinding and measuring workcell for blade edges is introduced in the paper, which is used to form desired blade edges. Focusing on the design concept of intelligent manufacturing, the workcell is composed of several subsystems such as on-line measuring subsystem, industrial robot subsystem, flexible grinding subsystem, loading/unloading subsystem and intelligent expert subsystem *etc*, which could serve as a major solution for the final process of the precision-forged blade edges in the aero engine. Firstly, the on-line measuring subsystem characterized with non-contact detection is adopted to realize the rapid digital inspection of the blade edges and then set up the removal allowance model according to the measuring results. Secondly, under the coordination and administration of the intelligent expert subsystem, the grinding motion and station transfer of blades by the industrial robot subsystem is achieved based on the removal allowance model established. At last, the leading and trailing edges of the blade grabbed on the robotic arm can be grinded adaptively on the flexible grinding subsystem. In this way, the automation of the whole manufacturing process of blade edges can be accomplished, which is of great practical significance and application values.

After a brief review and introduction, the rest of the paper is organized as follows. First of all, the structure features of the blade surface are described briefly in Section 2. And then, Section 3 introduces the working principles of the intelligent integrated grinding and inspecting workcell for blade edges proposed. Next, the system configurations are presented as the solving methodology in detail in Section 4. Afterwards, the grinding and inspecting experiments of blade edges are shown in Section 5, as well as the results and analysis. Finally, conclusions of this piece of work are summarized in Section 6.

STRUCTURE FEATURES OF BLADE SURFACE

The functions and characteristics of blades contribute themselves to be the most complex parts in the aeronautical engineering field. As the gradual development of the aero engine from turbojet series to turbofan series, the surfaces and structures of blades are becoming more and more complex, presenting as the trends of wide chord, thin body, small edges, large twisted bending and increased forward sweep *etc*, all of which bring large difficulties to the machining and inspecting procedure of blades [12].

In general, a blade surface can be divided into 4 different regions for convenience of machining and detecting, *i.e.* convex airfoil surface, concave airfoil surface, leading edge and trailing edge, which would be presented as 4 curves on a certain cross section of the blade surface produced by the intersection of a plane and the blade model, as shown in Fig. 1. It can be observed that when the blade is at the working position, the marginal region towards the airflow is just the leading edge, *i.e.* the arc or elliptical arc between P_1 and P_2; while that follows the airflow is the trailing edge, *i.e.* the arc or elliptical arc between P_3 and P_4. Besides, the concave airfoil surface is the pressure surface of the blade, *i.e.* the curve from P_4 to P_1; while the convex airfoil surface is the suction surface of the blade, *i.e.* the curve from P_2 to P_3.

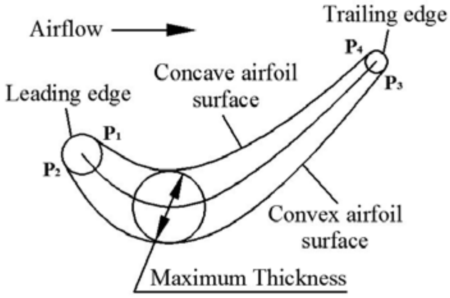


Fig. 1. Cross section of a blade surface.

DETERMINATION OF GRINDING ALLOWANCE OF BLADE EDGES

Currently, blades of the advanced aero engine of new generation are usually manufactured by a precision-forged process, in which the surface quality is guaranteed by the high molding accuracy, so that it does not need any secondary processing to derive the desired surfaces [13]. However, due to the large variation in the curvature of blade edges, the removal allowances at the leading and trailing edges are usually small and uneven, leading to difficulties in meeting the processing requirements with precision-forged procedure [14]. Accordingly, after the blade surfaces are formed by precision-forged process, there are still certain removal allowances at the regions of blade edges as shown in Fig. 2, as well as the burrs and flashing. In this case, it usually needs to eliminate the burrs and flashing at the blade edges and then mill the blade edges to the desired chord length according to the design demands in the previous process preparation stage [15]. Afterwards, the blade could be grinded and polished on the intelligent integrated grinding and measuring workcell described in the paper to satisfy the machining requirements of blades.

