Grinding of Fir Tree Slots of Powder Metallurgy Superalloy FGH96 using Profiled Electroplated CBN Wheel

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Title Page

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Conflict of interest:

The authors declare that they have no conflict of interest.

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Abstract—Broaching is commonly used for machining fir tree slots on turbine disk, which has outstanding advantages and disadvantages, such as high quality machined surface, high manufacturing accuracy and high productivity as well as fast tool wear, extremely high processing costs and long preparation time, poor process flexibility. Utilizing the electroplated cubic boron nitride (CBN) profiled grinding wheels and single sided local profiled grinding process, the experiments of FGH96 turbine disk slots are carried out. The results show that the high precision of slot profile can be achieved by the developed process. Using the given experimental parameters n=48000 rpm, a_p=0.002 mm, v_f =100 mm/min and 600# electroplated CBN profiled wheel, the profile error of FGH96 slots is within ±0.012 mm, and the grinding surface roughness is less than Ra0.8 μm. After four whole slots are machined completely, the grinding wheel still has grinding capability, which proves that 600 # electroplated CBN profiled wheel can meet the grinding needs of FGH96 turbine disk slots.

Keywords—Grinding; Slot; CBN wheel; FGH96

1. Introduction

Powder metallurgy superalloy is the preferred material for manufacturing high temperature load-bearing parts of aero-engines, which has excellent high-temperature mechanical properties and fatigue creep resistance. FGH96 alloy is a typical material of the second generation damage tolerance type superalloy. Because of its mature preparation technology, uniform material structure and stable mechanical properties, it has been widely used to manufacture turbine disks and other hot components of aero-engines [1]. However, the excellent mechanical properties at high temperature lead to poor cutting performance, and the machining of fir tree slots on turbine disk is very difficult especially [2].

At present, broaching is known to be the best process to machine fir tree slots of turbine disk on powder metallurgy superalloy, which can offer very high productivity and is the first selection to serial production of the turbine disk [3][4]. Klocke presented a suitable carbide broach structure, which further improved the machining efficiency and tool life of the broaching. At the same time, the ceramic side milling process was utilized for rough machining fir tree slots, which greatly improved the rough machining efficiency [5][6]. However, major shortcomings of the broaching process are also very prominent, include of high capital cost, large size of machine tools together with their inflexibility, costly tooling, lengthy setup, validation and changeover times, high cutting forces (up to 10000N) [7].

For these reasons, wire-EDM becomes more and more a serious alternative to the established and critical defined broaching process for fir tree slot production [9]. Klocke deeply studied the application of Wire-EDM for machining fir tree slots through developing a process monitoring tool for processing quality assessment and correlating surface integrity evaluation, which obtained some good experimental results [9][10][11]. The profile error of the slots machined by Wire-EDM can be within ±0.01 mm. From technological point of view, wire-EDM can be an alternative to the established broaching process for the production of fir tree slots [12]. But, wire-EDM process also has an outstanding drawback that recast layers with different thicknesses will be formed on machined surfaces, which will have a negative influence on the fatigue performance of a dynamic component [12][13]. Thus, wire-EDM process is limited further application in the field of powder metallurgy superalloy slots machining.

With the development of high speed spindle and electroplated superabrasive grinding wheel technology, high speed grinding with profiled electroplated superabrasive wheel is gradually applied to the field of fir tree slots machining. Aspinwall also pointed out the drawback of broaching fir tree slots, and the experiments of using the profiled superabrasive wheels to machine Udimet 720 fir tree slots were carried out. Machining data were presented, which verified the feasibility of small diameter, profiled, electroplated CBN grinding wheels when cutting Udimet 720 fir tree slots [14]. Meanwhile, combined with the electrochemical superabrasive machining, superabrasive grit type and electrical parameters were developed to improve the processing efficiency and flexibility [15]. Lanes proposed a method that using a cup grinding wheel to machine fir tree slots in the theory [16]. But the verification experiments were not carried out and the advantages of this process had not been presented.

From the above research results, machining the fir tree slots utilizing profiled electroplated grinding wheel is feasible. But little research achievement on the grinding technology and machining accuracy of FGH96 turbine disk slots is presented. So, utilizing the electroplated CBN profiled grinding wheels and single sided local profiled grinding process, the grinding experiments of FGH96 turbine disk slots are carried out. The influence of grinding process and grinding parameters on the profile accuracy of fir tree slots is studied, and the feasibility of this process is verified, which provides an effective process method for machining high-precision fir tree slots of FGH96 turbine disk.

2. Experimental conditions

2.1. Experimental material and workpiece

The experimental material is powder metallurgy superalloy FGH96 and the chemical composition is listed in Table 1. The mechanical properties of FGH96 at room temperature are shown in Table 2 and based material microstructure is shown in Fig 1.

Table 1 Chemical composition of FGH96 (ω / %)

Cr	Co	W	Mo	Al	Ti	Nb
16.20	13.10	4.03	4.06	2.18	3.66	0.71

Table 2 Mechanical properties of FGH96 at room temperature

σ_y / MPa	σ_b / MPa	δ /%	Ψ /%
1106	1520	22.2	30.3

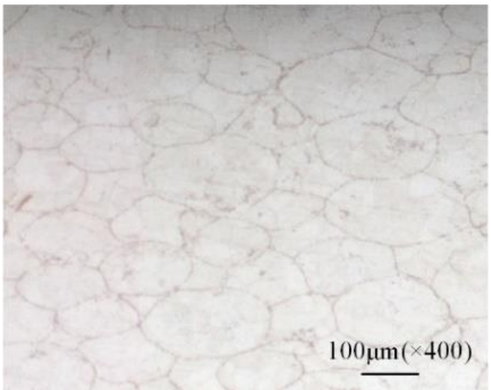


Fig. 1 Microstructure of FGH96

In general, the fir tree slot is straight, as shown in Fig. 2, and the symmetrical plane of the slot has a certain angle with the axis of the turbine disk. The turbine fir tree slots could be pre-machined by Wire-EDM, as shown in Fig 3. The profile of slots was measured by a coordinate measuring machine, as shown in Fig.4.

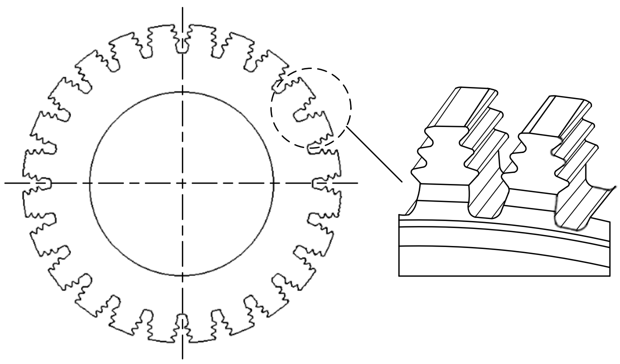


Fig. 2 Structural of the slot on powder metallurgy turbine disk

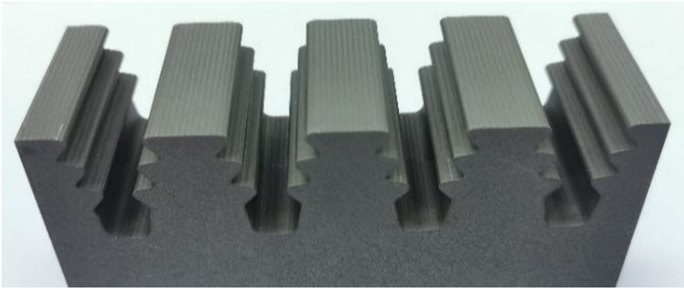
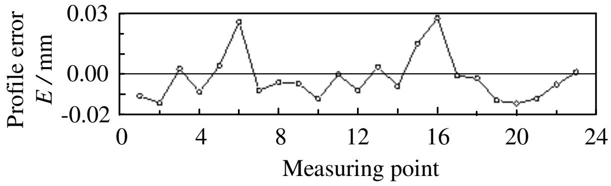
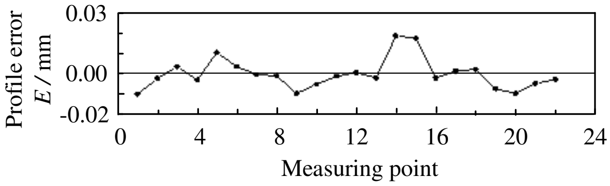


Fig. 3 Fir tree slots of FGH96 machined by Wire-EDM



(a) Profile error on the left side of slot



(b) Profile error on the right side of slot

Fig. 4 Profile error of slot machined by Wire-EDM

From Fig.4, the profile error is between －0.02 mm and ＋0.03 mm. However, the quality of the machined surface is poor and the surface roughness is about Ra3.2 μm. Meanwhile, there is an obvious recast layer which thickness is about 10 μm. If the recast layer not only could be removed by precision grinding but also the profile accuracy and surface quality of slots could be ensured, the precision grinding of FGH96 slots will be realized. Therefore, the FGH96 fir tree slots are pre-machined by Wire-EDM firstly in order to remove most of the material and only about 0.1mm is reserved for finishing grinding by profiled grinding wheel. The machined surface and microstructure of FGH96 fir tree slot machined by Wire-EDM are shown in Fig. 5.

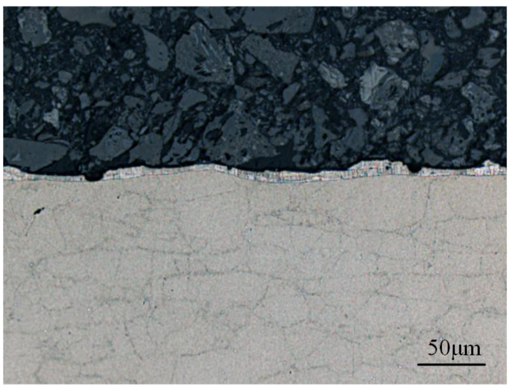


Fig. 5 Microstructure of FGH96 machined by Wire-EDM

2.2 Grinding experimental setup

The grinding speed is very important to the grinding efficiency and grinding performance of superabrasive grinding wheel. Because FGH96 is a typical difficult-to-cut material, the high-speed spindle is needed to meet the requirement of grinding linear speed. Therefore, a high-speed spindle which can get maximum rotating speed 60000rpm is attached to the machining center, as shown in Fig. 6. At the same time, Blasogrind HC 10 high-speed oil is used as coolant for all the grinding experiments. The outlet pressure of the coolant is 45bar and the flow rate is 80 L/min.

