



# A novel polishing technology for leading and trailing edges of aero-engine blade

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## Abstract

As one of the most important part of an aero-engine, blade has a critical effect on its manufacturing level. Especially, surface quality and profile accuracy of the leading and trailing edges have a direct influence on the aerodynamic performance of an aero-engine. At present, the machining methods of the leading and trailing edges are milling or grinding firstly, and then polishing by hand. This combination pattern of milling or grinding and polishing by hand has low efficiency and poor consistency. Therefore, a novel polishing technology for leading and trailing edges of blade using the flexible polishing wheel is proposed in this manuscript. Firstly, the overview of proposed novel polishing technology is presented. And then the basic principle and flexible polishing law of the flexible polishing wheel are introduced and analyzed. Finally, the verification experiments are carried out, including sample verification and blade verification. And the experiments results validate the feasibility of the proposed polishing technology. This novel polishing technology which instead of combination pattern of milling and polishing can simultaneously guarantee both profile accuracy and surface roughness, and the machining efficiency of blade edges will improve 2 times than the conventional method.

**Keywords** Aero-engine blade · Leading and trailing edge · Polishing technology · Flexible polishing wheel

## 1 Introduction

As one of the most important part of an aero-engine, blades have a critical influence on its aerodynamic performance. The quality and accuracy of the aero-engine blades determine directly the overall manufacturing level of an aero-engine [1, 2]. Nowadays, many aero-engine blades are usually manufactured with a precision-forging process. The dimensional precision and quality of a blade body surface can be guaranteed by the precision forging instead of secondary machining operation. However, because of large changes

in the curvature of the leading and trailing edges, it is difficult for precision forging to make the dimensional precision and quality satisfy the design requirements. Furthermore, the machining allowances of the leading and trailing edges are not uniform and equivalent [3, 4]. At present, the machining methods of the leading and trailing edges are milling or grinding firstly, and then polishing by hand. This process flow is inefficient and the manual polishing process of the leading and trailing edges will easily result in higher rejection rates and poor machining consistency. Moreover, the leading and trailing edges are the air inlet and air outlet of a blade, and their shapes have a significant impact on the aerodynamic performance of a blade. Therefore, surface quality and profile accuracy of the leading and trailing edges are very important to an engine performance and lifetime. It is very urgent and necessary to study a high efficiency numerical control (NC) polishing method of the leading and trailing edges to replace the artificial polishing process in the field of aero-engine blade manufacturing [5, 6].

Up to now, many scholars also have been made to research on the automatic polishing and grinding methodologies for the leading and trailing edges of aero-engine blades. Huang et al. [7, 8] analyzed the key technology of NC abrasive belt

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grinding for the leading and trailing edges of aero-engine blades in which the results of experiments show that the dimensional accuracy of the edges radius can reach  $\pm 0.07$  mm. Zhang and Wang studied on the flexible polishing technology for edge of aero-engine blades [9]. they used belt grinding to grind a blade edges and the results of grinding experiments showed that the surface quality of the blade edges was obviously improved. He [10] proposed a belt grinding tool system for the leading and trailing edges and the root part of a blade. A way of double return roller belt grinding was innovatively designed in his manuscript. Xiao et al. [11] proposed the method of self-adaptive belt grinding for the leading and trailing edges of an aero-engine precision-forged blade, and the results showed that the surface quality and dimensional accuracy were evidently improved compared with the conventional method. Zhang et al. [12] presented a five-axis abrasive belt flap wheel polishing method for leading and trailing edges of aero-engine blades. Zhang and Shi et al. [13] proposed a freestyle belt polishing method to polish the leading and trailing edges of an aero-engine blade, and the polishing experiments showed that profile shape errors and surface quality were decreased basically.

However, these literatures mentioned above reveal that current researches on the polishing blade are mostly focused on belt polishing and grinding, which are complicated and prone to appear some interferences between aero-engine blade and polishing mechanism. Furthermore, all of the above studies are focused on the polishing of the blade edges after milling. But the new polishing technology proposed in this paper can directly polish the blank of blade edge, eliminating the traditional milling process of aero-engine blade edge.

Therefore, to improve surface quality, profile accuracy, and processing efficiency of the blade edges, a novel polishing technology for the leading and trailing edges of blade is proposed in this manuscript. As a new polishing method, the flexible polishing wheel has both the function of grinding and the property of polishing [14]. Furthermore, the shape and structure of the flexible polishing wheel can be designed or modified according to practical polishing requirements of workpieces, which will effectively avoid the problems of machining interference [15]. Document [16] studied the structural design of the flexible polishing wheel for blade polishing and the optimization of polishing parameters. Zhang M L [17] analyzed the polishing process for the difficulty processing areas of the aero-engine blade, including pressure surface, suction surface, and root filet. What's more, it is very convenient for the flexible polishing wheel to polish a complex surface (such as aero-engine blades) on a three-axis NC machine due to the special drum shaped generatrix. The presetting contact deformation for a flexible polishing wheel can be controlled to realize different removed quantity of material, which can effectively improve the profile accuracy of blade edges.