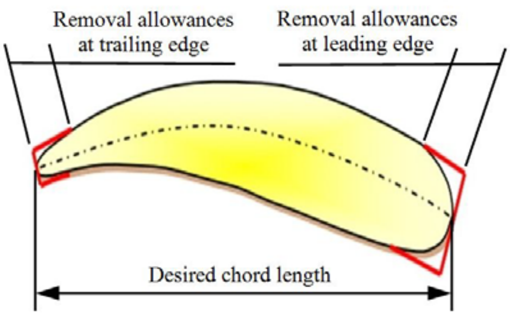


Fig. 2. Grinding schematic of blade edges.

In the paper, the removal allowances at the blade edges are determined by the thickness of the cross section at the specified positions. Therefore, at first, a family of planes perpendicular to the stacking axis of blade is selected to disperse the blade surface into a family of cross sections on the basis of the measuring requirements, in which the corresponding profile curve of the blade on every cross section is derived [16]. And then, the blade profile curve can be divided into convex airfoil surface, concave airfoil surface, leading edge and trailing edge. Afterwards, the edge curves would be extracted and dispersed into measuring points, *i.e.* leading edge points and trailing edge points, which are utilized for the scanning path planning. Finally, it needs to measure the blade edges along the scanning path and then fit the measuring data to the actual contour curves.

According to the fitted actual contour curves and the theoretical ones of the blade, the thickness at specified positions can be calculated. And then, by comparing the actual thickness with the theoretical values, the removal allowance model of the blade could be established. As shown in Fig. 3, 5 transversals are selected at the region of leading edge or trailing edge on every cross section, which are coded as A-A, B-B, C-C, D-D and E-E. Thus, the removal allowances at the region of blade edges could be determined by the thickness of contour on the 5 transversals. In this way, the machining allowance model of the measured blade could be built up by combining the actual contour curves with the theoretical ones.

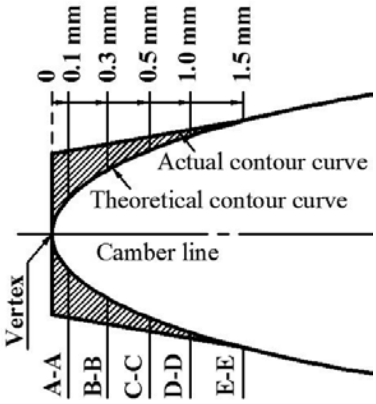


Fig. 3. Removal allowance model of blade edges.

WORKING PRINCIPLES AND SYSTEM CONFIGURATIONS

Working Principles of the Workcell

In recent years, as the perpetual development and improvement of the aeronautical manufacturing technology, the intelligent production of blades gradually becomes a hot issue in the aviation field. Thus, the research and development of intelligent processing equipments at the level of manufacturing workcell is achieved by the establishment of the intelligent integrated grinding and inspecting workcell for blade edges in the paper. As a kind of processing equipment for blade edges of high intelligentization and automation, the workcell reveals the typical features of intelligent manufacturing, which could be considered as a perfect application example for the intelligent manufacturing technology. As can be seen in the block diagram of the workcell illustrated schematically in Fig. 4, the system includes several subsystems such as on-line measuring subsystem, industrial robot subsystem, flexible grinding subsystem, loading/unloading subsystem and intelligent expert subsystem *etc*.

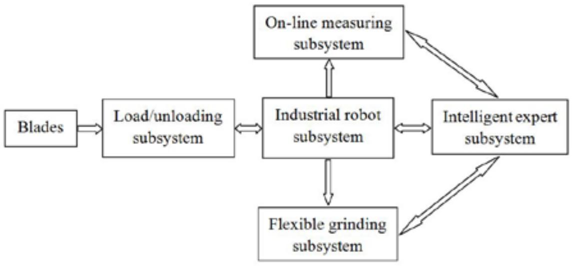


Fig. 4. Block diagram of the intelligent integrated grinding and measuring workcell for blade edges.

