Chapter 2
Barrel Finishing Technology

2.1 Introduction

In the process of the free abrasive tool finishing, the abrasive tool (also known as media) is in a free state, which is based on relative motions and action forces caused by the direct contact with parts to complete the finishing of part surface and to increase the surface qualities of parts. For various methods of free abrasive tool finishing, machining mechanisms, process parameters, finishing effects, and technology scopes have their own uniqueness due to different constituted forms, action modes, machining status of abrasive tools.

Surface barrel finishing, as one of the typical-free abrasive tool finishing methods, has advantages such as low processing cost, good finishing effect, high efficiency, simple device.

2.1.1 Connotation

Surface barrel finishing belongs to free abrasive tool finishing technology. First of all, parts which are in a free or non-free state are placed in the container with machining media (covering abrasive blocks, compounds, as well as water). Based on the driving motion produced by parts, container, or both, the complex relative motions between parts and abrasive blocks are generated in the process of finishing. Under the relative motion, abrasive blocks in a free state perform the micro-grinding action of collision, rolling, sliding, and scratching with a certain amount of force to change the geometrical characteristics of part surface (to reduce the value of surface roughness, to increase material ratio of the profile, to change surface texture, and to remove the defects such as burrs), to improve the physical–

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mechanical properties of surface layer (to increase micro-hardness, to form denatured layer on the surface, to improve surface stress state, etc.), to increase the cleanliness of parts, to synthetically improve the surface integrity of parts, to increase the usability and service life of parts and products, and to achieve the goal of surface finishing [1–6].

Surface barrel finishing is a kind of machining methods. According to Einstein's energy equation, the relative motion and interaction between the part and the abrasive blocks can be generated only when the abrasive blocks with certain mass have a certain degree of energy, that is

$$E + m \Rightarrow v \tag{2.1}$$

or

$$E + m \Rightarrow F \tag{2.2}$$

where E represents the energy, m represents the mass, v represents the velocity, and F represents the acting force.

As indicated in Eqs. (2.1) and (2.2), when a certain energy E acts on a certain mass m, the velocity and acting force can be generated. The interaction and micro-grinding effect of collision, rolling, sliding, and scratching are produced due to the existence of motion. Then, the finishing of parts is completed.

Results mentioned above also satisfy Poisson equation:

$$\mathrm{MMR} = KFv \tag{2.3}$$

where MMR is the material remove rate, K is the coefficient, F is the acting force, and v is the velocity.

In order to achieve the barrel finishing of part surface, the abrasive blocks and the part must touch each other. The key is how to enable the energy and force to act on the mass, because the same abrasive blocks or parts with different barrel finishing processes can cause different velocities and acting forces, and obtain different finishing effects and efficiencies.

The main effects generated in barrel finishing processes are shown below [3, 4].

(1) Collision effect. When the free abrasive blocks with mass hit the part surface at a certain relative velocity, an impact force F_N is generated. It can cause the part surface to generate elastic and plastic deformation, and to change the microscopic geometry and the physical–mechanical property of part surface layer. According to momentum theorem, the impact force F_N is

$$F_N = \frac{m\left(v_N - v'_N\right)}{\Delta t} \tag{2.4}$$

where m is the mass of abrasive blocks, v_N, v'_N are normal components of abrasive blocks velocity on the part surface before and after abrasive block forces on the part surface, respectively, and Δt is the action duration.

It can be shown from Eq. (2.4) that the impact force to the part surface can be increased, and the finishing efficiency can be enhanced by increasing the mass of abrasive block m and the change of the velocity $v_N - v'_N$. For example, among various surface barrel finishing processes, larger-sized abrasive blocks (for the same kind of abrasive blocks, larger size means greater mass) can be usually selected to improve the finishing efficiency in the rough machining. When there is a restriction on the size of the abrasive blocks during machining, the denser abrasive blocks should be selected. The forced flow area (means the change of the velocity) is formed to increase the finishing efficiency and improve finishing effects in centrifugal barrel finishing.

(2) Rolling effect. When the free abrasive blocks extrude the part surface with a certain amount of force, the abrasive block must generate any rotation motion due to many other surrounding abrasive blocks. Roll-finishing is formed under the relative movement, micro-peaks on the part surface which yields micro-plastic deformation locally under the effect of rolling, and then it can gain a better surface. Meanwhile, there would be certain degree of surface hardening, and therefore the wearability and the fatigue strength of the part are increased since the residual compressive stress is generated.

    For higher normal pressure, the micro-peaks on the part surface are flattened by the plastic deformation on the effect of rolling. The micro-peaks left on the surface are not completely flattened, and the valley is not completely filled due to limit of the normal pressure. The rolling effect of abrasive blocks on part surface includes two forms: surface plastic deformation and elastic deformation. When the contact area is small, the plastic deformation develops in the local contacting area, and the valley is filled by the micro-peaks. When the contact area becomes larger, the finite-sized normal pressure is not enough to generate the plastic deformation of the micro-peaks on the part surface, but only elastic deformation. Under the alternating action of plentiful abrasive blocks, these micro-peaks are fractured in fatigue due to repeating elastic deformations. As a result, it produces chip-breaking.

(3) Micro-grinding effect. Under the action of certain force, the free abrasive blocks slip along the part surface at a certain velocity. The abrasive particle which is bonded to the surface of the abrasive blocks performs the action of sliding, scratching, and cutting, as same as the abrasive particle bonded to the surface of grinding wheel does. When the abrasive particle glides and scrapes across the metal surface of the part one or more times, the plastic deformation limit of the surface metal would be occurred one or more times. If the plastic deformation reaches the yield strength, the microchip might fall off from the metal base, and the micro-grinding is completed.

(4) The effect of liquid medium. Water and specific compound additive as liquid medium are used in many surface barrel finishing processes, and it is very critical to reasonably select the additive and dose for finishing effect and efficiency. On the one hand, they can promote or restrain the grinding and finishing effects. Meanwhile, the compound itself can set off the chemical reaction and involve in finishing to maintain or improve the surface quality of the part (covering luster, color, surface roughness, etc.) and to change finishing time. On the other hand, the compound can regulate and soften water for giving full play to the buffer and flushing action of water (avoiding or reducing the violent collision among parts and abrasive blocks, scratch, deformation, crushing, etc.), changing the pH of the medium, and controlling the formation and the number of the foam. In addition, liquid medium can clean the oil fouling, abrasive dust, microchip and other impurities on the surface of the part, and the abrasive blocks to prevent the corrosion of the part, to keep the abrasive block clean and sharp, and to improve the cutting ability of the abrasive blocks.

To deeply understand the surface barrel finishing in theory, the key is to research the main effect in which the abrasive blocks play on the part during barrel finishing, and even more important is to identify requirements for the main effects. Based on viewpoints of machining process morphology, surface barrel finishing process can be regarded as materials processing, energy conversion process, and the changing of information, and materials machining cannot do it without the energy conversion and the information changing. The material flow in surface barrel finishing processes is the mechanical changing during plastic deforming and chemical changing during corrosive finishing for the solid part to complete the removal of metal on the part surface layer. The energy flow is to use abrasive blocks and definite liquid medium for transferring energy under the action of relative motion and the chemical action, and stressing the part with mechanical force and chemical reaction. The information flow is changed by the mixture medium which makes the part do complex relative motion and completes the free forming of the part with special shape. In surface barrel finishing, the energy conversion includes three aspects, (1) energy types (mechanical energy and chemical energy), (2) energy transfer medium (abrasive blocks with rigid and definite liquid medium), and (3) energy transmission styles (relative motion and chemical action). The change of the information includes two aspects, (1) the forming method (free forming) and (2) the relative motion way (compound motion) [7].