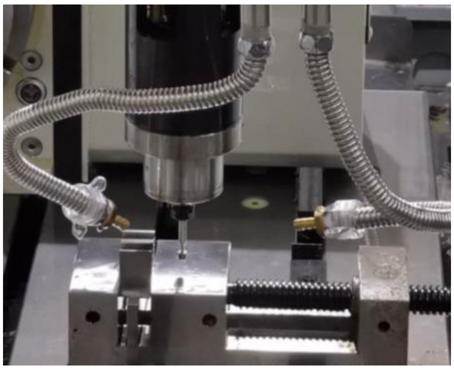


Fig. 6 Experimental equipment for grinding turbine disk slots.

2.3 Structure of profiled grinding wheel and profiled grinding process

According to the structural characteristics of the turbine slot, the structure of profiled electroplated CBN wheel is developed, as shown in Fig. 7. At the same time, the diameter of the grinding wheel at any grinding point is less than the width of the fir tree slot, which can ensure that only one side of the grinding wheel is in contact with the profile of slot, as shown in Fig. 8, and that the coolant can fully lubricate and cool the grinding wheel and grinding area. The grinding performance of grinding wheel and grinding surface quality can be guaranteed stably.

Fig. 7 Profiled electroplated CBN wheel

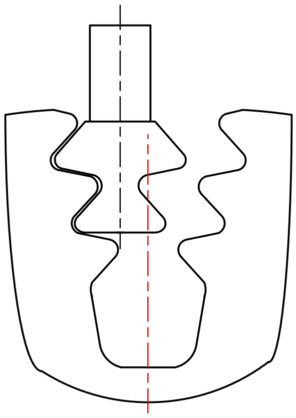


Fig. 8 Single sided local profiled grinding process

Utilizing the above profiled electroplated CBN wheel, it is necessary to translate the grinding wheel for several times, and allow the generatrix of the grinding wheel to overlap locally, so as to realize the profiled grinding of one-sided profile of turbine disk slot. Meanwhile, the grinding process of the whole slot tooth is shown in Fig. 9.

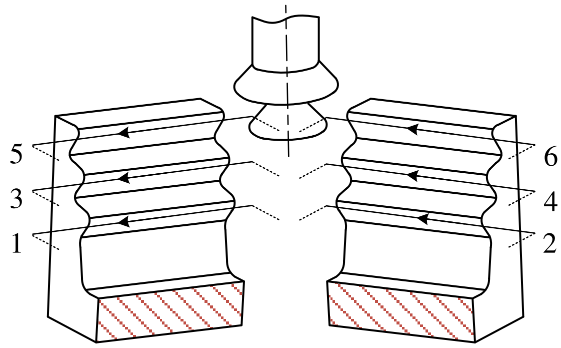


Fig. 9 Path of grinding wheel during the grinding process of the whole slot tooth

3. Experimental results and analysis of the slot grinding

3.1. Selection of grinding wheel parameters and grinding parameters

FGH96 is a typical difficult-cut material, the grit size of grinding wheel has a direct influence on the machined surface quality and grinding efficiency. So, it is very important to choose the grit size of grinding wheel according to the machined surface quality. And the experimental workpiece is shown in Fig. 10.

Fig. 10 Workpiece of one-sided slot

Grinding experiments are carried out on the FGH96 workpiece utilizing electroplated CBN grinding wheel with different grit sizes and the grinding parameters n=48000 rpm, a_p=0.002 mm, v_f=100 mm/min, and the surface roughness is measured along the direction perpendicular to the grinding linear velocity by a TIME3220 roughness tester. The measurement results are shown in Fig. 11.

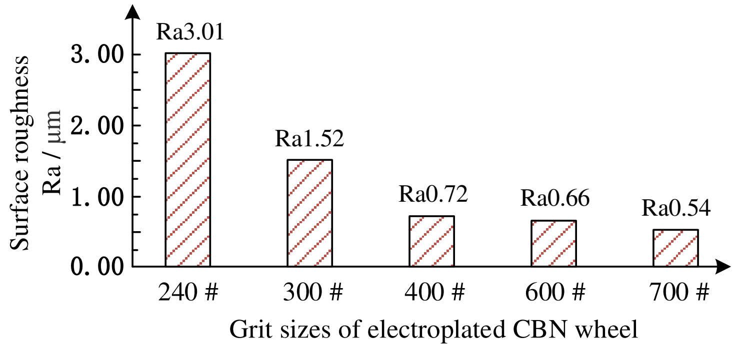


Fig. 11 Influence of grit sizes on surface roughness

Under the same grinding conditions, when the grit size of grinding wheel increasing from 240# to 400#, the surface roughness decreases from Ra 3.01 μm to Ra 0.72 μm obviously. When the grit size of grinding wheel increases to 700# continuously, the surface roughness still decreases to Ra 0.54 μm moderately. It can be known that the grit sizes have an obviously influence on the surface roughness.

According to the machining requirements of turbine disk slot, the surface roughness should be better than Ra 0.8 μm. Meanwhile, the grit size of grinding wheel also has a great influence on the grinding efficiency and the wheel wear. From the above analysis comprehensively, 600# electroplated CBN profiled grinding wheel is utilized for finish machining FGH96 turbine disk slots, which can make sure the surface roughness stably and meet the use requirements of Ra $\leq$ 0. 8μm.

On the other hand, the typical microstructure of machined surface and grinding wheels are examined by a scanning electron microscope (SEM), as shown in Fig. 12. The grinding grooves appear on the machined surface along the direction of grinding linear velocity, which caused by the scratch of the higher abrasive grits on the peripheral surface of wheel. The size of abrasive particles has a direct influence on the depth of the grinding grooves.

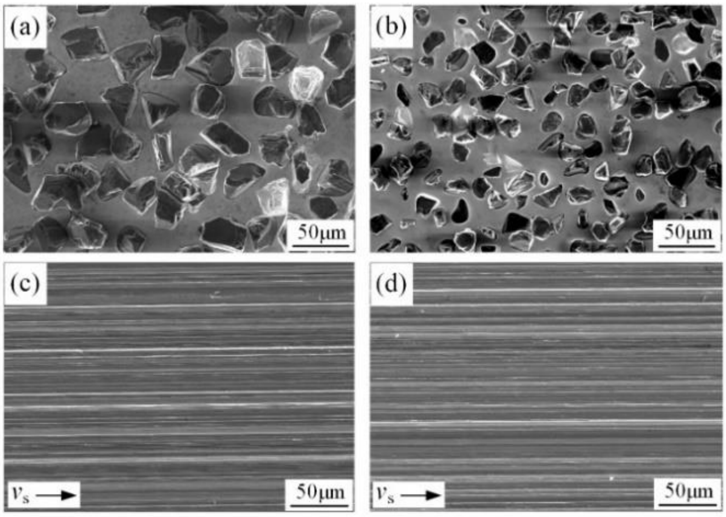


Fig. 12 (a) Surface topography of 400# wheel. (b) Surface topography of 600# wheel. (c) Surface topography machined by 400# wheel. (d) Surface topography machined by 600# wheel.

3.2. Experimental results and discussion

Using electroplated profiled CBN wheels, the grinding experiments of FGH96 fir tree slots pre-machined by Wire-EDM are carried out, as shown in Fig. 14. The profile of slot is rough ground for 10 times using 400# electroplated profiled CBN wheel, the parameters are n =42000 rpm, a_p =0.005 mm, v_f =200 mm/min. Then it is fine ground for 5 times using 600# electroplated profiled CBN wheel and the parameters are n =42000 rpm, a_p =0.002 mm, v_f =100 mm/min. The slots after finishing grinding are shown in Fig. 15.

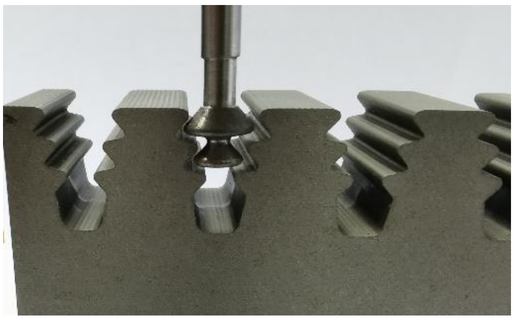


Fig. 14 Grinding experiments of FGH96 fir tree slots

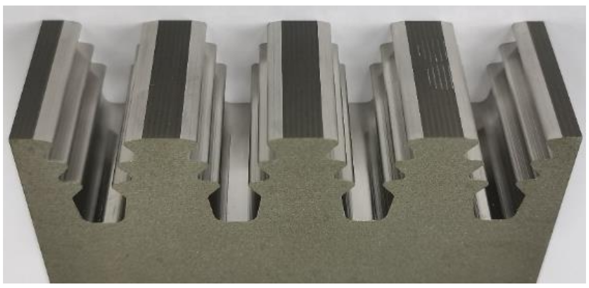
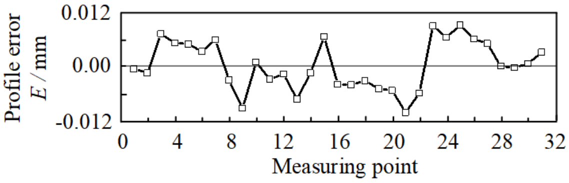
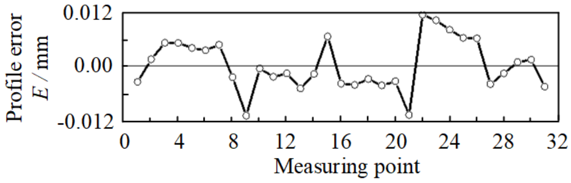


Fig. 15 Slots after finishing grinding

The profile of slots is measured by a coordinate measuring machine. The results are shown in Fig. 16 and the profile error of slots is within ±0.012 mm, which is better than that machined by Wire-EDM. Meanwhile, the profile accuracy of slots can meet the use requirements of FGH96 turbine disk slots, which is about ±0.015 mm.