In particular, the loading/unloading subsystem appears as an automatic revolving turntable, being used to load and unload a certain number of blades at the same time, so as to improve the automation level of the blade machining process. The on-line measuring subsystem is employed to scan and detect the contour profiles of the blade edges in a rapid manner, so as to derive the actual contour curves of the blade edges. The flexible grinding subsystem is used to profile the blade edges by the self-adaptive grinding wheels, determining their dimensional precision and surface quality. The industrial robot subsystem plays an indispensable role in the whole grinding and inspecting procedure of blade edges, which is applied to hold the blade and realize the grinding motion and station transfer. In this way, procedures of loading, unloading, transfer, on-line measuring and flexible grinding *etc* of blades are completed. As the core of the whole system, the intelligent expert subsystem could control the on-line measuring subsystem to complete the inspection of blades and receive the measuring data so as to establish the removal allowance model of the current blade through data fusion. And then, it dominates the industrial robot subsystem to hold the blade and the flexible grinding subsystem to finish the final machining of the blade edges.

The whole intelligent integrated grinding and measuring workcell for blade edges described above is presented in Fig.5, while the more clear and intuitive presentation of every subsystem is shown in Fig. 6.


Fig. 5. Intelligent integrated grinding and measuring workcell for blade edges.

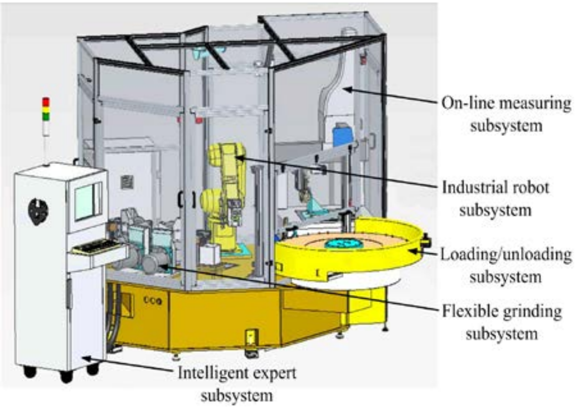


Fig. 6. Block diagram of the workcell.

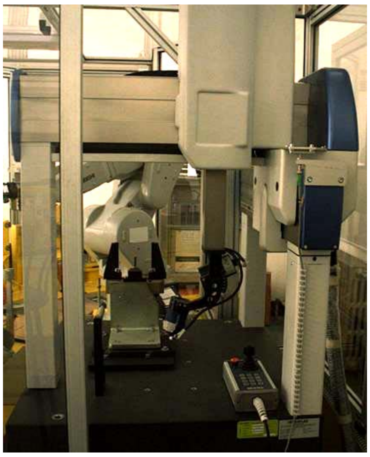


Fig. 7. On-line measuring subsystem.

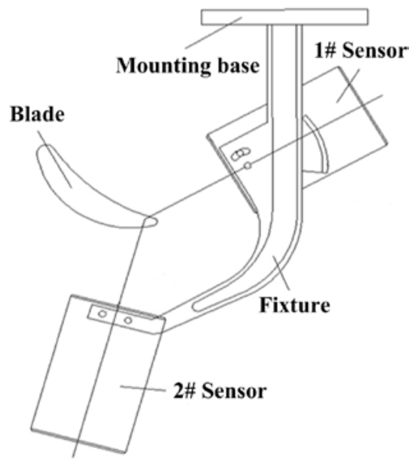
On-line Measuring Subsystem

Characterized with high accuracy and versatility, the on-line measuring subsystem plays as a bridge in the whole system, which is used to collect the cross section information of the blade edges rapidly. It not only measures the blade before grinded so as to feedback the measuring results to the intelligent expert subsystem, but also detects the blade after grinded to execute the analysis and evaluation of machining errors. Consequently, the on-line measuring subsystem connects the procedures of designing, manufacturing and measuring of blades together. In addition, it helps to improve the machining accuracy and efficiency obviously, as well as the solution of the problem of information isolated island in the manufacturing procedure.