In conclusion, the requirements for producing the main effects in barrel finishing are (1) the complex relative motions between abrasive blocks and part surface, (2) forces driven by relative motions between abrasive blocks and part surface, (3) the abrasive blocks with definite property parameters, and (4) the liquid medium with definite chemical effects.

2.1.2 Classification

According to different states of parts during processing, surface barrel finishing includes three major categories of parts in a free state, in a half free state, and in a non-free state. Table 2.1 lists the classification of surface barrel finishing.

2.1.3 Functional Characteristics and Application Scope

Surface barrel finishing as one of the typical-free abrasive tolls finishing ways has the following characteristics:

(1) The complex relative motions between parts and abrasive blocks are generated due to one or several kinds of moving ways. Depending on certain relative speed of motion and applied force, the finishing of part surface is implemented [8–10].
(2) Surface barrel finishing works for the deflashing and removing of oxide layer and surface cleaning of middle or small-sized casting-forging stamping parts. It

Table 2.1 Classification of surface barrel finishing

Method	Classifications		
Surface barrel finishing	Parts in free state	Rotary type	Horizontal placement
			Inclined placement
		Whirling type	Static whirling
		Vibratory type	Vertical vibration
			Horizontal vibration
		Reciprocating type	
		Centrifugal type	Horizontal placement
			Inclined placement
			Vertical placement
		Other types	
	Parts in half free state	Spindle type	
		Vibratory type	
	Parts in non-free state	Spindle type	Vertical spindle type
			Intermeshing spindle type
			Horizontal spindle type
		Non-spindle type	Dynamic whirling
			Workpiece vibration
		Combined type	Spindle–non-spindle
			Spindle-vibration

also works for the deburring, filleting, refining the surface, and decreasing the surface roughness values of parts machined.

(3) Surface barrel finishing can realize the surface finishing of parts with large or middle dimension, such as crankshaft, camshaft, gear, wheel hub, transmission housing [11, 12].

(4) Surface barrel finishing is an all-round finishing method. It can carry out not only the finishing of machined surface, but also the finishing of non-processing surface. It can improve the cleanliness of parts synthetically [13, 14].

(5) Surface barrel finishing has the collision and rolling effects on the surface of parts. It can increase the micro-hardness and improve the stress state, the physical and mechanical performance on the surface layer of parts.

(6) Surface barrel finishing has the characteristics of simple operation, easy management, low processing cost, good finishing effects, efficient production, light pollution, etc [15–17].

(7) For surface barrel finishing, it is constrained by part dimensions, structure shape, finishing area, etc. It could realize the finishing on the apparent surface of middle- and small-sized parts easily. However, for the finishing of large parts, such as inner bores, grooves, and dented surfaces, it becomes much more difficult to implement.

(8) Abrasive blocks are main working media in the surface barrel finishing. The shapes of the abrasive blocks include square, rectangle, rhombus, cylinder, tetrahedron, sphere. The shape, size, and material of the abrasive block make a difference to finishing effects and efficiency, and can be determined by the material, overall dimension, finishing area, and the finishing requirements of workpiece.

(9) The compound used in surface barrel finishing is also the main working medium. The compound and water played a helpful role in grinding, brightness, foaming, lubrication, buffering, cleaning, etc.

Surface barrel finishing can realize deburring, derusting, surface finishing, chamfering, removing various defects left after heat treatment or other processing, pre-treatment before plating and painting, etc. Ferrous metals, nonferrous metals, plastics, composite materials, ceramics, even wood, and other imaginable materials can be finished with high productive efficiency and satisfactory finishing results. Meanwhile, the technology has the advantages of high cleanliness, low equipment and process costs, easy operation, low labor intensity, etc. Just as the other processing methods, surface barrel finishing also has certain scope of application. For example, the barrel finishing of inner bores, grooves, and dented surfaces becomes much more difficult to implement. And, there are also different applicable scopes corresponding to different surface barrel finishing ways. For example, horizontal spindle barrel finishing is mainly applicable to the surface finishing of large- or middle-sized parts, such as crankshaft and camshaft. Table 2.2 shows the characteristics and applicable scopes of most common surface barrel finishing technologies.

Table 2.2 Characteristics and applicable scopes of surface barrel finishing technology

Finishing methods	Metal removal capacity	Finishing efficiency	Part surface brightness	Surface roughness decrement	Improvement of physical–mechanical performance	Collision among parts	Degree of automatization	Scope of application
Rotary type	Very weak	Low	Worse	About 0.5 magnitude	Worse	Great	Average	Small special-shaped parts
Vibratory type	Weaker	Average	Better	About 1 magnitude	Worse	Small	Easy	Small and medium special-shaped parts
Centrifugal type	Strong	High	Better	1–2 magnitude	High	Medium	Difficult	Small and medium special-shaped parts
Whirling type	Stronger	High	Better	1–2 magnitude	High	Medium	Easy	Small and medium special-shaped parts (except for sheet parts)
Vertical spindle type	Strong	High	Good	1–2 magnitude	High	None	Easier	Small and medium parts, shaft parts, and special-shaped parts
Intermeshing spindle type	Strong	High	Good	1–2 magnitude	High	None	Easier	Small and medium parts, plate-shaped parts, and special-shaped parts
Horizontal spindle type	Strong	High	Good	1–2 magnitude	High	None	Easy	Parts like crankshaft, camshaft, etc.

2.2 Rotary Barrel Finishing

2.2.1 Finishing Principle and Characteristics

1. Finishing principle

Figure 2.1 shows the schematic of rotary barrel finishing. In the finishing, the workpieces and working media (abrasive blocks, compounds, water included) are put into one drum. When the drum rotates at a certain speed, the workpieces and abrasive blocks in the drum are lifted up with rotation direction in the drum, under the action of gravity, centrifugal force, and friction. In the lifting process, the workpieces and abrasive blocks located at the bottom of the drum are in a dynamic balance, and they remain to be relatively motionless. When the workpieces and abrasive blocks located at the top of the drum are lifted up to a certain height, they will lose their balance and slide down. The workpieces and abrasive blocks on the outer layer subject to least resistance, and their sliding velocities are fast; thus relative movements occur among layers. Even in the same layer, the slipping velocities vary, due to large differences in the shapes, qualities of the workpieces and the abrasive blocks. Therefore, with the rotation of the drum, the workpieces and abrasive blocks in the drum roll over and over, which cause the collision, rolling, rubbing, and scoring among workpieces and abrasive blocks, and the finishing is implemented.

2. Main factors affecting finishing effects

Rotary barrel finishing is one of the barrel finishing technologies at the earliest stage, and it is suitable to the finishing of small special-shaped parts [18]. Its capacity of metal removal is weaker, machining efficiency is lower, certain collision among part surface exists, and the integrity of machined surface is much poor. The

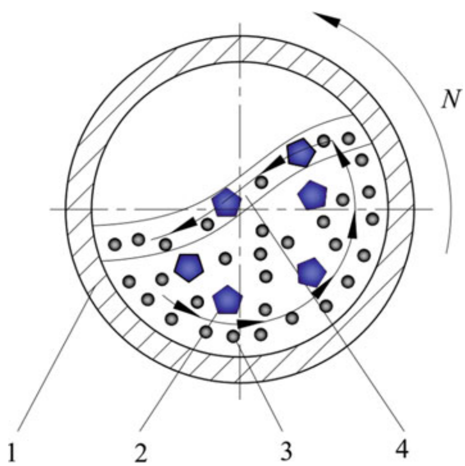


Fig. 2.1 Schematic of rotary barrel finishing. 1—drum; 2—workpieces; 3—working medium; 4—sliding layer

Table 2.3 Characteristics of rotary barrel finishing with different drum placements

Factor	Drum placement	
	Horizontal placement	Tilted placement
Processing condition adjustment Work-handling Monitoring of machining process	Rotating speed adjustable Inconvenient Inconvenient	Rotating speed and tilt angles adjustable Convenient Convenient
Equipment cost Machining uniformity Size range of workpiece	Low Good Large	High Poor Limited
Main purpose	Finishing	Acid cleaning, drying, and small parts finishing

characteristics of rotary barrel finishing with different drum placement are shown in Table 2.3.