The remainder of the paper is organized as follows: In section 2, the overview of the novel polishing technology is presented. In section 3, the basic principle and the polishing law of the flexible polishing wheels is introduced. And the section 4 illustrates the experimental verification of the proposed methodology. Finally, the conclusion is presented in the section 5.

## 2 Overview of the novel polishing technology

Current machining process for leading and trailing of blade is as follow: Firstly, milling or grinding the basic shape of the leading and trailing, then polishing by hand to remove the machining mark and ensure the surface roughness. This combination pattern of milling or grinding and polishing by hand has low efficiency and poor consistency. The artificial buffing polishing depends on experience and the consistency could not be ensured. In order to achieve high efficiency polishing and save processing costs, a novel polishing technology for leading and trailing edges of the aero-engine blade is proposed in this manuscript. And the novel polishing technology process is shown in Fig. 1.

## 3 The principle of polishing using flexible polishing wheel

### 3.1 The principle of flexible polishing wheel

The basic principle of the flexible polishing wheel is that to enhance bonding force of the abrasive and control its local supporting stiffness by putting some moderate reinforcement structures between abrasive and elastomeric matrix [18]. Figure 2 shows the structure diagram of flexible polishing wheel. And in Fig. 2,  $E_m$  represents elastic matrix,  $S_b$  represents abrasive and abrasive support body,  $A_m$  represents abrasive matrix, and  $I_s$  represents inner sleeve. From the microscopic point of view, each abrasive particle equates to a cutting tool with different cutting-edge angle. The polishing process was accomplished by these abrasive particles arranged on the surface in a certain law. This structure of a flexible polishing wheel ensures both soft contact in a wide range and a strong grinding effect in a small range, which will effectively solve troubles of conventional polishing, such as abrasive is easy to fall off and fall into the matrix, and low grinding capacity [18]. From the macroscopic point of view, the flexible polishing wheel has simple structure and commendable consistency of precision. It has good applicability for polishing microstructures of a blade, such as the leading and trailing edges, and transition arcs. Especially, it is very convenient for the flexible polishing wheel to grinding a

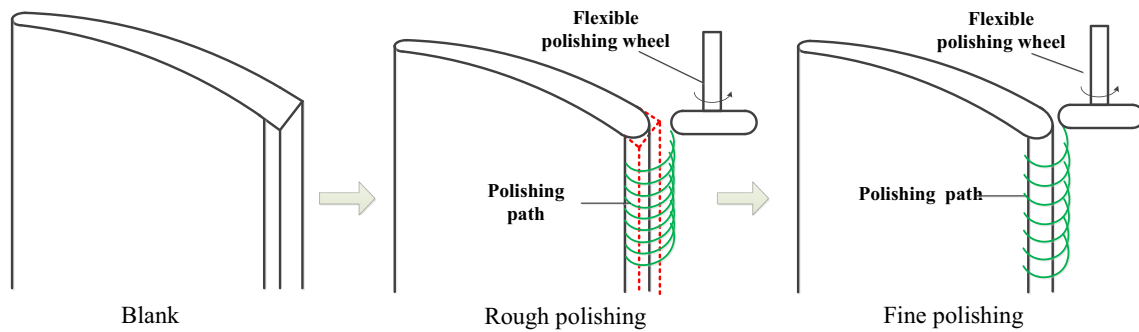


Fig 1. proposed polishing technology process

complex surface on a three-axis NC machine due to the different generatrix. The flexible polishing wheels are shown in Fig. 3.

As the flexible matrix, the polishing wheel will produce the corresponding deformation when polished surface has different remainder (such as the residual height after milling). As shown in Fig. 4(a), when polishing in deformation area 1, the polishing wheel has smaller deformation. At this time, both the polishing force and the removal rate of the material are relatively small. However, when polishing in deformation area 2, deformation of the polishing wheel is large and it has great polishing force and high removal rate of the material [17]. After multiple polishing, surface quality of the polishing workpiece will be greatly improved. As shown in Fig. 4(b), it shows the relationship between surface residual errors and polishing times. The flexible polishing wheel can not only reach nearly grinding efficiency of the grinding wheel but also obtain top-quality surfaces of polishing.