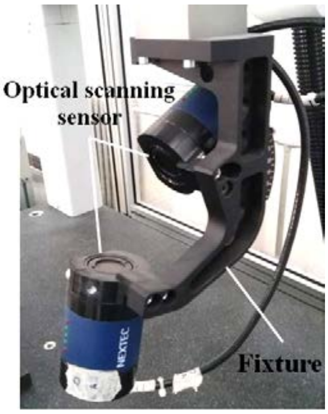
As can be seen in Fig. 7, the on-line measuring subsystem is built up by the improvement of a traditional coordinate measuring machine (CMM). The terminal probe at the end of Z axis is composed of two non-contact optical scanning sensors typed by WIZprobe, which are installed at a certain angle to each other by a fixture, as shown in Fig. 8. Therefore, the advantages of large motion range, high location accuracy and good generality *etc* of CMM and those of non-contact, rapid response and high sampling frequency *etc* of optical scanning sensors are combined together to provide a convenient, rapid, reliable and precise measuring solution for blade edges. Also, there are several base establishment and result evaluation methods imbedded according to the measuring task of blade edges.

According to the shape features and measuring requirements of the blade edges, two optical scanning sensors described above are installed at a certain angle to each other on a specified fixture, which are denoted by 1# Sensor and 2# Sensor respectively. In this way, the terminal probe used for inspection of blade edges is established, which can be fixed on the end of Z axis of the CMM to realize the effective and accurate measurement of blade edges, as shown in Fig. 8.

As to different blades, the relative position relationship between the measured blade and the terminal probe could be adjusted by two means if necessary. One is to adjust the angle between the two sensors by the bolts; the other is to change the angle between the measured blade edges and the terminal probe by rotating the blade [17]. As a result, the distinctive terminal probe improves flexibility of the subsystem to make itself be applicable for blades of various kinds.



(a)



(b)

Fig. 8. Terminal probe: (a) schematic diagram; (b) actual object.

Under the control and coordination of the intelligent expert subsystem, the scanning motion of the terminal probe could be accomplished by the movement of X, Y and Z axes of the CMM in accordance with the measuring path planned. In the scanning procedure, the leading edge or trailing edge is divided into two parts before being scanned [18]. At first, the 2# Sensor is switched on to scan the edge curves facing down, and then switching to 1# Sensor to scan those facing up. Finally, the data collected by the two sensors are stitched together to form a whole leading edge curve or trailing edge curve, as shown in Fig. 9. Consequently, the complete curves of blade edges and a small quantity of the curves of convex and concave airfoil surfaces on designated cross section are reconstructed for the follow-up analysis and evaluation.

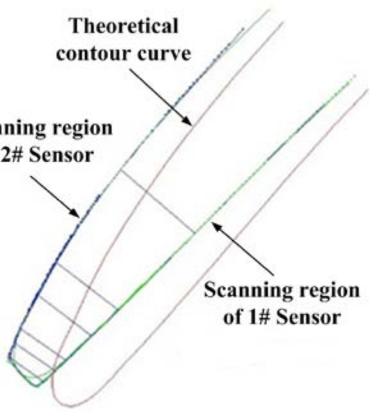


Fig. 9. Measuring results of a blade section.

Industrial Robot Subsystem

By integrating an industrial robot subsystem as the manipulator, the intelligent integrated grinding and measuring workcell becomes especially suitable for processing those blade surfaces with complex geometries, which is mainly composed of an industrial robot of multi-degree of freedom and its controller. The processing mode of those grinding systems with industrial robots possesses both the advantages of manual grinding manner and CNC grinding system, which not only improves the grinding efficiency and the machining quality, but also reaches better conformity. Therefore, an industrial robot from Mitsubishi Corporation of Japan is selected as the main actuator in the system, as shown in Fig. 10. Provided with better motion speed, location accuracy and execution efficiency, this kind of industrial robot is equipped with new servo control technology and optimized arm structure, which improves the automatic level of itself greatly. Also, the function of the industrial robot is so powerful that it can be equipped in a small space.