2.2.2 Main Factors Affecting Finishing Effects

The rotating speed of the drum is an important parameter and has a strong effect, finishing efficiency, and quality. The reasons may be analyzed from the following three points.

(1) As the rotating speed increases, the centrifugal force will increase. And the collision, rolling, rubbing, and scoring among workpieces and abrasive blocks in the drum become serious.
(2) As the centrifugal force increases, the friction forces from the drum wall to the workpieces and the abrasive blocks increase. The workpieces and abrasive blocks can lose their balance and slide down only when they lift up to a turnover. This can increase the impact force of the down-sliding, the sliding distance and the number of the collisions, rolling, rubbing, and scoring suffered by workpieces.
(3) As the rotating speed increases, the rolling frequency of the workpieces and abrasive blocks in the drum quickens, and the sliding number of the workpieces and abrasive blocks per unit of time increases.

Under the influence of three factors mentioned above, the finishing efficiency increases with the increase of the rotating speed. But when the speed increases to more than $\frac{1337}{\sqrt{D}}\,\mathrm{r/min}$ (where D represents rotating radius of the drum wall, mm), the workpieces and abrasive blocks evenly snuggle up on the drum wall along with the rotation of the drum. They are in a dynamic balance and remain relatively motionless. By this time, the rolling forces among the workpieces and abrasive blocks are large, but the workpieces could not be machined due to non-existing relative sliding. Therefore, the rotary barrel finishing is difficult to improve the finishing efficiency and quality due to the rotating speed constraints.

2.2.3 Equipment Types and Design

1. Equipment types

The concrete types of rotary barrel finishing equipment are shown in Fig. 2.2. Where, Fig. 2.2 (a) shows the common tilting type; (b) named bottle type is the improved type of common tilting type; for it combines the advantages of horizontal type and tilting type; (c) designed with material handling port is horizontal type; (d) is multi-compartment type, could apply to machine different shape and sizes of workpiece at the same time; (e) is multiple barrel type, which is one improved type of horizontal type, several drums are fastened together on one connecting plate, the tilt levels of each drum can be adjusted by changing angle of connecting plate; (f) is triple action type, which is designed for improving the phenomena that the easy appearance of workpieces snuggle up on both side of the drum wall in the process of machining flat workpieces with horizontal type rotary barrel finishing equipment; (g) is end loading type, could apply to machine slightness workpieces; (h) designed with one water tank on the bottom is submerged type.

2. Equipment shape

The shape of the drum used for machining small-sized parts is usually 6–8 polygons. When the size of parts increases, the shape can be 10–12 polygons. Figure 2.3 shows several photographs of different rotary barrel finishing equipments.

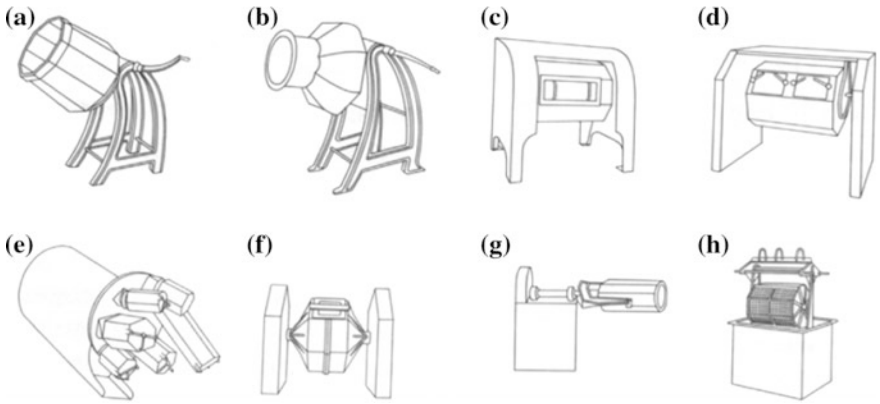


Fig. 2.2 Types of rotary barrel finishing equipment. **a** Tilting; **b** bottle; **c** horizontal; **d** multi-compartment; **e** multiple barrel; **f** triple action; **g** end loading; **h** submerged

Fig. 2.3 Photographs of several different rotary barrel finishing equipments

2.3 Vibratory Barrel Finishing

2.3.1 Finishing Principle and Characteristics

1. Finishing principle

In the vibratory barrel finishing process, the workpieces, abrasive blocks, and liquid medium are put into a shaped container according to certain proportioning, and the workpieces and abrasive blocks move along a certain pattern when the container vibrates with fixed amplitude and frequency. During the movement of the workpieces and the abrasive blocks, due to their differences in weight, shape, and location, abrasive blocks are forced to make collision, rolling, and micro-grinding to the workpiece surface for achieving the deburring, chamfering, and surface finishing of the workpiece.

Figure 2.4 is a horizontal vibratory barrel finishing equipment, which is driven by a single-shaft inertia vibration generator with a planar motion. The shaft of vibration generator 2 is installed horizontally, and the two eccentric parts with adjustable setting angle and offset are mounted on the shaft. When the horizontal shaft of the vibration generator rotates at high speed, the eccentric parts generate centrifugal force to make the container 6 (slot shaped) generating periodical vibration. The abrasive blocks and workpieces in the container roll oriented along the wall of the container under the action of centrifugal exciting force.

Figure 2.5 is a vertical vibratory barrel finishing equipment, which is driven by single-shaft inertia vibration generator 3 with spatial motion. The shaft of vibration generator is installed vertically, and two eccentric parts are mounted on the upper and the lower ends of the shaft. There is an angle between the two eccentric parts projection in the horizontal plane. When the shaft of the vibration generator rotates at high speed, the eccentric parts not only generate a certain centrifugal exciting force in the horizontal plane, but also a certain exciting torque in the vertical plane to make the container 4 (annular shaped) to generate a complex periodical vibration. Since the bottom of the container is an annular shape, the abrasive blocks and workpieces in the container not only orbit around the center shaft (vertical) of the container, but also roll around the center of the annular. Thus, the resultant motion is an annular spiral motion under the action of horizontal centrifugal exciting force and the vertical exciting torque.

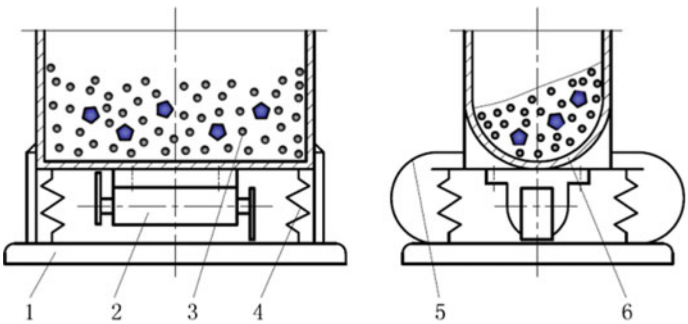


Fig. 2.4 Horizontal vibratory barrel finishing equipment diagram. 1—Base; 2—vibration generator; 3—workpiece and medium; 4—spiral spring; 5—plate spring; 6—container

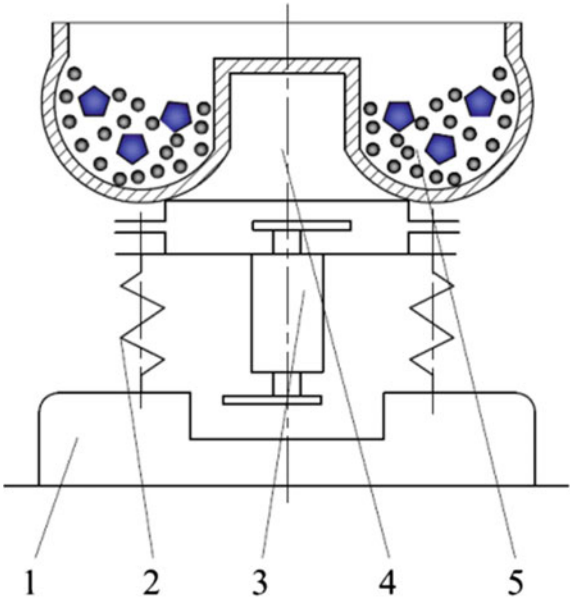


Fig. 2.5 Vertical vibratory barrel finishing equipment diagram. 1—Base; 2—spiral spring; 3—vibration generator; 4—container; 5—workpiece and medium

2. Force analysis

Here, take the vertical vibratory barrel finishing method as an example to conduct force analysis [19].