(a) Profile error on the left side of slot



(b) Profile error on the right side of slot

Fig. 16 Profile error of slot machined by profiled grinding

At the same time, the surface quality of FGH96 slot is examined by SEM, and it can be seen that the micro-recast layer on the surface machined by Wire-EDM has been removed completely. The microstructure of the machined surface is evenly arranged and without any damage, as shown in Fig. 17

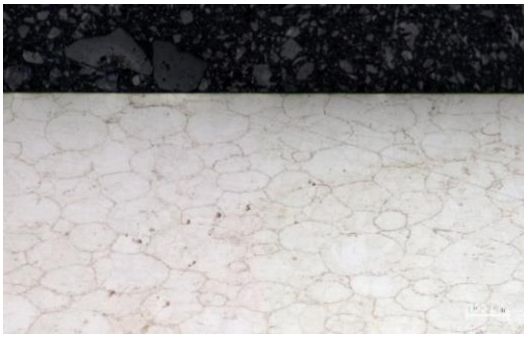


Fig. 17 Microstructure of grinding surface

Meanwhile, the wear and the performance of the grinding wheel are the key factors to ensure the grinding accuracy of the slot. Therefore, it is necessary to detect the wear of grinding wheel after grinding, and the wear degree of grinding wheel surface is shown in Fig. 18.

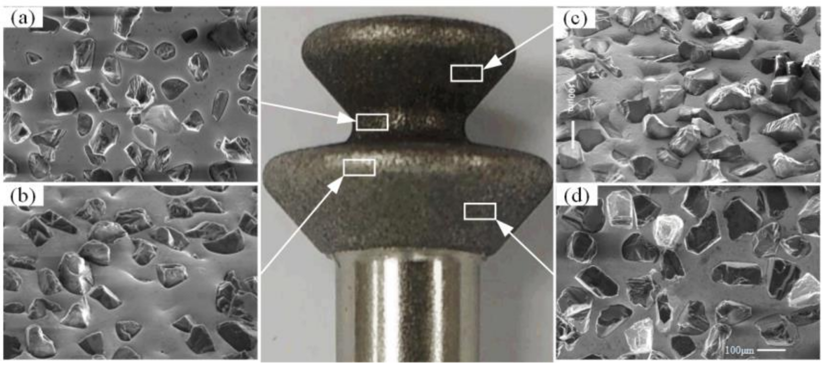


Fig. 18 Wear degree of grinding wheel surface

From the above results, after four whole slots are ground completely, CBN grits on the surface of the profiled electroplated wheel have any wear, but no grits pullout appears obviously. The grits are evenly distributed on the wheel surface and have grinding capability, which can meet the requirements for precision grinding slots. Meanwhile, the grit wear at the groove of the profiled grinding wheel is more serious than that at the inclined plane and flange, because the grinding wheel at the groove has a low grinding speed which affects the grinding performance.

4. Conclusions

(1) For the FGH96 fir tree slots after rough machining by Wire-EDM, single sided local profiled grinding of slots is presented utilizing 600 # electroplated CBN profiled grinding wheel. In addition, under the conditions of experimental parameters, electroplated CBN profiled grinding wheel has excellent grinding ability and no obvious wholesale grit pullout is observed, which can ensure the use requirements of FGH96 fir tree slots precision grinding.

(2) Compared with Wire-EDM, recast layer appears on the surface of FGH96 fir tree slots machined by grinding, which can avoid the negative influencing of the recast layer on the fatigue performance of turbine disk.

(3) Under the grinding parameters n=48000 rpm, v_f =100 mm/min, a_p=0.002 mm, utilizing 600 # electroplated CBN profiled grinding wheel, the machined surface can meet the quality requirement of FGH96 turbine disk slots, and the grinding surface roughness is less than Ra 0.8 μm, and the profile error is within ± 0.012 mm. So, an effective process method for the precise and low cost machining of FGH96 turbine disk slots is developed, which can promote the efficient development of turbine disk of new aero-engines.

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Conflict of interest:

The authors declare that they have no conflict of interest.

Declaration of Interest Statement:

All authors declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript entitled “Grinding of fir tree slots in powder metallurgy superalloy FGH96 using profiled electroplated CBN wheels”. And all authors have seen the manuscript and approved to submit our manuscript to this journal.

Authors Contributions:

Xun Li, Overall framework, experimental planning, draft writing of the manuscript.

Bin Qin, Grinding experiments operation, experimental results analyzing.

Ziming Wang, Grinding wheel design, grinding parameters optimization.

Yu Zhang, Profile accuracy measurement, grinding mechanism analysis.

Jianhua Yu, Grinding experiments operation, experimental results analyzing.