### 3.2 The polishing law of the flexible polishing wheel

The principle of flexible polishing wheels is introduced in section 3.1. And, the materials of the workpiece are removed through the abrasive particles arranged on the surface. The radius of polishing wheel with high speed will be larger than static condition because of inertial centrifugal force. And the flexible polishing wheel will generate elastic deformation under the contact force when polishing, which has a direct influence on the polishing depth and efficiency. Therefore, it is necessary to know law between the flexible deformation and

the polishing material removal of the polishing wheel before being used.

Mostly the shapes of blade edges are circular arcs, and the radius of curvature are relatively small. Meanwhile, the elasticity of the flexible polishing wheel is considerably far greater than the elasticity of blade edges. Therefore, the contact between the polishing wheel and blade edges can be considered as an elastic contact between a rigid semicylinder and an elastic ring, which is shown in Fig. 5. Based on the Hertz elastic contact theory [19], the relationships among contact force  $F_n$ , preset deformation of the polishing wheel  $\delta$  and half-contact width  $d$  are listed in Eq. (1) and Eq. (2).

$$F_n = \frac{\pi E l}{4R'} d^2 \tag{1}$$

$$\delta = \frac{d^2}{2R'} \left( 2 \ln \frac{4R'}{d} - 1 \right) \tag{2}$$

where,  $R' = Rr/(R+r)$ ,  $R$  is the radius of flexible polishing wheel,  $r$  is the radius of blade edges, and  $E$  is the elastic tensile modulus of flexible polishing wheel.  $l$  and  $d$  are the contact length and half-contact width between flexible polishing wheel and blade edges, respectively,  $0 \leq d \leq r$ . Polishing material removal rate of the polishing wheel is approximately

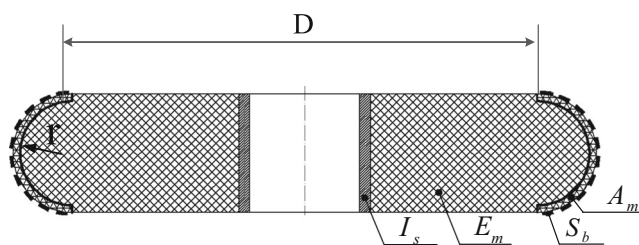
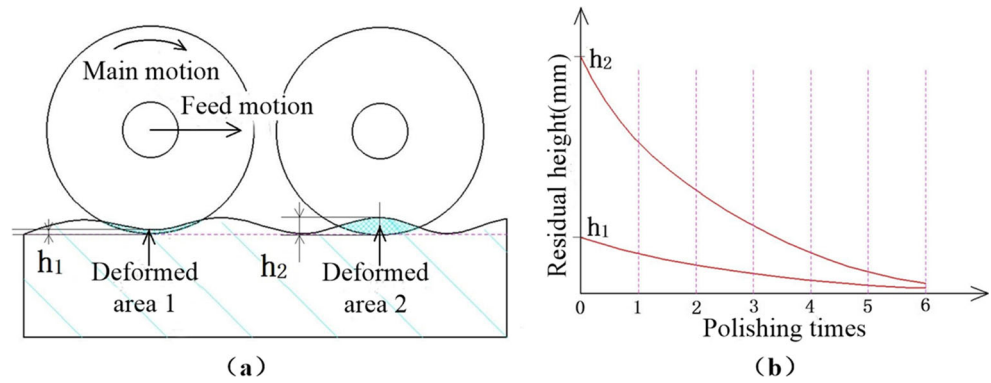


Fig. 2. The structure of flexible polishing wheel



Fig. 3. Flexible polishing wheel

**Fig. 4.** polishing principle of flexible polishing for surface



expressed by the Preston equation [20], which shown in Eq. (3).  $H$  is the thickness of material being removed.  $k_p$  is the Preston coefficient, which is determined by the materials of the flexible polishing wheel and the machined blade.  $V$  is the relative speed between the polishing wheel and workpiece.  $P$  is the contact force of polishing.

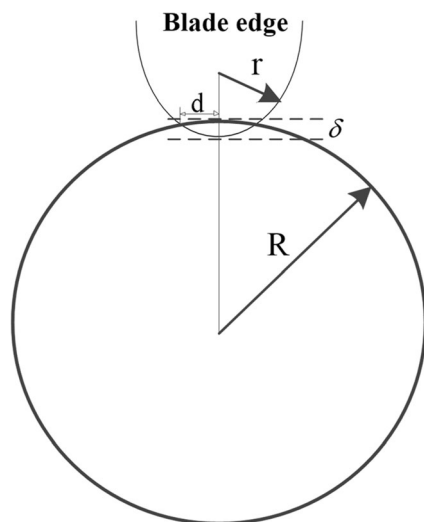
$$dH/dt = k_p PV \tag{3}$$

Synthesizing Eq. (1), Eq. (2), and Eq. (3), we can conclude the following equation:

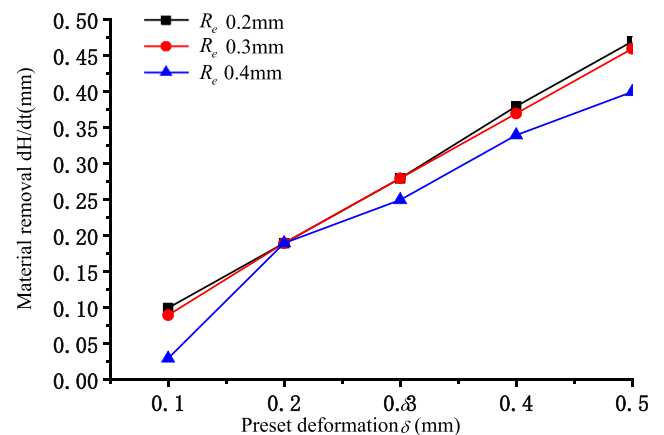
$$dH/dt = k_p V \frac{\pi E l \delta}{4 \ln \frac{4R'}{d} - 2} \tag{4}$$

Equation (4) reveals that polishing material removal rate  $dH/dt$  is mainly affected by the preset deformation  $\delta$  when all the polishing parameters are determined, because they are not

influenced by the machining process and environment. In this manuscript, many polishing experiments using different flexible polishing wheel were carried out. 400# CBN (cubic boron nitride) and 2000# CBN polishing wheels with  $D=17\text{mm}$  and  $r=1.5$  are selected as polishing tool of our experimental study. 400# CBN polishing wheel is used for rough polishing and 2000# CBN polishing wheel is used for fine polishing. Figure 6 reveals the relation between  $\delta$  and  $dH/dt$  of 400# CBN flexible polishing wheel for polishing blade edges.  $R_e$  means the radius size of blade edge. The material removal rate  $dH/dt$  increased with the preset deformation  $\delta$ , which is in accordance with the Eq. (4). Similarly, Fig. 7 shows the relation between  $\delta$  and  $dH/dt$  of 2000# CBN flexible polishing wheel. And the experimental results also are in accordance with the Eq. (4). According to Fig. 7, we can know that the material removal effect of 2000# CBN flexible polishing wheels is poor, which is only used for fine polishing and to improve the surface roughness.



**Fig. 5.** Polishing contact between blade edges and flexible polishing wheel



**Fig. 6.** The relationship between  $\delta$  and  $dH/dt$  of 400# CBN flexible polishing wheels

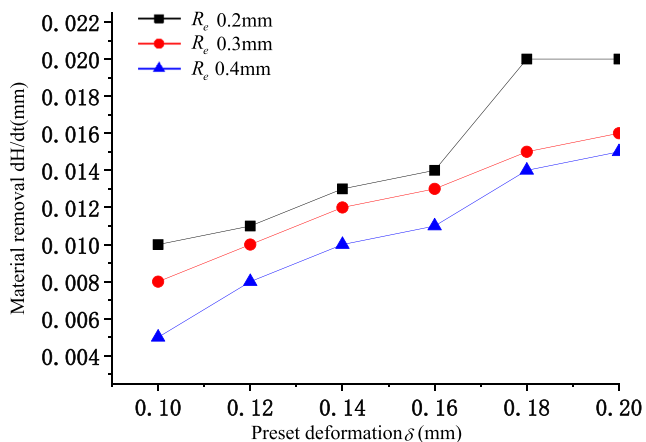


Fig. 7. The relationship between  $\delta$  and  $dH/dt$  of 2000# CBN flexible polishing wheels

### 4 Verification experiments of proposed polishing technology

To improve the work efficiency and reduce the weight of an aero-engine, the blades are designed to be thinner and thinner and the leading and trailing edges are getting smaller and smaller. However, because of the small radius, the leading and trailing edges have serious and centralized machining stress and there will be overcut easily when polishing. Therefore, in order to prove the validity of proposed polishing technology for the leading and trailing edges, two verification experiments are analyzed in this section.

#### 4.1 Verification experiment for sample

As shown in Fig. 8, an experimental sample is produced. Both sides of the experimental sample are milled into  $R_e$  0.3mm fillet and  $R_e$  0.2mm fillet respectively, which are shown in detailed view of Fig. 8. The proposed polishing technology is adopted to polishing the sample on the three-axis polishing machine.