Let the weight of the two eccentric parts equal to each other is m_0; the angular velocity of the vibration generator shaft is ω; the angle between the two eccentric parts projection in the horizontal plane is α; the distance from the gravity center of the eccentric parts to the vertical shaft is r; the center-to-center distance between the two eccentric parts is l_0; the distance from the upper eccentric part to the gravity center of the container is l. The exciting force generated by vibration generator in the horizontal plane is

$$P(t) = 2m_0\,\omega^2 r\,\cos\frac{\alpha}{2}(\cos\,\omega t + i\,\sin\,\omega t) \tag{2.5}$$

The exciting torque about horizontal shaft generated by vibration generator is

$$M(t) = 2m_0\omega^2 r\left[\left(\frac{l_0}{2}+l\right)\cos\frac{\alpha}{2}(\cos\,\omega t + i\,\sin\,\omega t) + \frac{l_0}{2}\sin\frac{\alpha}{2}(\sin\,\omega t - i\,\cos\,\omega t)\right] \tag{2.6}$$

The exciting force causes abrasive blocks and workpieces in the container to orbit around the center shaft (vertical) of the container, and the exciting torque causes abrasive blocks and workpieces to roll around the center of the annular. The influence of the vibration generator position at an angle between the two eccentric parts and so on can be analyzed by curve plotting.

3. Functional characteristics and application scope

Vibratory barrel finishing is one kind of surface finishing process developed abroad in the 1950s; it has been widely used in the deburring, rounding, chamfering and finishing of small- or medium-sized components made of different materials (like steel, copper, aluminum, bakelite). Horizontal vibratory barrel finishing method can easily make a separation between the workpiece and abrasive blocks in processing, and leave the trace of impulse shock on the workpiece surface, and therefore it is not suitable for the precision finishing. Vertical vibratory barrel finishing method makes the mutual cyclic surrounding among the workpiece and abrasive blocks not leaving any trace of impulse shock on the workpiece surface; therefore, it is suitable for the precision finishing [20–23].

According to the simple analysis of the finishing principle, vibratory barrel finishing processes have the following characteristics.

(1) High finishing efficiency

In the whole machining cycle, the finishing effect of abrasive blocks on the workpiece goes on without a break, so the efficiency is high (its efficiency should be several times even dozens of times higher than that of rotary barrel finishing) [24].

(2) Extensive application range

This kind of finishing method not only machines black metal pieces, nonferrous metal parts, but also machines nonmetal parts, such as plastic parts, ceramic parts. Moreover, it can machine large or medium-sized complicated shaped shell parts with inner holes or hidden surface and other easy-deformed object [20, 21].

(3) Good finishing quality

This kind of finishing method not only removes burrs, but also removes the oxide layer, so as to achieve chamfering and surface polishing [22]. It has a good finishing uniformity, and surface roughness degree can be increased by 1°–2°; the surface micro-hardness can be increased, the residual tensile stress can be relieved, the fatigue resistance can be enhanced (typically about 10%), and also the physical–mechanical properties can be improved.

(4) The equipment is simple in construction, easy to operate, and easy to realize the operation of several sets of equipment by one operator and the automation of manufacture [24].

2.3.2 Main Factors Affecting Finishing Effects

1. Equipment parameters

    (1) The configuration parameters of the eccentric parts
    The configuration parameters of the eccentric parts on the vibrating shaft have direct influences on the amplitude, which mainly refer to the quality, the center-of-mass offset of the single eccentric part, the axial distance, and relative angle between the two eccentric parts.
    In theory, when the vibrating shaft is rotated, the higher the quality and the center-of-mass offset of the eccentric part are, the higher the centrifugal force developed by the eccentric part is, the more intensive the vibration is, the higher the finishing efficiency is. However, the finishing quality tends to decrease to some extent. For the equipment structure, the quality and the center-of-mass offset of the eccentric part cannot be too large, and otherwise it will not only make the equipment heavier, but also greatly shorten the service life of the support bearing mounted on the vibrating shaft. Conversely, if the quality and the center-of-mass offset of the eccentric part are small, the centrifugal force developed by the vibrating shaft is small, and the vibration becomes more moderate. Although the efficiency is low, a finer surface quality can be obtained, and the deformation of the easy deformability workpiece can be prevented when machining. Therefore, the quality and the center-of-mass offset of the eccentric part need to be decided based on the actual situation, and the counterweight of the eccentric part can be solved. It is convenient to adopt adjustment method using screw fixation for the addition or removal of the counterweight on the eccentric part.
    The relative angle between the two eccentric parts not only has an effect on the movement of the workpiece and abrasive blocks in the container, but also affects the finishing efficiency and quality, which shows that it is a very important equipment parameter. The practice shows that the angle between the eccentric parts is related to the effective length of the vibrating shaft, the centrifugal force developed by the eccentric part, and so on. If the setting angle of the eccentric parts is less than 90 °C, the workpiece and abrasive blocks will roll moderately, and the finishing efficiency will be relatively low. Conversely, the movement will be intensive, and resulting in a high efficiency, but the quality will be relatively poor. Generally, it is suitable to select 90 °C as the setting angle of the two eccentric parts [23].

    (2) The rigidity coefficient of the spring
    The rigidity coefficient of the spring has an impact on the finishing efficiency. Generally, the larger the rigidity coefficient is, the higher the finishing efficiency is, but the louder the noise is. The lower the rigidity coefficient is, the lower the finishing efficiency is, and the lower the noise is.

(3) The rotary speed of the vibrating shaft
The higher the rotary speed of the vibrating shaft is, the higher the vibration frequency is, the better the finishing efficiency is. Generally, the rotary speed of the vibrating shaft is not less than 1500 r/min. The rotary speed of the equipment with small container can be higher and be lower the equipment with large container.

2. Technological parameters

(1) Finishing time
The determination of finishing time relates to the finishing requirements of parts: Deburring processing usually takes 1–2 h. Reduction of the surface roughness value takes 3–5 h. Improvements of surface micro-hardness and residual stress take about 10 h.

(2) Volume ratio and load amount
When finishing small workpieces, the volume ratio of workpiece to abrasive blocks should be controlled at 1:2 $\sim$ 1:6, with the total load amount at 50–80% of the total volume of the container. When finishing large-scale workpieces or parts with special requirements on horizontal vibratory barrel finishing equipment, the clamping device is adopted to fix workpiece. This not only avoids the collision among workpieces, but also improves the finishing efficiency. It is worth noting that when the clamp fixes the workpiece, it must ensure that the workpiece loaded on the clamp can freely rotate for guaranteeing the finishing uniformity of the workpiece; meanwhile, it also allows the workpiece to have enough distance from the wall of the container in order to guarantee the smooth flow of abrasive blocks around the workpiece.