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Figures

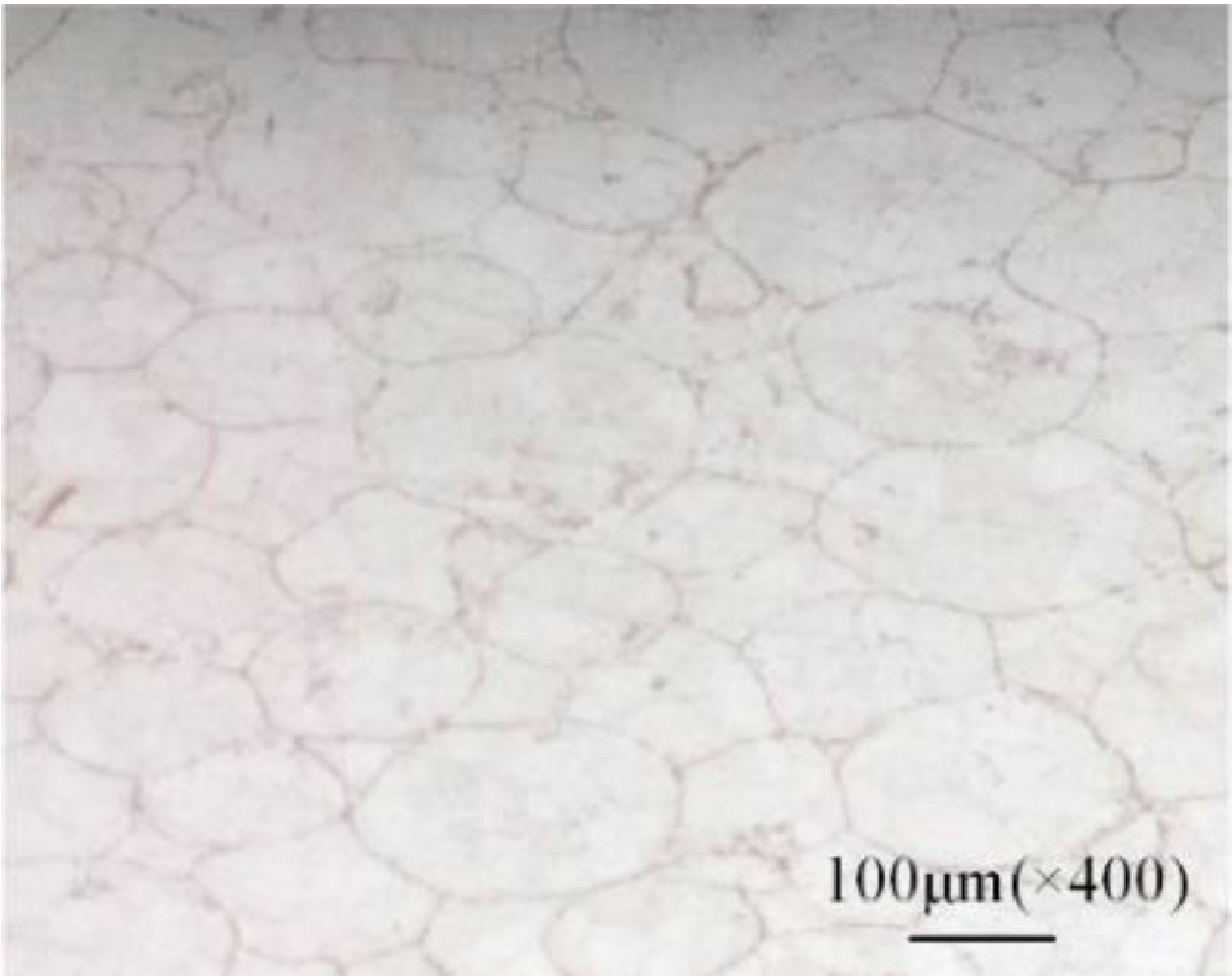


Figure 1

Microstructure of FGH96

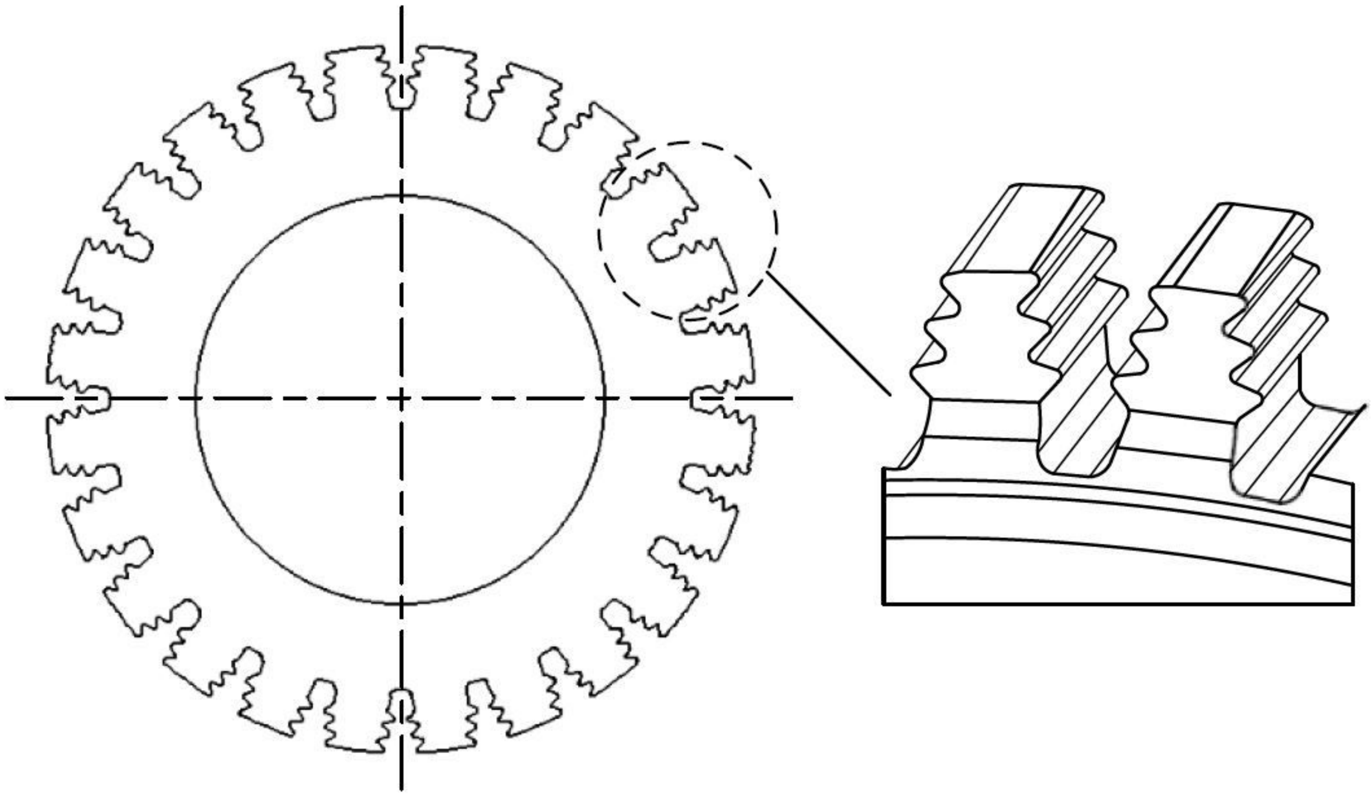


Figure 2

Structural of the slot on powder metallurgy turbine disk

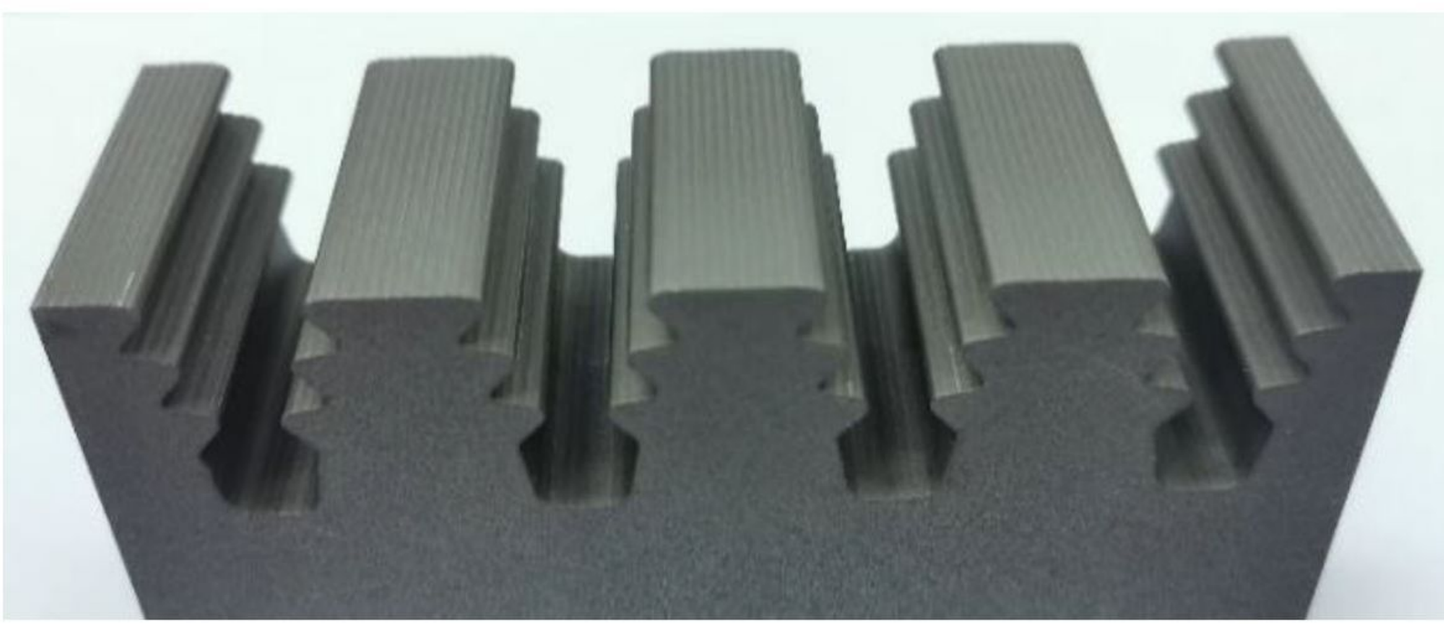
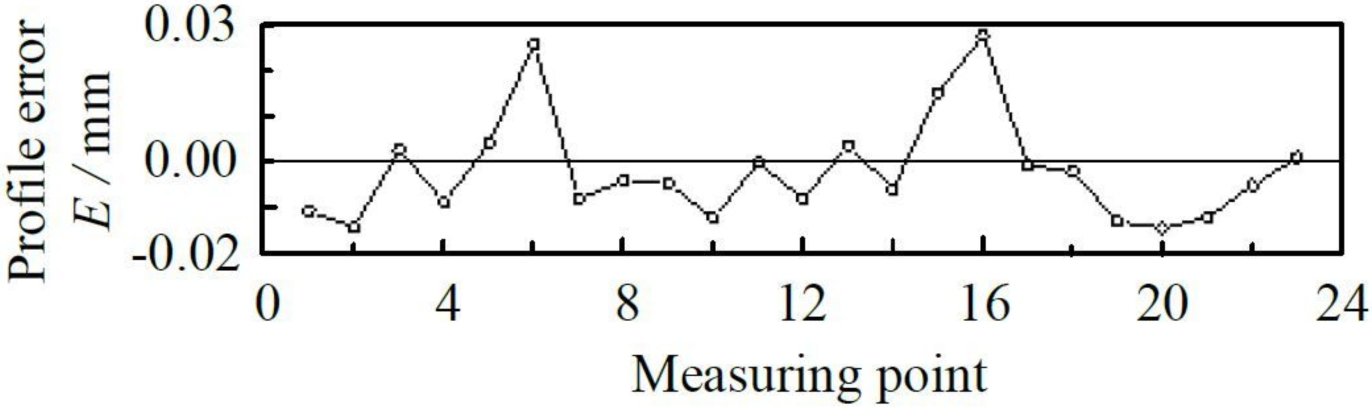
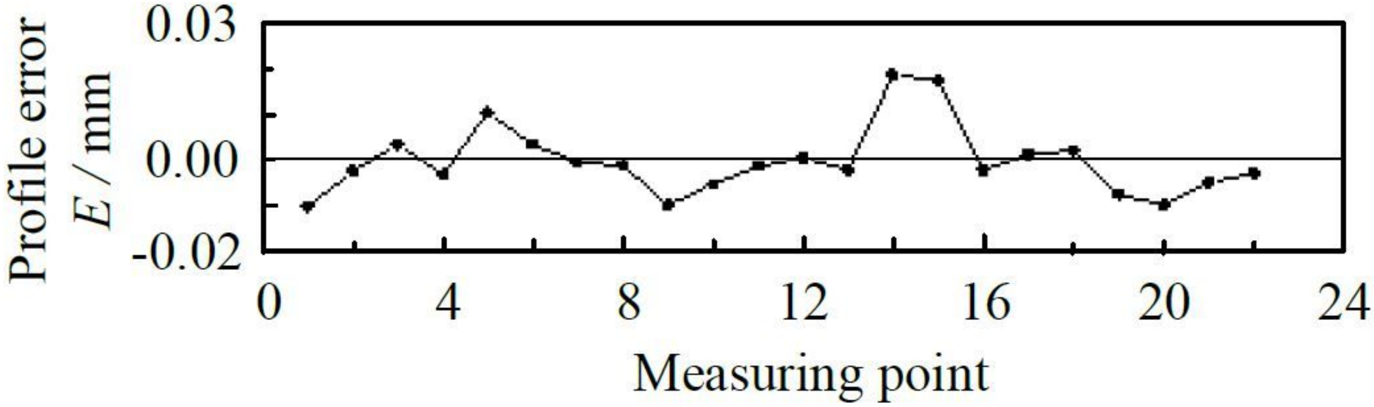