In addition, the polishing parameters in this experiment are shown in Table 1 with the use of microscope, the profile of

experimented fillet of polished sample is shown in Fig. 9. And Fig. 9(a) shows the polished profile of  $R_e$  0.3mm and Fig. 9(b) shows the polished profile of  $R_e$  0.2mm. According to Fig. 9, the polished profile of blade edges is extremely closed to design profile. Therefore, the proposed polishing technology process can effectively and directly complete polishing machined of blade edges.

#### 4.2 Verification experiment for blade

In this section, an aero-engine precision-forged blade is used to prove the validity of proposed polishing technology. The new generation blades of aero-engine are usually manufactured with a precision-forging process. The dimensional precision and quality of a precision-forged blade body surface can be guaranteed by the precision forging instead of secondary machining operation. However, in order to meet the dimensional precision required by the design tolerance, the leading and trailing edges of a precision-forged blade must need secondary machining operation. The material object of the blade is shown Fig. 10. Figure 11 shows the real profile errors of 4 sections shown in Fig. 10 of a precision-forged blade leading edge before secondary machining. The sections were measured by a coordinate measuring machine PONY866 (AVIC BPEI, Beijing, China; RENISHAW SP25M scanning probe). According to the current processing status, there are many difficulties in processing the edges of a precision-forged blade. The details are as follows.

1. From the Fig. 11, the removal allowances for the blade edges of a precision-forged blade are relatively small and distributed unevenly. Therefore, to ensure the dimensional precision and profile accuracy of the blade edge, it is important to control the removal of material accurately.
2. The aero-engine blade is the thin-walled structures. There will be serious deformation after precision forging and the bending deformation of blade could reach 0.12 mm, which is far greater than the dimensional precision of  $\leq 0.04$  mm. Therefore, it is important to adapt the

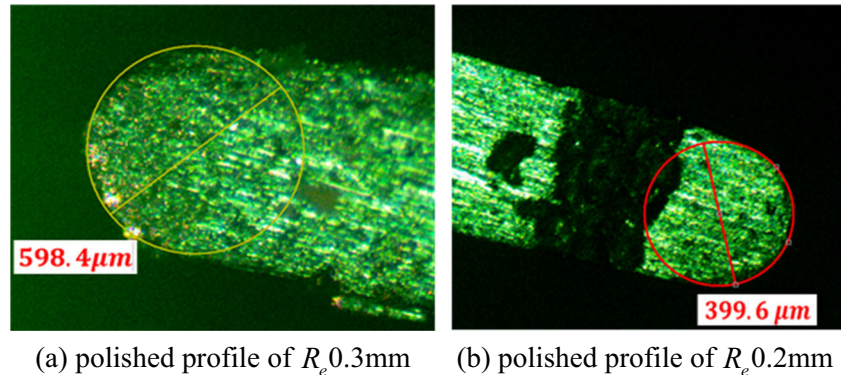
Fig. 8. Experimental sample





**Table 1** Polishing parameters of sample experiment

radius (mm)	Abrasive Size (#)		Feed rate (mm/min)	Speed (r/min)	Material of sample
	Rough polishing	fine polishing			
0.2	400#CBN	2000#CBN	500	8000	GH4169
0.3	400#CBN	2000#CBN	500	8000	GH4169

**Fig. 9.** Polishing results of sample measured by microscope

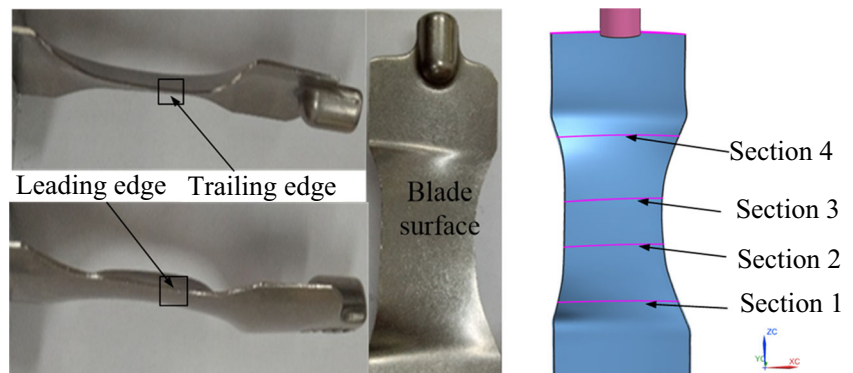
- deformation of the precision-forged blade to ensure acceptable dimensional precision of the blade edges.
3. Because of the heat-resistant and high-strength materials of GH4169 used in this precision-forged blade, and sharp curvature changes of blade edges, the removal amount of polishing using the flexible polishing wheels is difficult to control.