(3) Finishing medium
The abrasive blocks often keep moist condition (as with liquid medium), but they are used as dry state sometimes.
New sensors can be adopted to monitor force status of the workpiece from abrasive blocks during vibratory barrel finishing process. Figure 2.6 shows the curves of normal force with time measured by a sensor A101-1. A miniature color video camera can be used for recording the motion of abrasive blocks, analyzing the motion by replaying the video tape in frames. Figure 2.7 shows the motion photographs of abrasive blocks recorded by a camera IK-SM40A. These advanced test and observation methods can help us to establish the corresponding model of abrasive blocks and analyze the influence of the media on the finishing results. This can contribute to determining practical parameters according to specific finishing requirements. The rest contents will be detailed in Sect. 2.8 of this chapter [25].

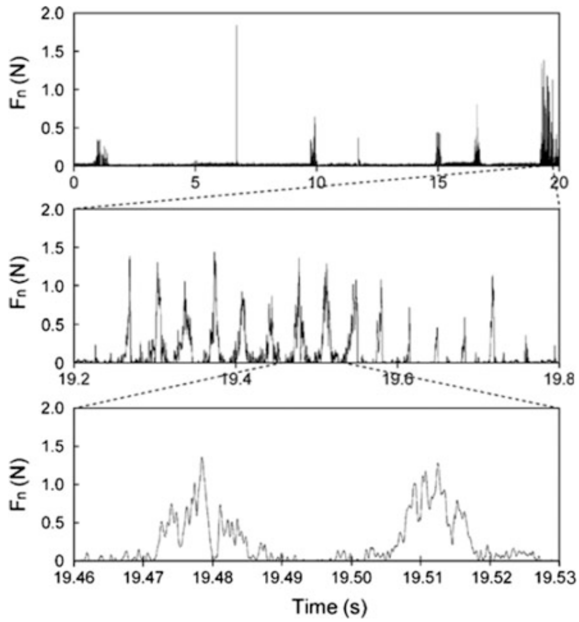
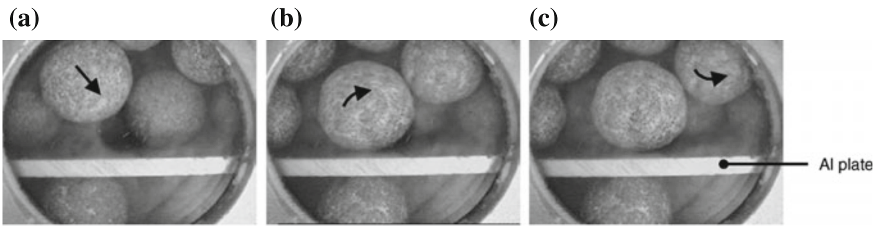


Fig. 2.6 Curves of measuring normal force with time



Aluminium panel

Fig. 2.7 Motion photographs of abrasive blocks

2.3.3 Equipment Types and Design

1. Equipment types

   According to the difference of vibrating object (barrel or workpiece), vibratory barrel finishing equipment can be divided into different types, as listed in Table 2.4.

   Here is a brief description of features of the double vibration source vibratory barrel finishing method, orboresonant resonance barrel finishing method, and cascade barrel finishing method.

Table 2.4 Types of vibratory barrel finishing equipment

Type	Vibrating barrel	Vibrating workpiece
Equipment	Horizontal vibratory barrel finishing equipment	Orboresonant barrel finishing equipment
	Vertical vibratory barrel finishing equipment	
	Double vibration source vibratory barrel finishing equipment	Cascade barrel finishing equipment

(1) Double vibration source vibratory barrel finishing method
Figure 2.8 is the structure principle diagram of the double vibration source vibratory barrel finishing method. As shown in the figure, it is basically the same as ordinary horizontal vibratory barrel finishing process and is composed primarily of the container, vibration source, motor, base, spring, and so on. The difference is that there are two vibration sources of this new kind of vibratory barrel finishing method; one installed under the container, which makes the container with workpiece and medium vibrate at certain amplitude and frequency; the other one installed in the middle of the container, which passes the vibration to the mass of workpiece and medium through the driving mechanism of vibration. It uses synthesis vibrations generated by the double vibration source for enabling the vibration frequency and the amplitude to have a wider adjustable range. This method can accelerate or slow down the relative motion of workpiece and medium to suit finishing requirements from various workpieces.

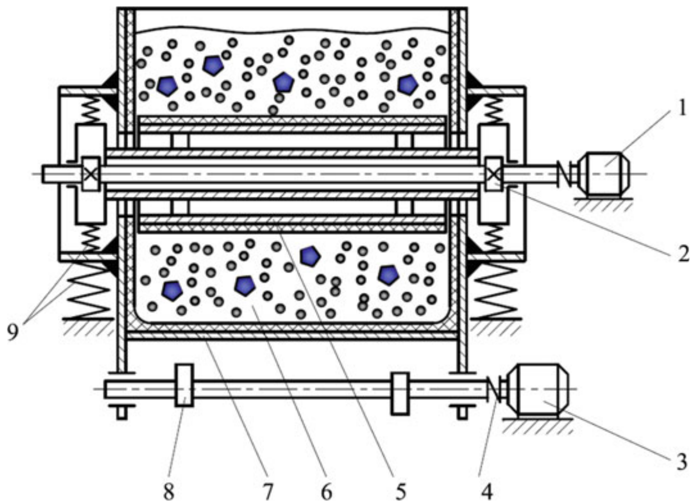


Fig. 2.8 Structure principle diagram of the double vibration source vibratory barrel finishing method. 1, 3—Motors; 2, 8—vibration generators; 4—coupling; 5—vibration transfer unit; 6—workpiece and medium; 7—container; 9—spiral spring

(2) Orboresonant barrel finishing method
The resonance performance of the steel beam can make the workpiece fixed on the end of the steel beam vibrate at an extremely high frequency. It realizes the finishing of workpiece surface for the workpiece soaked in a motionless container with the medium. The principle originators named it "orboresonant," schematic diagram shown in Fig. 2.9.
As shown in Fig. 2.9, resonant steel beam 2 is supported on the two Support 4, and its position corresponds to the center of vibration device (i.e., the position of the least vibration degree). The maximum vibration amplitude to steel beam will increase at both ends of Clamping 1 fixed with the workpiece. When working, the workpiece soaked in the medium begins to vibrate, and its vibration source is a kind of continuously variable mechanical vibration generator 3. When the speed of rapid repetitive pulse passed from vibration generator approaches the natural frequency of the steel beam, the effectiveness of the input energy will be greatly improved. As the frequency of the vibration generator is 90–100 times/s, the vibration frequency of the workpiece is about 6000 times/s, and its amplitude is about 3 mm. After finishing, container 5 lowers quickly. Meanwhile, the vibrating steel beam continues in the vibrational state under the inertia effect for removing the medium in the workpiece's chamber.
From the foregoing, orboresonant barrel finishing equipment is simple in construction, easy to operate, and there is no impingement between parts. This method can achieve excellent effects for removing burrs and flashes on

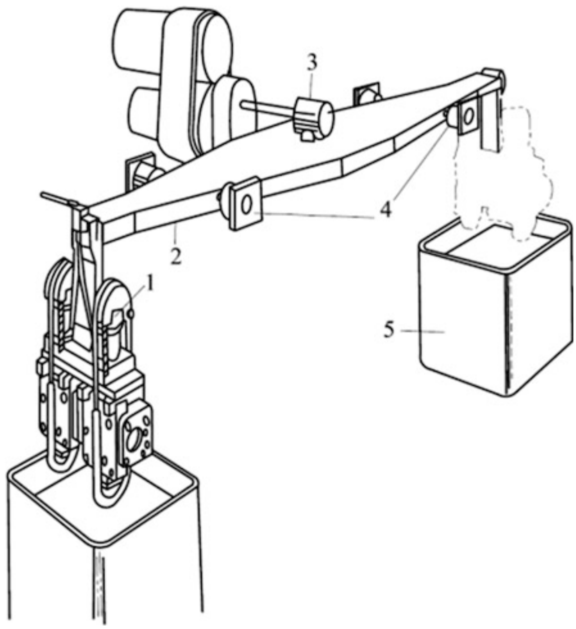


Fig. 2.9 Principle diagram of orboresonant barrel finishing method. 1—Clamping; 2—resonant steel beam; 3—vibration generator; 4—support for steel beam; 5—container

the internal and external surface of more complex castings such as hydraulic components (like pump case, valve body) and gearbox. The finishing time usually lasts 1–5 min.