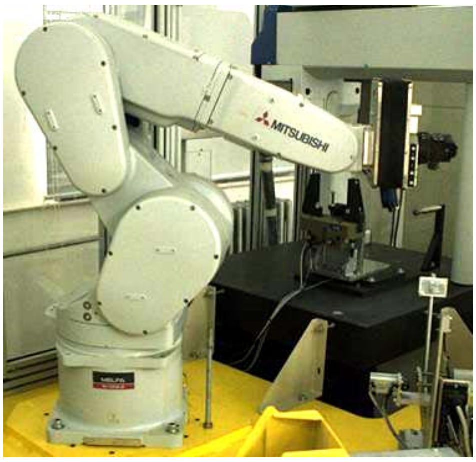


Fig. 10. Industrial robot subsystem.

There are many advantages to introduce an industrial robot into the intelligent integrated grinding and measuring workcell for blade edges set up in the paper. This is due to the reasons as follows. Firstly, with good compatibility, the robotic system can memorize a lot of complex work and alter the program or switch the grippers when necessary; secondly, compared with the special machine tools with complicated structures, industrial robot could complete the machining task of blade edges of different types so as to improve the applicability of robotized manufacturing system remarkably; Thirdly, the industrial robot possesses high degree of freedom, so that it provides convenience for the installation of its supporting equipments without the need to adjust the distance between the robot and other equipments [19].

Flexible Grinding Subsystem

Containing controller, driving circuits, motors, flexible self-adjusting grinding wheels and correction mechanism *etc*, the flexible grinding subsystem could provide promising prospects for relieving operators from noisy work environment, as well as improving the grinding accuracy and consistency, as shown in Fig. 11 (a).

(a)

(b)

Fig. 11. Flexible grinding subsystem and light flexible grinding wheel: (a) flexible grinding subsystem; (b) flexible grinding wheel.

In the grinding procedure of blade edges, the contact form between the general grinding wheel and the grinded surface is just a point or a line, which may decrease the grinding efficiency and make it difficult to form. However, the contact form between the flexible self-adjusting grinding wheel and the grinded surface is flexible contact, which has the advantages of large contact area, easy to fit, high grinding efficiency and good surface quality *etc*. Thus, the flexible self-adjusting grinding wheel is more suitable for the grinding task of the blade surfaces because of its superior material removal ability and lower overall system stiffness. As a result, the light flexible grinding wheels from 3M Grinding Corporation of America are selected in the system, as can be seen in Fig. 11 (b).

After finishing the grinding procedure of a blade, the flexible grinding wheels would be corrected by the correction mechanism integrated in the workcell under the control of the intelligent expert subsystem, aiming at keeping the sharpness of the flexible grinding wheels almost unchanged. In addition, the relevant parameters of the motion path of the industrial robot would be changed and modified automatically by the intelligent expert subsystem before the next grinding procedure, which makes the grinding motion associated only with the blade model and the removal allowance. In this way, the constant flexible grinding state is realized.

Loading/Unloading Subsystem

As shown in Fig. 12, the loading/unloading subsystem is mainly composed of a turntable and loading/unloading fixtures. The turntable can rotate automatically and possesses a certain positioning accuracy, so as to ensure the location repeatability of many blades, which helps to make the industrial robot easy to hold the blades. Moreover, the loading/unloading fixtures are fixed on the turntable, so that certain numbers of blades could be loaded on the turntable at the same time. In the procedure of loading and unloading blades, the turntable rotates every blade on it to the specified position to wait for the holder installed on the robot to grasp, as can be seen in Fig. 13.

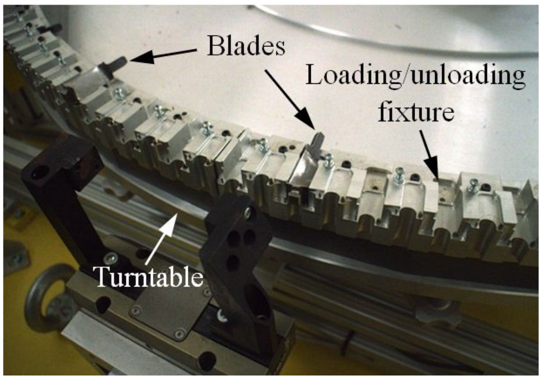


Fig. 12. Loading/unloading subsystem.