According to the above analysis, because of the special characteristics of the leading and trailing edge for an aero-engine precision-forged blade, such as heat-resistant, high-strength materials, uneven distribution, and small removal allowance, these conventional processing methods are easy to cause profile errors, which include the chamfered, sharp, flat, and obtuse edges, and cervical part shrinkage. It is difficult, therefore, to guarantee the expected shape of the blade edges.

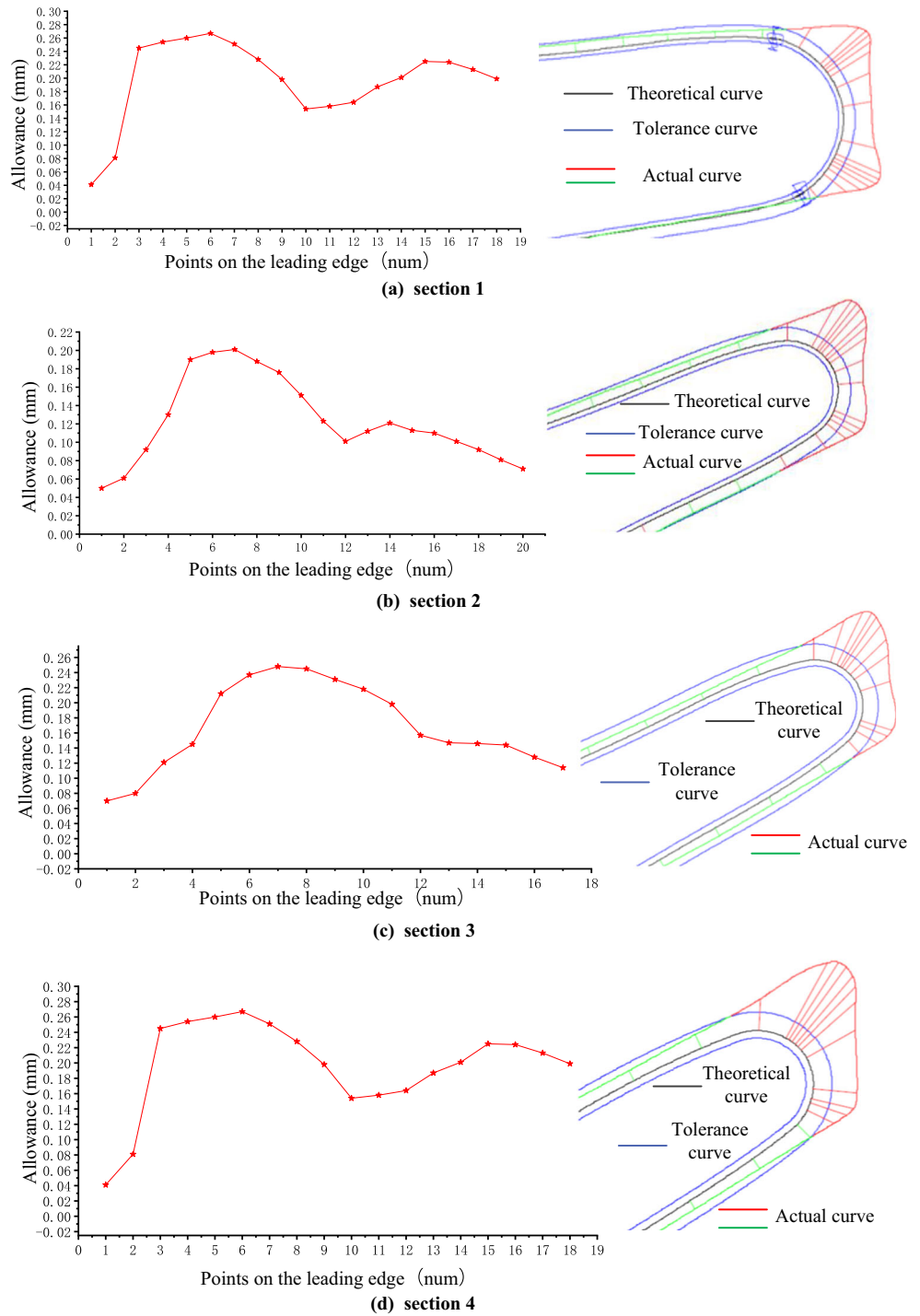
However, the proposed polishing technology in this manuscript can effectively realize precision polishing for the precision-forged blade edges. Furthermore, the deformation of the precision-forged blade is inhibited because of the flexible characteristics of this polishing wheel, so the residual errors between the blade edges machined and blade body surface unprocessed are removed.