Figure 3

Fir tree slots of FGH96 machined by Wire-EDM



(a) Profile error on the left side of slot



(b) Profile error on the right side of slot

Figure 4

Profile error of slot machined by Wire-EDM

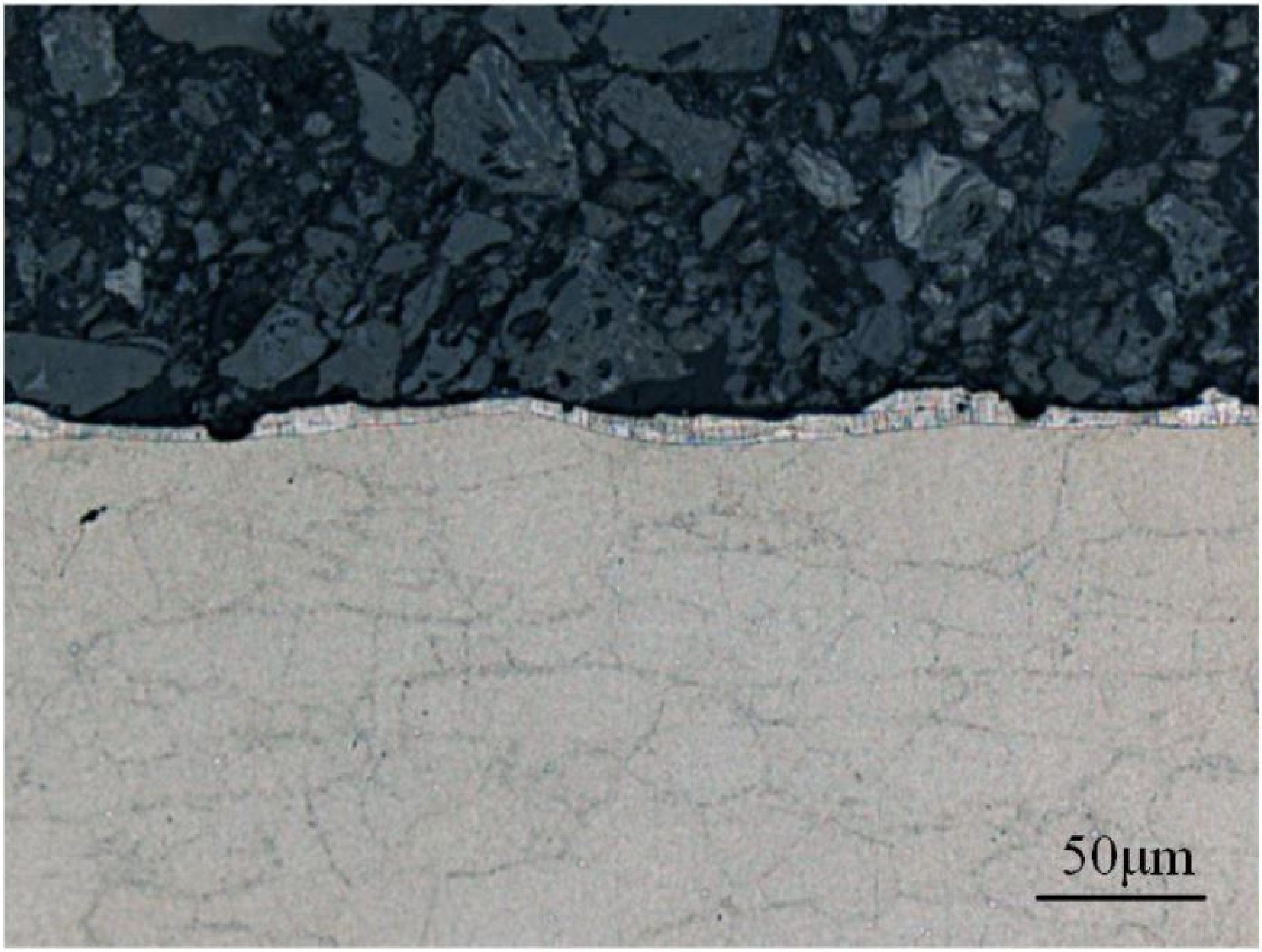


Figure 5

Microstructure of FGH96 machined by Wire-EDM

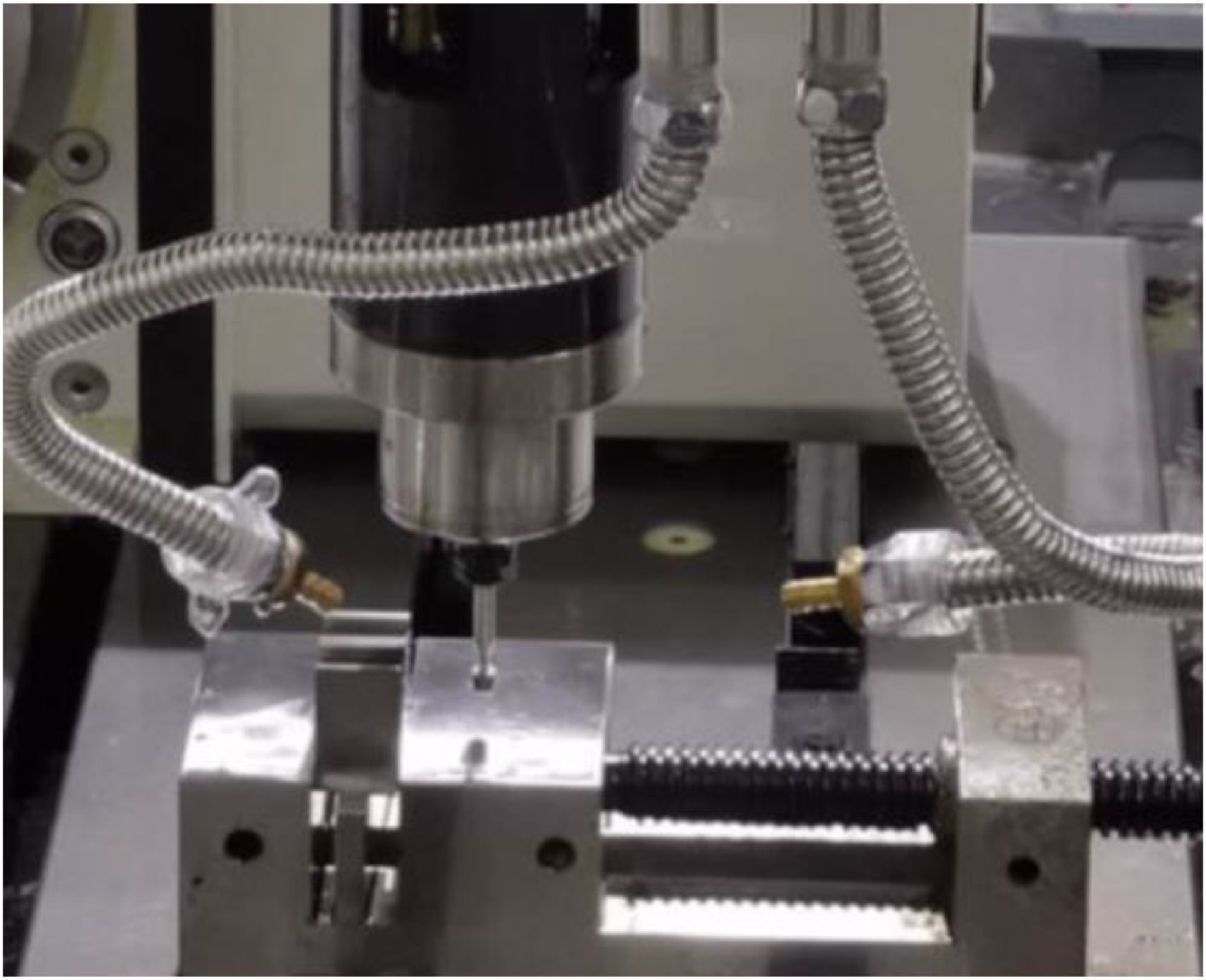


Figure 6

Experimental equipment for grinding turbine disk slots.