(3) Cascade barrel finishing method
Cascade barrel finishing method was developed for the Iowa Engineered Processor Corporation in 1983. Its mechanism is a freely cascading stream of the medium flowing into specific passages (e.g., the internal passages of a part). A part or parts are rigidly fixture and are mechanically driven by a vibration unit. A stream of abrasive blocks is fed into the ingress above the part down onto the interior edges of the fixture, while it is vibrated. As the part vibrates, the volume of abrasive blocks is impacted by the internal surfaces. This impact deaccelerates the abrasive blocks and then immediately accelerates abrasive blocks in a rebound direction as the vibration reverses. Because of the rapid vibrations generated within abrasive blocks flow, energy transfer from the forced part to abrasive blocks results in a high finishing efficiency. Figure 2.10 is the structure principle diagram of cascade barrel finishing method.
Let the weight of the two eccentric parts equal to each other is m; the angular velocity of the vibration generator shaft is ω; the angle between the two eccentric parts projection in the vertical plane is α; the distance from the gravity center of the eccentric parts to the vertical shaft is r. The exciting force generated by vibration generator in the horizontal direction is

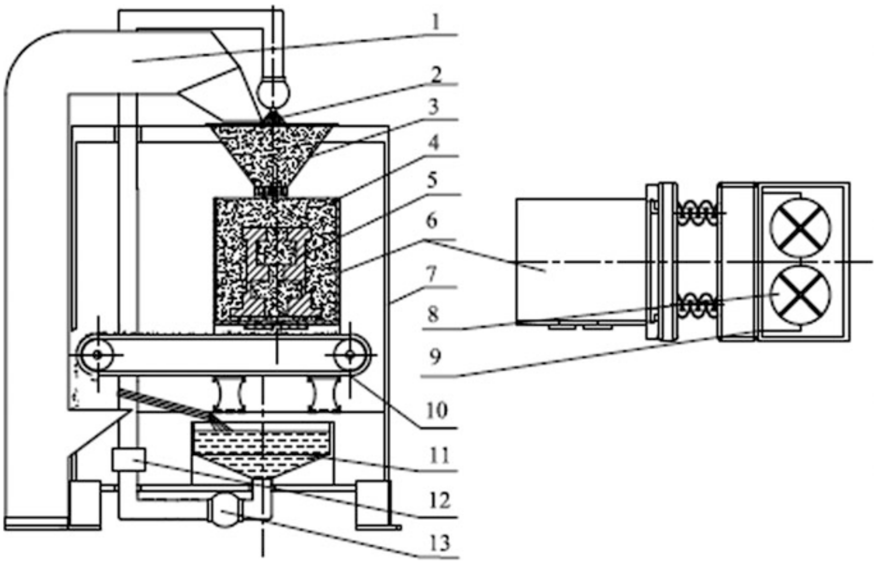


Fig. 2.10 Structure principle diagram of cascade barrel finishing method. 1—Bucket elevator; 2—liquid medium; 3—hopper; 4—medium; 5—workpiece; 6—container; 7—open type chamber; 8—eccentric part; 9—vibration unit; 10—vibrating screen; 11—filter tank; 12—pump; 13—filter unit

$$P(t) = 4m\omega^2 r \cos \omega t \cos \frac{\alpha}{2} \tag{2.7}$$

Additionally, the vibrating amplitude is one main factor affecting finishing effect and efficiency. Considering only the effect of the horizontal direction springs, the horizontal amplitude of all vibrating parts is

$$A = \frac{4mr}{M}\left|\frac{z^2 \cos\left(\tan^{-1}\left(\frac{2\zeta z}{1-z^2}\right)\right)}{1-z^2}\right| \quad (z \neq 1) \tag{2.8}$$

where M is the quality of all vibrating parts (kg); ζ is damping ratio; $z = \frac{\omega}{\omega_0}$, and ω_0 is natural frequency of spring (rad/s).

This method is considerably different from the more traditional vibratory processes.

The mass of abrasive blocks causes the part to move, and the flow is primarily dependent upon the driving force transmitted through the mass of abrasive blocks. Cascade finishing process allows finishing a wide range of parts with few restrictions on the physical dimensions of the part.

In this finishing method, the fixture design is very important. The part fixture design must allow that the necessary parts hold, and it must provide the medium ingress and egress features that may not be inherent in the part configuration.

2. Equipment design

(1) Container design

The container capacity is the original parameter, which is determined by the size of the workpiece, production lot, finishing requirements, and so on. In the finishing process, high rigidity is required to meet the requirement that the container is the main part of the vibration. Weld forming and casting forming can be adopted to make the container. When using the steel plates welding formation, one thing to note is that the container must be equipped with ribs to increase its rigidity.

The internal shape of the container is an important condition for forming the continuous turnover flow of workpiece and medium. Given that the container needs to have a good turnover property in the directional excitation of workpiece and medium, the container's inner bottom of the horizontal vibratory barrel finishing equipment often adopts cylindrical structure, and the container's inner chamber of the vertical vibratory barrel finishing equipment adopts ring-shaped curved surface structure. Meanwhile, in order to reduce the noise, extend the service life of the container, reinforce the turnover effect of the container inside wall on the workpiece and medium by the friction, and it is necessary to paste rubber or smear polyurethane liner on the container inside wall.

(2) Recommended values of the main parameters
Tables 2.5 and 2.6 list the main parameters of the common horizontal, vertical vibratory barrel finishing equipment, respectively.
(3) Liquid circulation device
Metal powders and micro-powders of abrasive particles can be removed from the solution in the container through the settler of the circulation system, and the liquid circulation device can ensure the sharpness of the abrasives and the cleanness of liquid medium. The settled liquid can be returned back to the container through the pump of the liquid circulation device and can be reused later. Figure 2.11 is the typical liquid circulation device.

Table 2.5 Recommended parameters values of horizontal vibratory barrel finishing equipment

Total capacity of container/L	Centrifugal force exerted by eccentric parts/$\times 10^2$N	Motor power/kW	Coil spring		Plate spring	
			Number	Rigidity coefficient of a single spring/(kg/cm)	Width/mm	Thickness/mm
50	50–60	1	4	55–75	400	40
100	65–85	1.7	4	80–100	500	40
150	90–120	1.7–2.8	4	100–120	600	50
200	110–150	2.8–4.5	4	115–140	700	60
300	160–220	4.5–7	4	140–180	800	70
400	220–300	7–10	4	180–230	900	80
500	300–400	10–14	6	150–200	1000	80

Table 2.6 Recommended parameters values of vertical vibratory barrel finishing equipment

Total capacity of container/L	Centrifugal force exerted by eccentric parts/$\times 10^2$N	Motor power/kW	Rotating speed of vibration axis/(r/min)	Coil spring	
				Number	Rigidity coefficient of a single spring/(kg/cm)
10	15–18	0.25	3000	6	20–30
25	25–30	0.6	3000	12	30–40
50	35–45	1	3000	12	40–55
100	50–65	1.7	3000	12	55–70
150	70–90	1.7–2.8	3000	12	70–85
200	90–120	2.8–4.5	3000	18	55–70