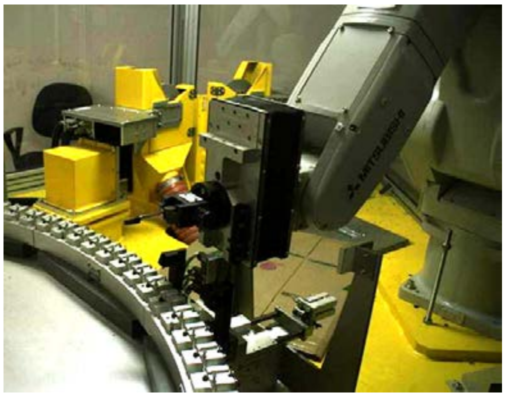


Fig. 13. Holding procedure of blades.

Intelligent Expert Subsystem

For a manufacturing system with flexible self-adjusting grinding wheels, controlling the industrial robot to perform precise material removal from blade surfaces is a huge challenge, leading to a pivotal potion for the intelligent expert subsystem. In the intelligent integrated grinding and measuring workcell for blade edges, the intelligent expert subsystem plays a really important role, which makes itself the core of the whole system. Containing so many modules such as path planning module, motion controlling module, data analysis module, grinding process module and decision analysis module *etc*, it highlights the intelligent features of the workcell. As shown in Fig. 14, the interactive relationship of information and control between the intelligent expert subsystem and other subsystems is presented.

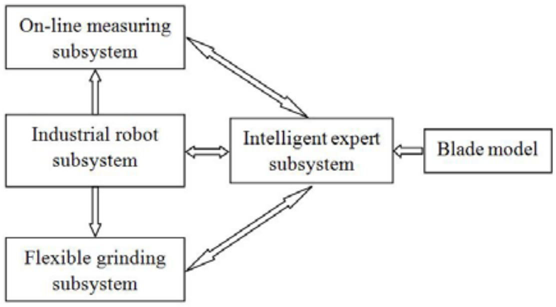


Fig. 14. Interactive relationship between the intelligent expert subsystem and other subsystems.

On the one hand, the intelligent expert subsystem plans the measuring path of the blade edges according to the theoretical CAD model imported by the path planning module, and then controls the industrial robot to hold the blade and place it in the measurement space, so that the on-line measuring subsystem can scan and detect the geometric characteristics of the blade edges on the basis of the planned path, in which the actual contour information of blade edges is derived. By comparing the actual contour curve with the theoretical one, as well as the thickness at the specified positions, the distribution of the removal allowance of the blade edges could be determined, which leads to the establishment of the removal allowance model. Therefore, the closed-loop control is realized by feeding back the measuring information to the intelligent expert subsystem. On the other hand, by receiving the feedback information of the on-line measuring subsystem and combining with the theoretical CAD model, it could establish the removal allowance model of the blade edges and then plan the grinding path of the blade edges. In the grinding procedure, the industrial robot grasps the blade and moves along the grinding path while maintaining the regions to be grinded contact with the flexible self-adjusting grinding wheels. Finally, the on-line measuring subsystem is controlled by the intelligent expert subsystem to execute the final inspection of blade to evaluate the blade edges qualified or not. Moreover, it can drive the correction mechanism to correct the flexible grinding wheels to improve their grinding efficiency and accuracy.

GRINDING AND MEASURING EXPERIMENTS

In this section, the experimental verification of the intelligent integrated grinding and measuring workcell for blade edges introduced in the paper is carried out, in which the workcell is used to execute the grinding and measuring experiments of the edges of a precision-forged blade. As indicated in Fig. 15 is the whole grinding and measuring process for blade edges in the workcell.