Figure 7

Profiled electroplated CBN wheel

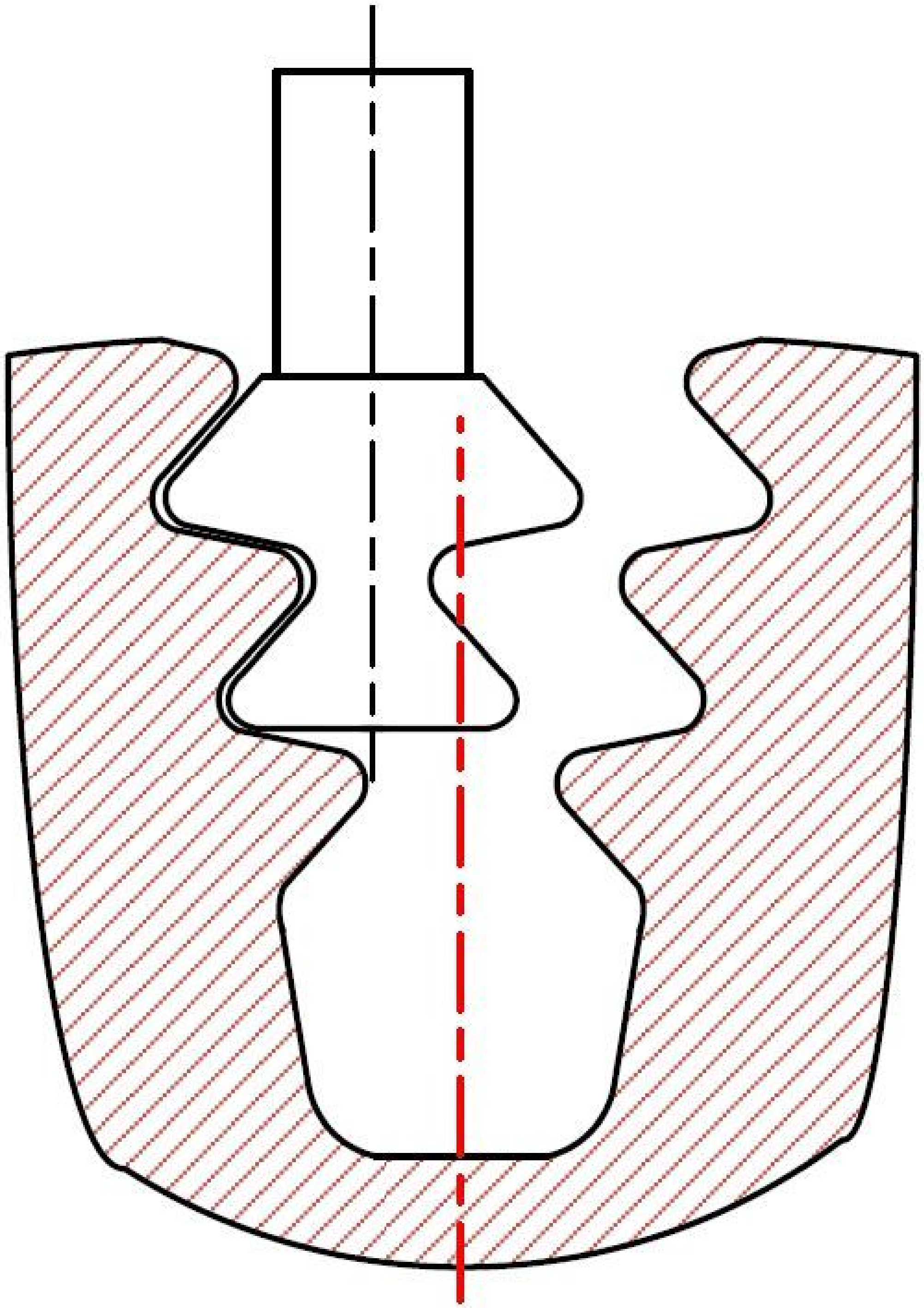


Figure 8

Single sided local profiled grinding process

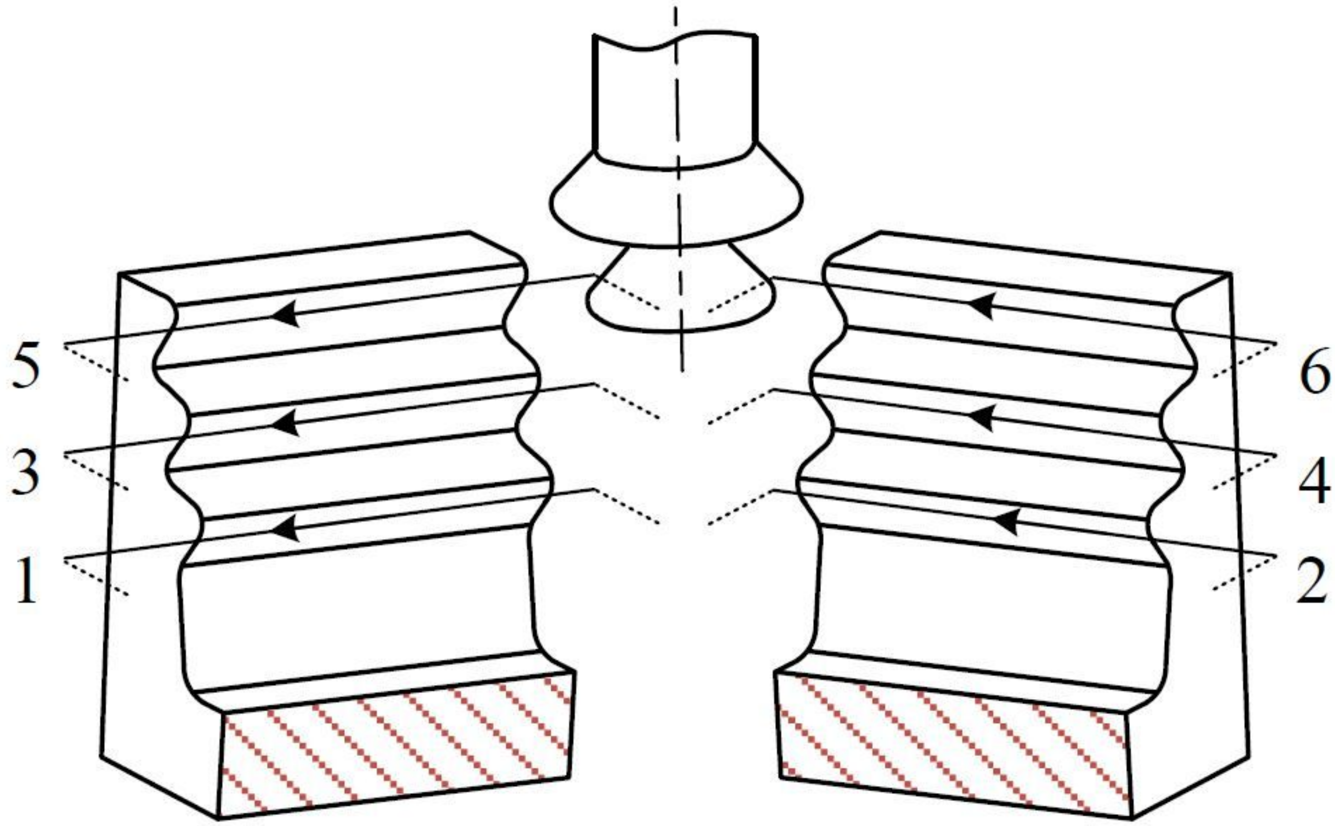


Figure 9

Path of grinding wheel during the grinding process of the whole slot tooth

Figure 10

Workpiece of one-sided slot

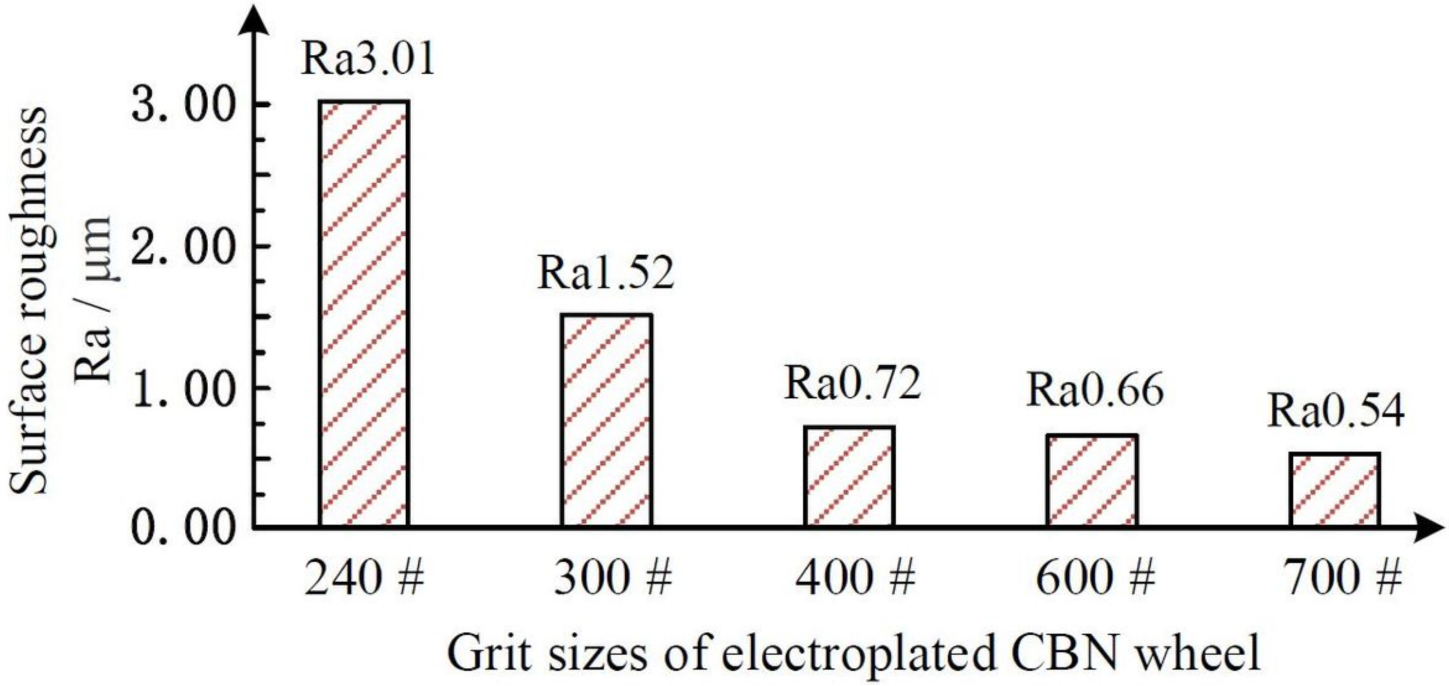


Figure 11

Influence of grit sizes on surface roughness

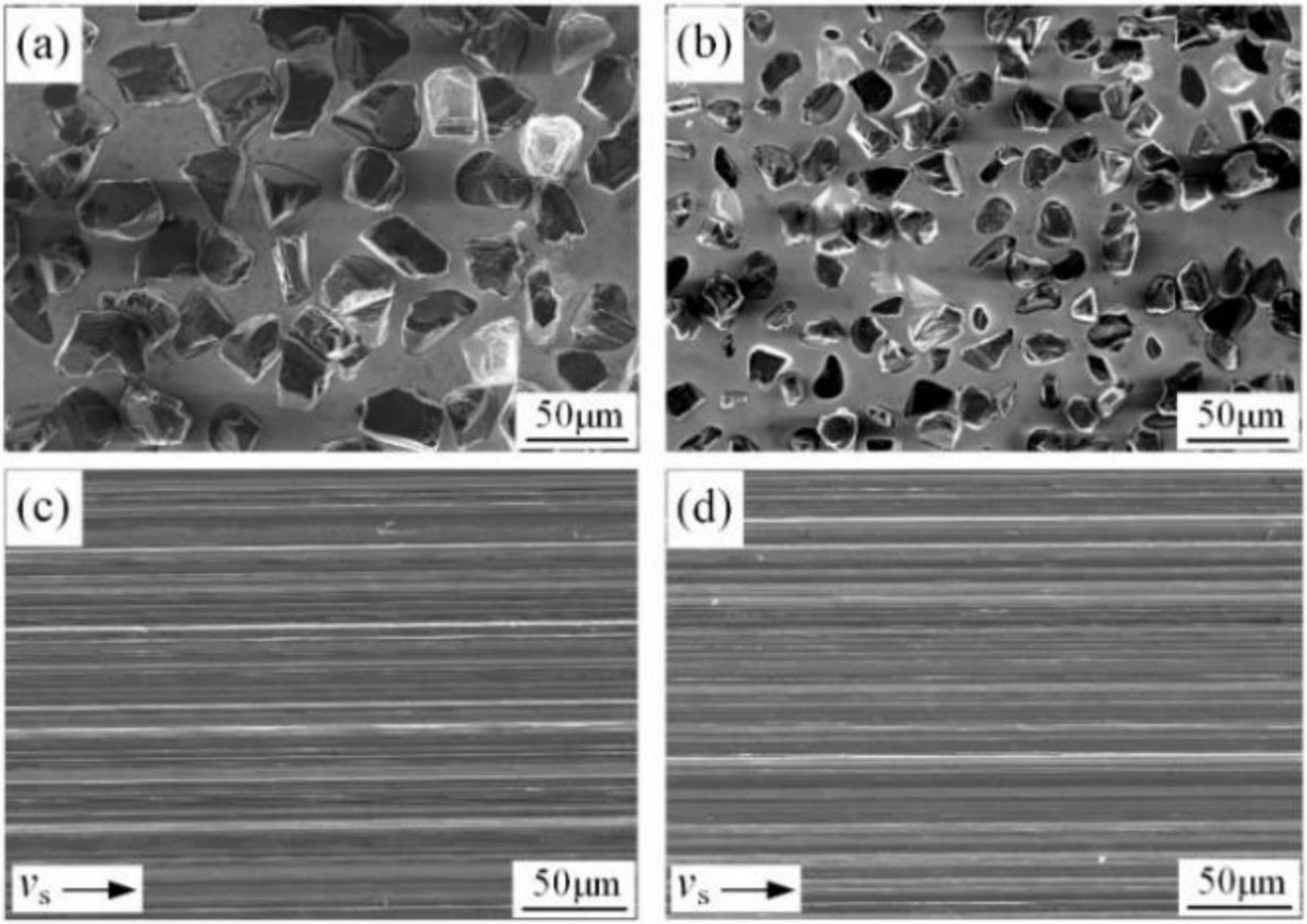


Figure 12

(a) Surface topography of 400# wheel. (b) Surface topography of 600# wheel. (c) Surface topography machined by 400# wheel. (d) Surface topography machined by 600# wheel.