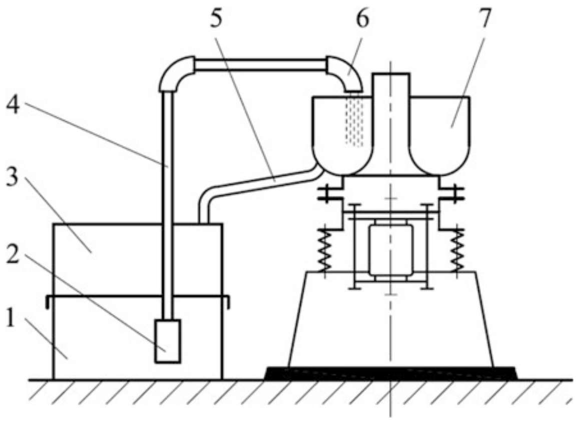


Fig. 2.11 Liquid circulation schematic diagram. 1—Water tank; 2—pump; 3—settler; 4—pipeline; 5—flexible pipe; 6—valve; 7—vertical vibratory barrel finishing equipment

3. Equipment shapes
   Figure 2.12 shows the photographs of several different vibratory barrel finishing equipments. In practice, most conventional vibratory barrel finishing equipment comes with an amplitude label attached on them from which the amplitude of vibrations can be determined.

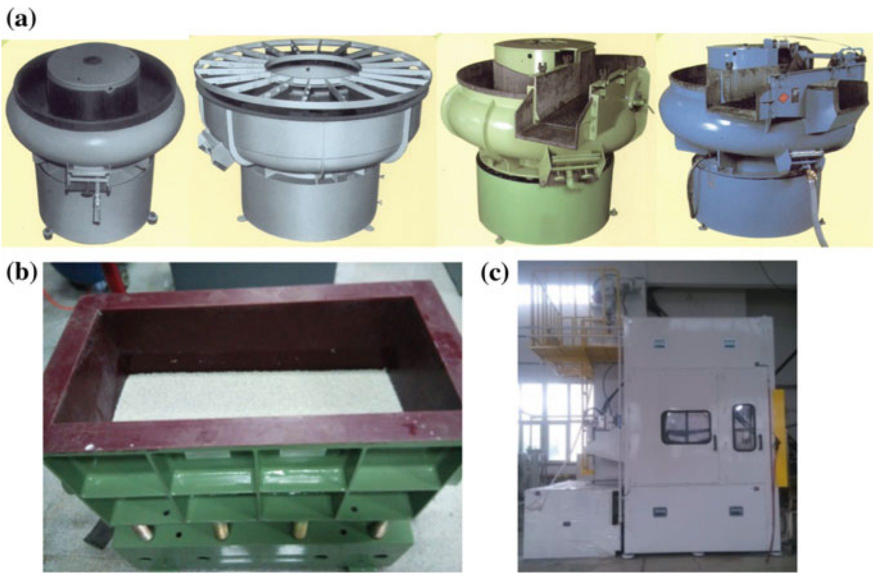


Fig. 2.12 Photographs of several different vertical vibratory barrel finishing equipment. **a** Vertical vibratory finishing; **b** horizontal vibratory finishing; **c** cascade finishing

2.4 Whirling Barrel Finishing

2.4.1 Finishing Principle and Characteristics

1. Finishing principle
   Whirling barrel finishing process, also called centrifugal disk finishing, is a relatively new barrel finishing method developed rapidly in the past 30 years. As shown in Fig. 2.13, the barrel is composed of fixed barrel wall 1 (stationary sidewalls) and rotary disk 2 for a base. As rotary disk 2 rotates at a certain speed, the workpieces and working medium 3 in the barrel are accelerated outwardly under centrifugal force. When the workpieces and working medium contact the stationary sidewalls, the sidewalls act as a brake and the load starts to decelerate, and they are forced upward by the load behind them. When arriving at a certain height, they will fall toward the disk. In the process of continuous rotary motion, the above moving process recurs continually and causes the load of workpieces and working medium to produce a spiral whirling motion. Then, strong finishing action is produced between the workpiece and the abrasive blocks, and the aims of deburring evenly, chamfering, and polishing are achieved. Figure 2.14 is the motion state photograph of whirling barrel finishing process [26–29].
2. Functional characteristics and application scope
   Whirling barrel finishing process is suitable to the finishing of small or medium special-shaped parts (except for sheet-shaped parts). It has a strong finishing capacity and is easy to realize automation control. However, there is a certain degree of collision. The main characteristics of whirling barrel finishing process are shown as follows [27, 28].

   (1) The applied force on the workpiece is strong, and the machining efficiency is high.
   (2) The machining range is wide but is not wide as vibratory barrel finishing process.

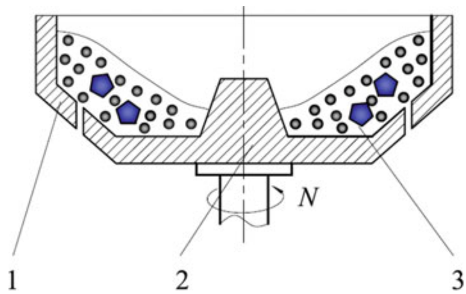


Fig. 2.13 Whirling barrel finishing principle diagram. 1—Stationary sidewalls; 2—rotary disk; 3—workpieces and working medium

Fig. 2.14 Motion state photograph of whirling barrel finishing process

(3) The machining process is as follows: feeding of workpieces → water supplying → barrel finishing → water discharge → abrasive blocks/ workpieces discharge → separation → rinsing → out. It is easy to realize automation control, relates quite well with the prior process and the next process, and facilitates formation of automatic production line and merging into FMS (flexible manufacturing system).

(4) It has the merits of low noise, low vibration, free of liquid medium splashing. The working environment has been improved.

2.4.2 Main Factors Affecting Finishing Effects

1. Speed of the rotary disk

   Figure 2.15 is the status of medium flow in a certain finishing equipment (with a barrel capacity of 290 L, and an inside barrel diameter of 1100 mm) at different

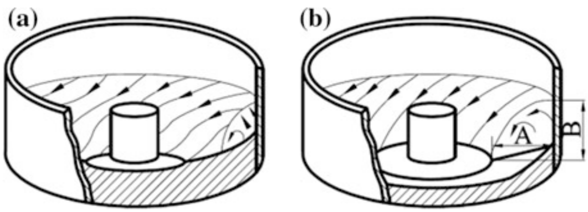


Fig. 2.15 Status of medium flow at different rotational speed. **a** 60 r/min; **b** 90 r/min; **c** 120 r/min

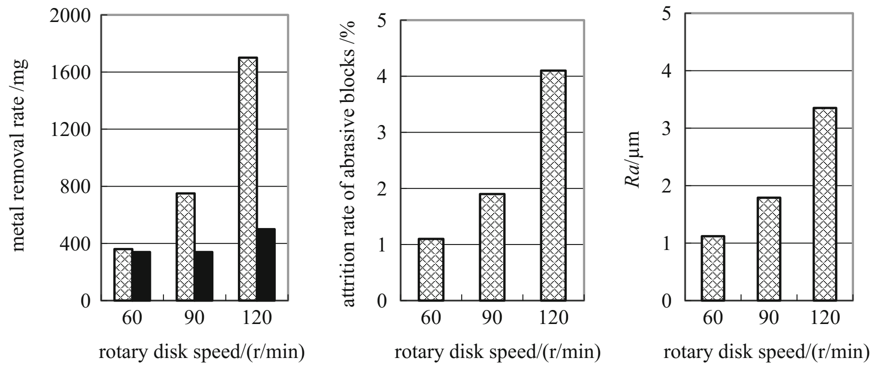


Fig. 2.16 Impact of the rotary disk speed on metal removal rate, attrition rate of abrasive blocks, and surface roughness value

rotational speed. Under the same condition, the higher the rotational speed of the rotary disk is, the higher the rising altitude of the workpieces and working medium in the barrel along stationary sidewalls under the action of centrifugal force is, and the higher the relative flow speed of the load is. Then, the metal removal rate of workpiece is higher, the surface roughness value after machining is larger, and the attrition rate of the abrasive blocks is proportionally higher. Figure 2.16 shows the relationship among the metal removal rate, the attrition rate of the abrasive blocks, and the surface roughness value after machining under different speed of the rotary disk.