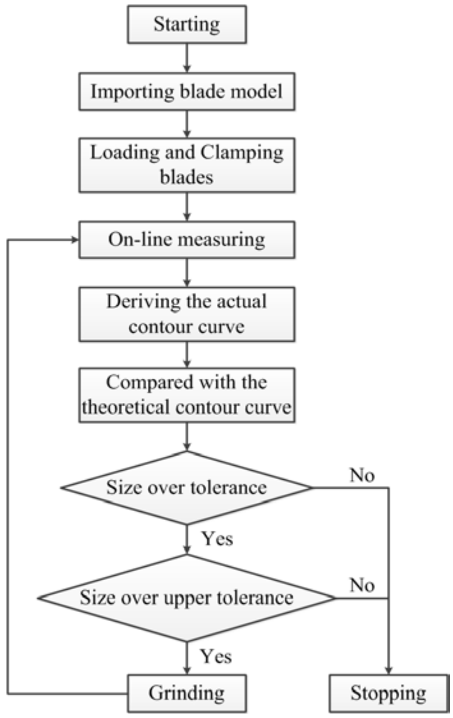
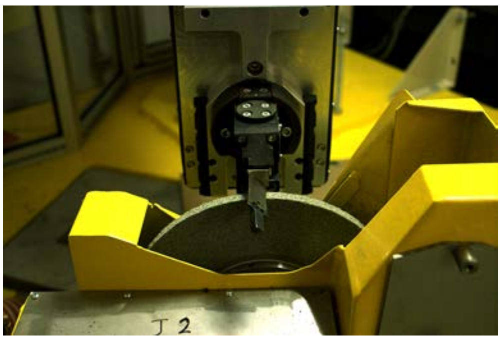


Fig. 15. Flowchart of the grinding and measuring process for blade edges.

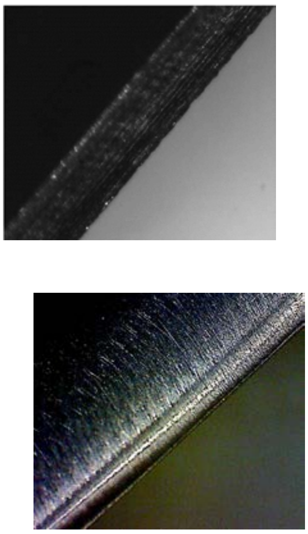
In the experimental investigation procedure, 3 cross sections are selected on the grinded blade. And then, the measuring results before and after grinding on these 3 cross sections are compared and analyzed to evaluate the application performance of the system. The experimental scene is shown in Fig. 16, which contains the grinding procedure and measuring procedure. Besides, states of the blade edge before and after being grinded are shown in Fig. 17.



(a)

(b)

Fig. 16. Experimental scence: (a) grinding procedure; (b) measuring procedure.



(a) (b)

Fig. 17. Blade edge: (a) before being grinded; (b) after being grinded.

According to the design requirements of this kind of precision-forged blade, the maximum allowable machining errors on the transversals coded as A-A, B-B, C-C, D-D and E-E are shown in Tab.1 respectively.

In General, the direct method to test the quality of a blade is whether its geometric errors satisfy the design tolerance. Therefore, the measuring results on every transversal of the blade after being grinded on the workcell are presented in Tab.2.

As can be observed from the results of the 3 cross sections shown in Tab.2, after the blade edges are grinded, the maximum error of A-A is 0.048mm, while the minimum is -0.045mm; those of B-B are 0.037mm and -0.063mm; those of C-C are 0.068mm and -0.055mm; those of D-D are 0.087mm and -0.092mm; those of E-E are 0.106mm and -0.103mm. According to the design requirements of the blade illustrated in Tab.1, all of the machining errors are in the allowable range. Consequently, the machining scheme of the system is practical and the machining accuracy can meet the requirements.

As can be seen in Tab.3, the removal allowances on every cross section of the blade edge before and after grinding are shown.

Table 1. Maximum allowable machining error on every transversal

Section	A-A	B-B	C-C	D-D	E-E
Maximum allowable machining error/mm	±0.072	±0.09	±0.108	±0.120	±0.2

Table 2. Maximum and minimum errors of every cross section

		A-A	B-B	C-C	D-D	E-E
1st cross section/mm	Max	0.048	-0.037	0.068	0.083	-0.062
	Min	-0.024	-0.063	-0.055	-0.092	-0.103
2nd cross section/mm	Max	0.026	0.037	0.067	0.073	0.051
	Min	-0.041	-0.035	-0.027	0.028	-0.017
3rd cross section/mm	Max	0.020	-0.025	0.033	0.087	0.106
	Min	-0.045	-0.049	0.024	0.035	0.037