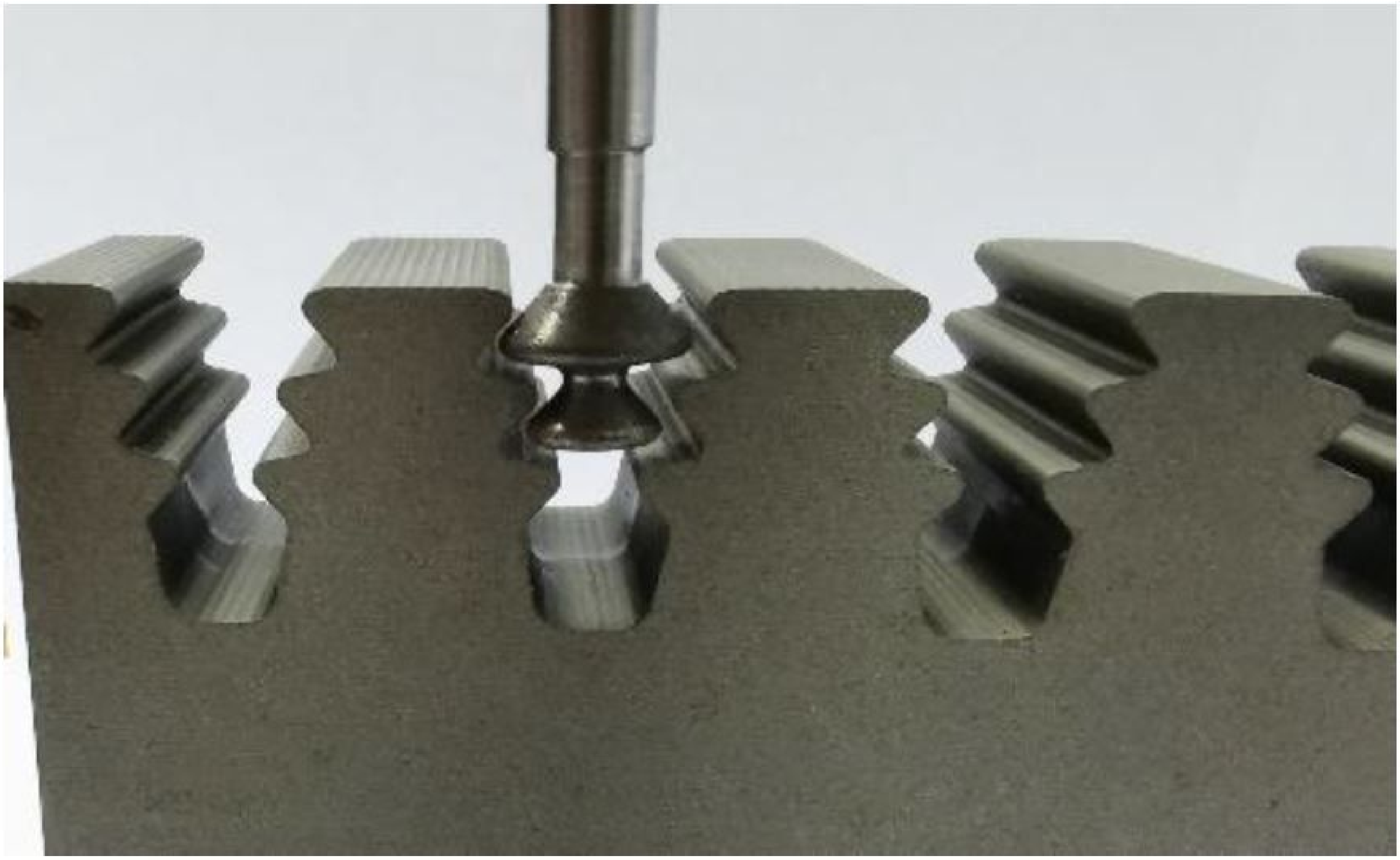


Figure 13

Grinding experiments of FGH96 fir tree slots

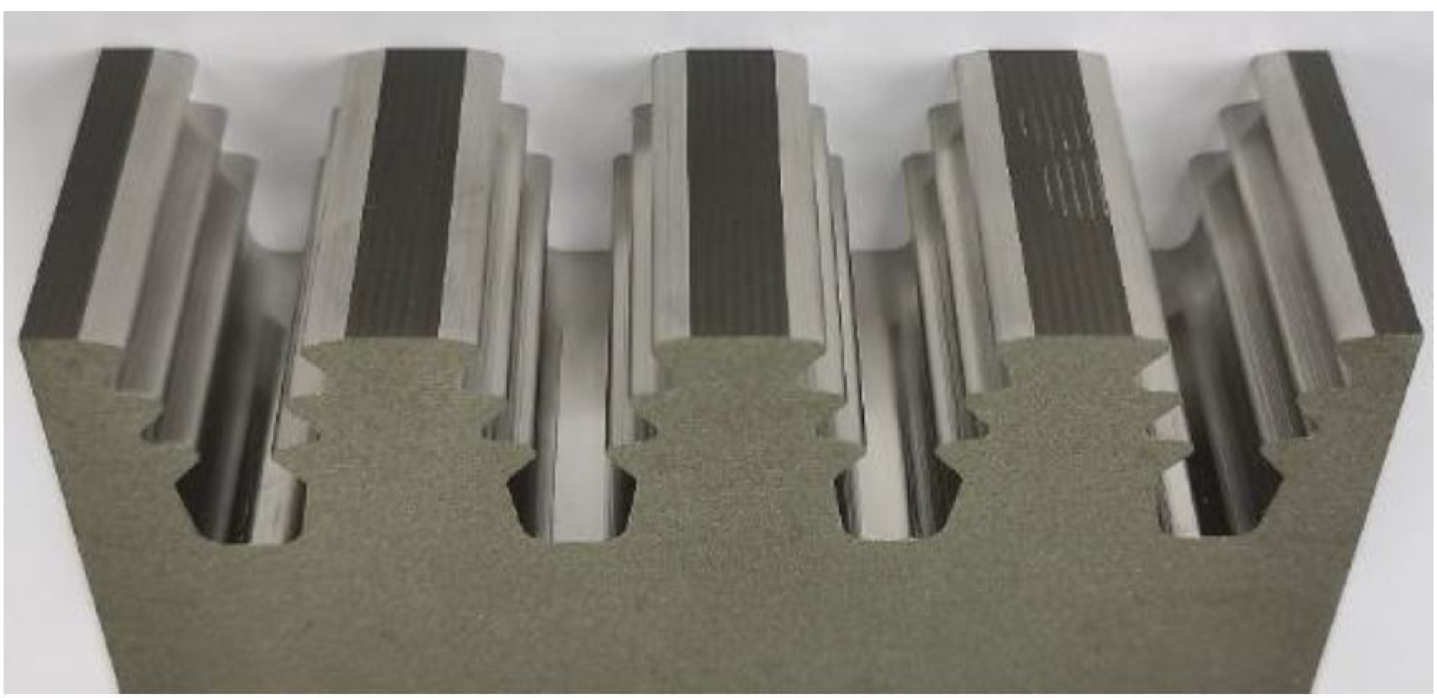


Figure 14

Slots after finishing grinding

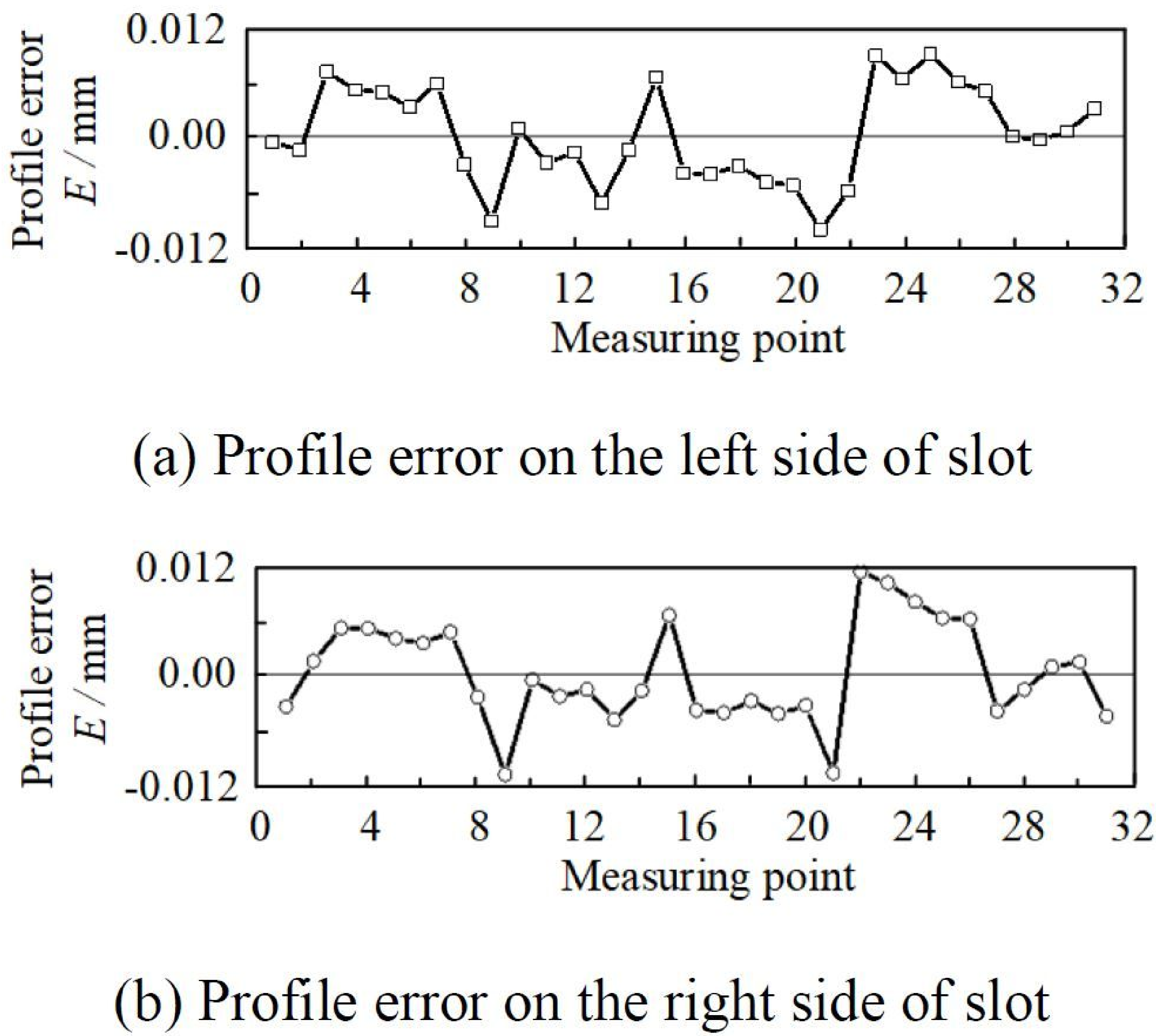


Figure 15