The leading edge of this precision-forged blade shown in Fig. 10 is polished using proposed polishing technology on a polishing machine tool, which is shown in Fig. 12(a). The cutting direction of polishing blade edge is shown in Fig. 12(b). And the polishing parameters in this experiment are listed in Table 2.

Figure 13 shows the profile errors of 4 sections shown in Fig. 10 on the leading edge of the experimental blade, which are measured through a coordinate measuring machine PONY866 (AVIC BPEI, Beijing, China; RENISHAW

**Fig. 10.** An aero-engine precision-forged blade

**Fig. 11.** Allowance of the leading edge before polished



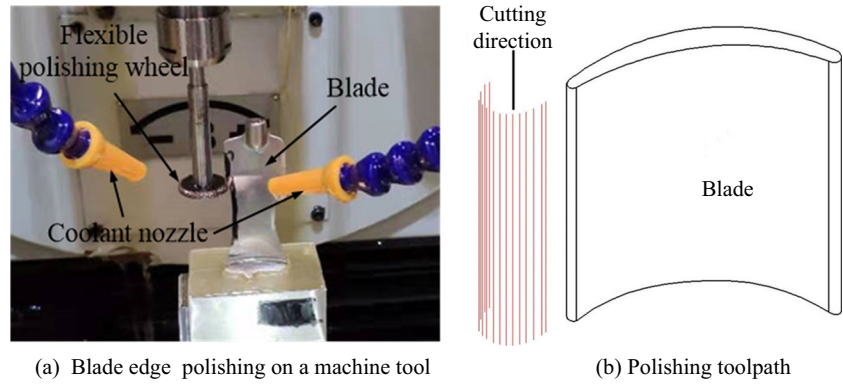
SP25M scanning probe). The result shown in Fig. 13 reveals that the profile errors after polishing have fallen to within 0.02mm, which reached adequately the requirements of this precision-forged blade edges. The actual profile of the leading edge before and after polishing is shown in Fig. 14.

The surface roughness of the leading edge after polishing was measured by the Taylor Hobson FTSI-6890 supplied by

Taylor Hobson limited in England. And the measurement locations for surface roughness are shown in Fig. 14. The measurement results are shown in Table 3. According to Table 3, we can know that the surface roughness reached adequately the requirements which less than  $Ra0.4\mu m$ .

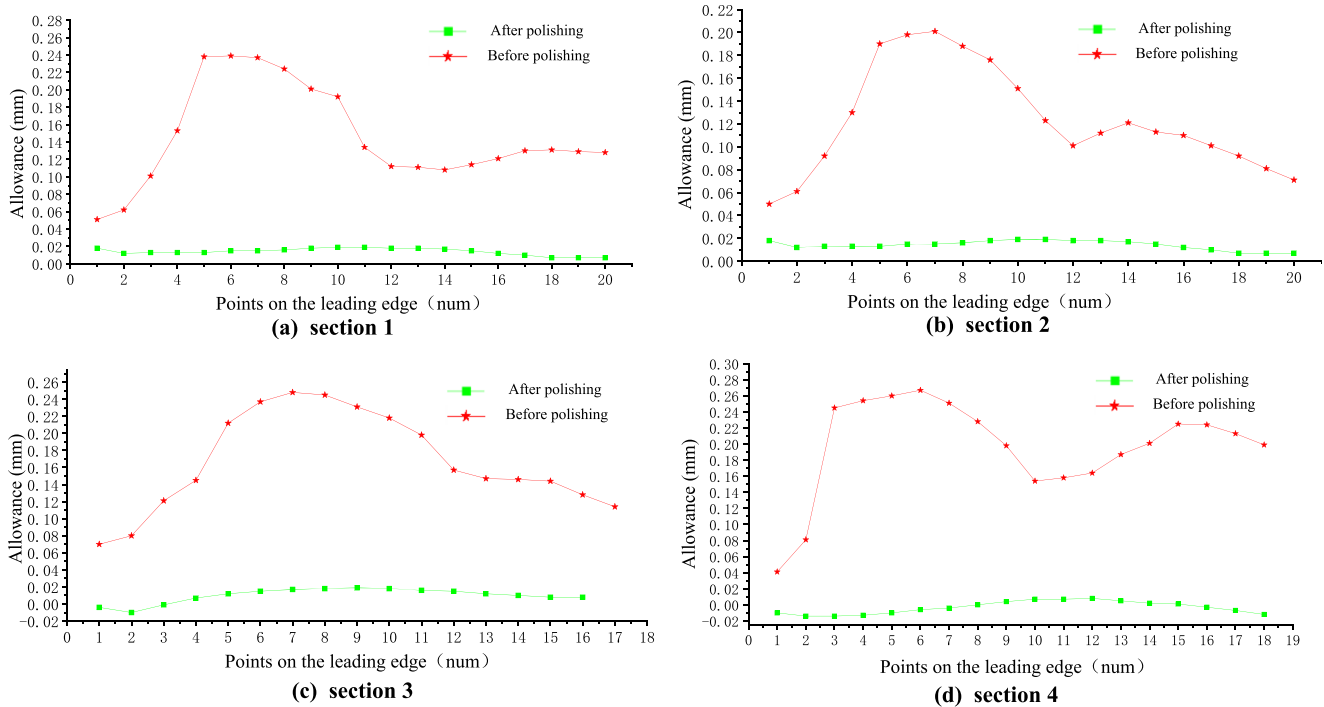
The above experimental results reveal that both the surface roughness and dimensional accuracy of the blade edges are