Table 3. Removal allowance on every cross section before and after grinding

		A-A	B-B	C-C	D-D	E-E
Before grinding/mm	1st cross section	0.097	0.091	0.067	0.046	0.040
	2nd cross section	0.175	0.154	0.133	0.086	0.064
	3rd cross section	0.156	0.129	0.096	0.063	0.052
After grinding/mm	1st cross section	0.088	0.061	0.046	0.034	0.031
	2nd cross section	0.074	0.042	0.065	0.066	0.054
	3rd cross section	0.059	0.033	0.037	0.054	0.051

As shown in Tab.3, before the blade is grinded, the removal allowance varies largely at the blade edge, while after grinded, the varying range of the removal allowance decreases. For example, on A-A, before the blade is grinded, the varying range is 0.175mm, while after grinded is 0.088mm; on B-B, before grinded, the varying range is 0.154mm, while after grinded is 0.042mm. Others are the same. As can be concluded through these experimental data, even if under the circumstance that the removal allowance of the blade edge varies a lot, the intelligent manufacturing workcell can complete the grinding procedure according to the removal allowance model of the blade, so as to guarantee the high machining accuracy and conformity of the blade edges, which manifests the intelligence of the system obviously.

CONCLUSIONS

Based on the urgent demands of the automatic manufacturing of blade edges in the production of an aero engine, the structure and components of a robotized grinding and measuring system for blade edges are described detailedly in the paper, *i.e.* the intelligent integrated grinding and measuring workcell, which is in accordance with the design idea of intelligent manufacturing. Adopting the self-adjusting machining method and industrial robot as the main executer, the workcell combines the on-line measuring, flexible grinding, precision positioning and intelligent decision-making technologies *etc* together. Under the support of the intelligent expert subsystem, the workcell can grind and measure the blade edges automatically. Therefore, it possesses the typical characteristics of intelligent manufacturing system. In the paper, the system is used to grind and measure the edges of a precision-forged blade. As the results show, the machining errors of 5 transversals are all in the maximum and minimum range according to the design requirements of the blade. Also, the workcell can plan the motion path according to the removal allowance model and then complete the grinding procedure to guarantee the blade edges possess higher machining accuracy and consistency. Therefore, the system can meet the requirements of modern aeronautical manufacturing, which could be used as an effective machining manner of blade edges in the future.

ACKNOWLEDGEMENT

This research was supported by the National Science and Technology Major Project for ‘‘High-grade Numerical Control Machine Tools and Basic Manufacturing Equipments” of the Ministry of Science and Technology of China (No. 2016ZX04001002). The authors would like to thank all the editors and anonymous reviewers for their help in improving the paper.

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葉片進排氣邊智慧磨削檢測單元的搭建與實現

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摘要

在航空發動機中，進排氣邊是葉片型面最為重要的部位，其製造精度和表面完整性對於整個葉片的氣動性能有著至關重要的影響。因此，迫切需要實現對葉片進排氣邊的高精度、高效率和高一致性的加工與檢測。本文在光學掃描測量技術和柔性自我調整磨削技術的基礎上，搭建了一套葉片進排氣邊智慧磨削檢測一體化單元。該系統以智慧製造的設計理念為核心，包括了線上測量子系統、工業機器人子系統、柔性磨削子系統和智慧專家子系統等多個子系統。在應用過程中，首先採用線上測量子系統對葉片進排氣邊實現快速的數位化測量並建立加工餘量模型，然後在磨削專家子系統的協調和控制下，利用工業機器人子系統抓取葉片並執行磨削運動和葉片工位傳遞，最後在柔性磨削子系統上完成進排氣邊的自我調整磨削加工，從而完成進排氣邊的“測量-磨削-測量”的自動化全過程。本文在該系統上進行了某精鍛葉片進排氣邊的磨削與測量實驗，以對系統的加工精度及加工方案的可行性進行驗證。實驗結果表明，該系統的加工精度和效率能夠滿足葉片現代化生產的要求，具有很大的現實意義和實際應用價值。