Profile error of slot machined by profiled grinding

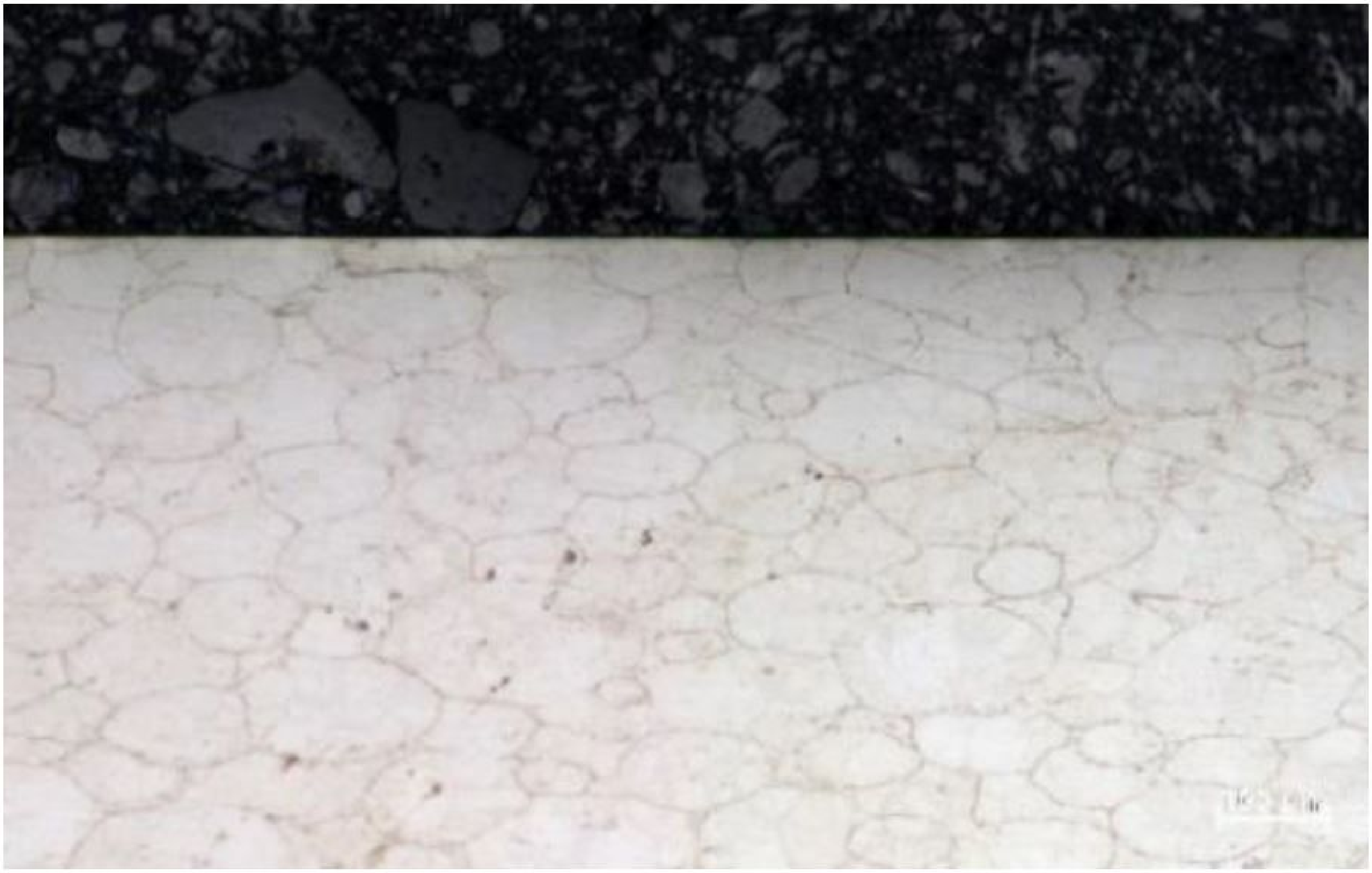


Figure 16

Microstructure of grinding surface

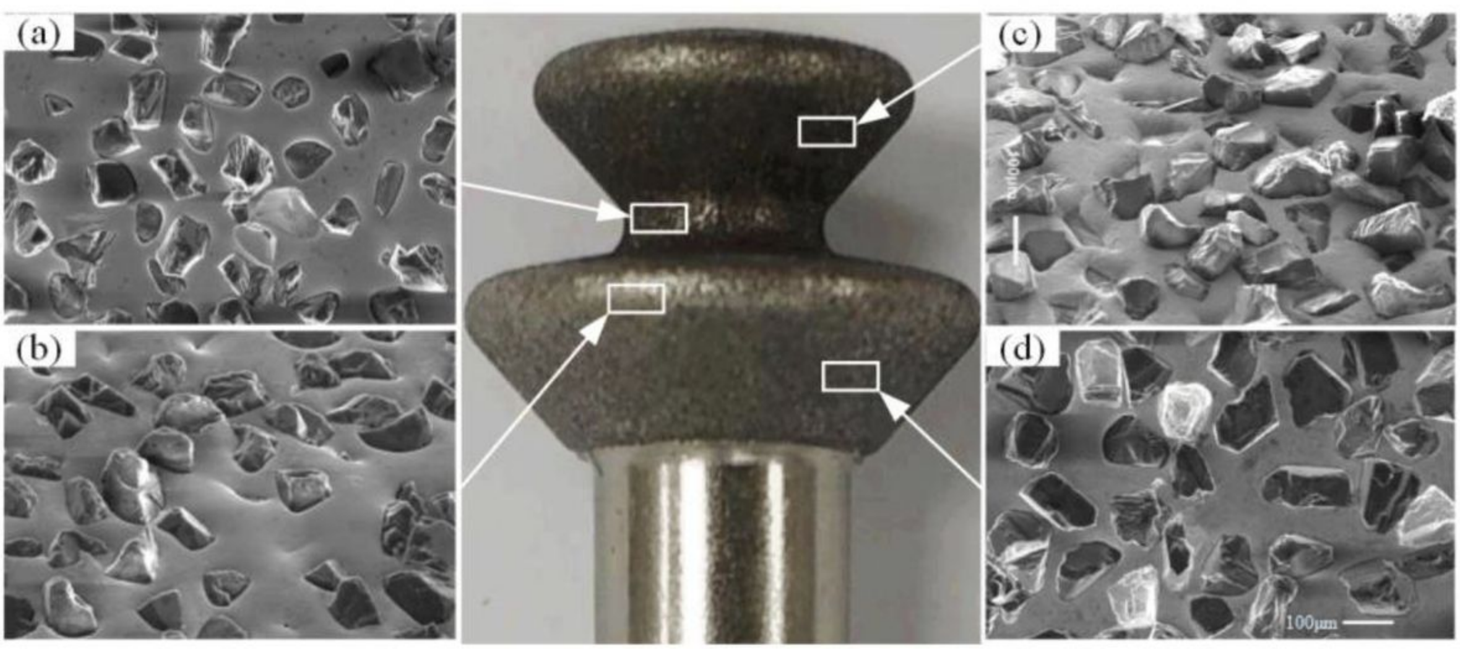


Figure 17

Wear degree of grinding wheel surface