**Fig. 12.** Blade edge polishing and polishing toolpath



**Table 2.** Polishing parameters for polishing blade edges

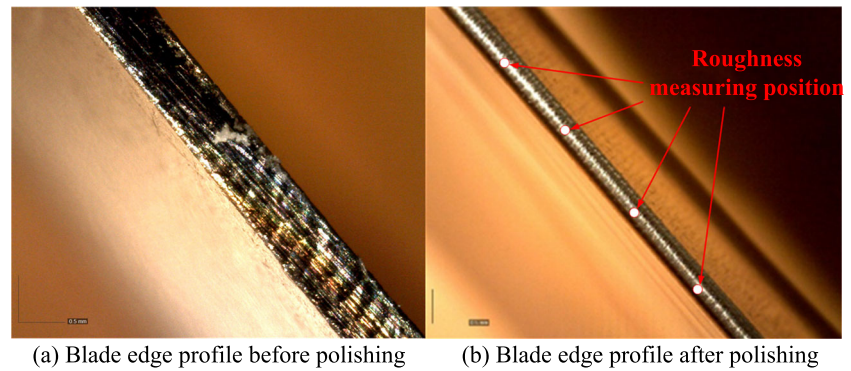
Blade	Material	GH4169	
	Radius of trailing edge	0.2mm	
flexible polishing wheel	Abrasive	CBN	
	Size(#)	Rough polishing	400#
		Fine polishing	2000#
	Speed $n$ (r/min)	8000	
	Feed rate(mm/min)	500	
	Diameter(mm)	20	
	$r$ (mm)	1.5	



**Fig. 13.** Profile errors of the leading edge before and after polishing



**Fig. 14.** Comparisons of the leading edge before and after polishing



reached adequately the design requirements by proposed polishing technology. And, at present, the machining methods of the leading and trailing edges are milling or grinding firstly, and then polishing by hand. This method proposed in the paper has the advantages of convenient and high efficiency for polishing precision-forged blade edges compared with the conventional method.

## 5 Conclusion

A novel polishing technology for the leading and trailing edges of blade using the flexible polishing wheels was developed in this manuscript to simultaneously guarantee both profile accuracy and surface roughness of the precision-forged blade edges. Firstly, the overview of proposed novel polishing technology is presented. And then the basic principle and flexible polishing law of the flexible polishing wheel are introduced and analyzed. Finally, the verification experiments for a sample and an aero-engine precision-forged blade are carried out. The experimental results reveal that dimensional accuracy of the blade edges is within 0.02mm and surface roughness is less than  $Ra0.4\mu m$ , which are reached adequately the design requirements. Presently, the machining methods of the leading and trailing edges are milling or grinding firstly, and then polishing by hand. This combination pattern of milling and polishing by hand has low efficiency and poor consistency. The artificial buffing polishing depends on experience and the consistency could not be ensured. This novel polishing technology which instead of combination pattern of milling and polishing can simultaneously

guarantee both profile accuracy and surface roughness. It was verified that the proposed polishing technology using the flexible wheel has advantages for blade edges in terms of profile accuracy and surface quality. Compared with the conventional method, the processing efficiency of blade edges has increased by 2 times.

**Authors' contributions** Methodology and original draft preparation: Zhu Zheng-Qing; validation and investigation: Chen Zhi-Tong; formal analysis: Zhang Yun.

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**Data availability** All data and materials generated or analyzed during this study are included in this manuscript.

## Declarations

**Ethical approval** Not applicable.

**Consent to participate** Not applicable.

Consent to publish  
Not applicable.

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

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**Table 3.** surface roughness after polishing

Surface roughness of each position (Ra)	Position 1	0.28 $\mu m$
	Position 2	0.31 $\mu m$
	Position 3	0.32 $\mu m$
	Position 4	0.29 $\mu m$

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