2. Load amount
In whirling barrel finishing process, the loads of the workpieces, abrasive blocks, water, and compound are put into the barrel for machining. In general, the total volume of the load makes up about 20% of the volume of the barrel. Based on the shape and finishing requirements of the workpiece, the volume ratio of workpieces to abrasive blocks should be controlled 1:3 ~ 1:6. In finishing, the amount of the compound depends on water volume, and 5 g for each liter of water is preferred in general. It is suitable for the amount of the water to just submerge the machining medium, generally about 15% of the barrel volume. If too much water, the action of lubricating and buffering will increase, which reduces the finishing efficiency; if the water is too small, cleaning action of the workpiece and the grinding block may not be well, which will decrease the finishing quality and increase the attrition rate of abrasive blocks [29].

2.4.3 Equipment Types and Design

1. Equipment design

   (1) Rotating chassis shapes and fixed barrel wall shapes
   Figure 2.17 shows the status of medium flow under the condition of different rotary disk shapes and stationary sidewall shapes. When the total volume of the barrel is 290 L, the inside diameter of the barrel is 1100 mm and the rotational speed of the rotary disk is 90 r/min. As shown in Fig. 2.17a, when the stationary sidewall is cylinder and the rotary disk is tilted-line rotating surface, the height *B*, in which the load rises along the stationary sidewall, is less than the width *A* along radius distribution. Coarse-pitch spiraling flow layer with relatively low flow velocity is formed. As shown in Fig. 2.17b, when the stationary sidewall is cylinder and the rotary disk is curved-line rotating surface, the height *B* is greater than the width *A*, and fine-pitch spiraling flow layer with relatively high flow velocity is formed. As shown in Fig. 2.17c, when the stationary sidewall is prismatic surface and the rotary disk is curved-line rotating surface, variable-pitch spiraling flow layer with relatively high flow velocity is formed for that the prismatic surface of the stationary sidewall blocks the balance flow of the medium. Therefore, the motion state becomes relatively complicated.
   Figure 2.18 shows the metal removal rate, the attrition rate of the abrasive blocks, and the surface roughness value after machining 2 h under the condition of different rotary disk shapes and stationary sidewall shapes. I, II, III in Fig. 2.18 correspond to the three situations of Fig. 2.18a–c, respectively.
   According to the analysis mentioned above, and considering the finishing requirements, the stationary sidewalls weld into a cylindrical and regular polygon with formed plates, and the rotary disk is cast into shape with cast iron material. Their common requirements are lightweight and good rigidity.

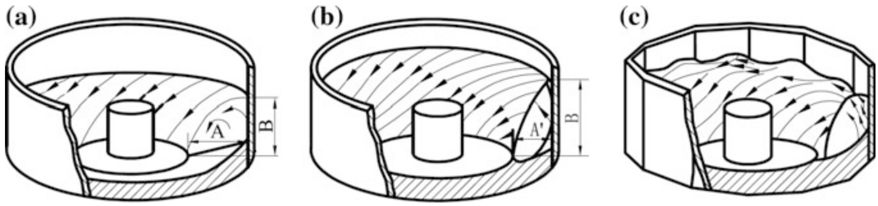


Fig. 2.17 Status of medium flow under the condition of different rotary disk shapes and stationary sidewall shapes. **a** The stationary sidewall is cylinder, and the rotary disk is tilted-line rotary surface; **b** the stationary sidewall is cylinder, and the rotary disk is curved-line rotary surface; **c** the stationary sidewall is prismatic surface, and the rotary disk is curved-line rotary surface

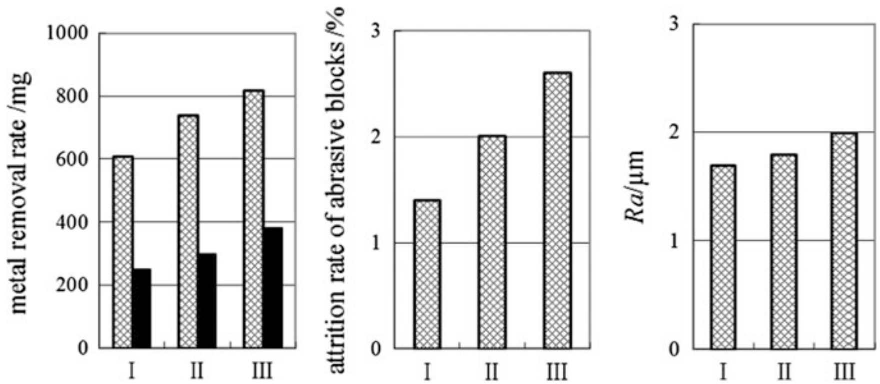


Fig. 2.18 Impacts of different rotary disk shapes and stationary sidewall shapes on the metal removal rate, the attrition rate of the abrasive blocks, and the surface roughness value. I the stationary sidewall is cylinder, and the rotary disk is tilted-line rotary surface; II the stationary sidewall is cylinder, and the rotary disk is curved-line rotary surface; III the stationary sidewall is prismatic surface, and the rotary disk is curved-line rotary surface

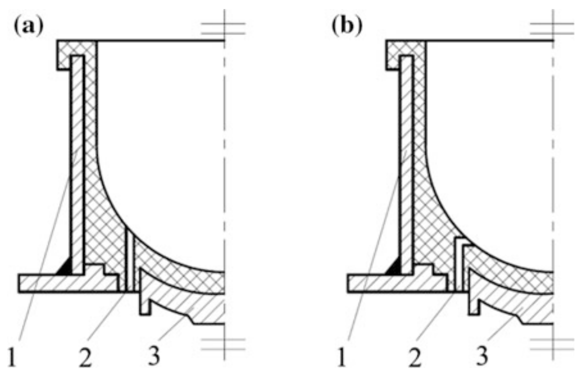
(2) The analysis of structural rationality

The analysis of structural rationality needs to consider the following factors:

(1) Considering the actual processing conditions, the inner wall surface of the barrel, which is assembled by the stationary sidewalls and rotary disk, should adhere or brush a 3–5 mm-thick rubber layer or polyurethane for the sake of preservation and abrasion resistance.

(2) There is a relative movement between the stationary sidewalls and the rotary disk during processing; therefore, there must have a gap between them. In order to prevent the phenomenon of workpieces locking because of the gap, the structural style shown in Fig. 2.19a can be replaced by the style shown in Fig. 2.18b. Meanwhile, considering the inevitable existence of the gap, one container for liquid medium storage should be added below the bottom of the rotary disk in equipment design. In order to improve finishing results, a liquid circulation system can be added by using the container for liquid medium storage.

Fig. 2.19 Local structure comparison of whirling barrel finishing equipment before and after optimizing. **a** Before optimizing; **b** after optimizing. 1—Stationary sidewalls; 2—gap; 3—rotary disk



(3) In order to increase the level of automation, the barrel should automatically turn over 180° to discharge the load. Generally, double-hinge support can be adopted, and the operation can be performed by handle.
(4) Considering the suitability of the equipment, the speed of rotary disk must be adjustable, and this function can be realized by using the speed adjusting motor or the frequency conversion control.

2. Equipment shape

Figure 2.20 shows the photographs of ordinary small and full-automatic whirling barrel finishing equipment.

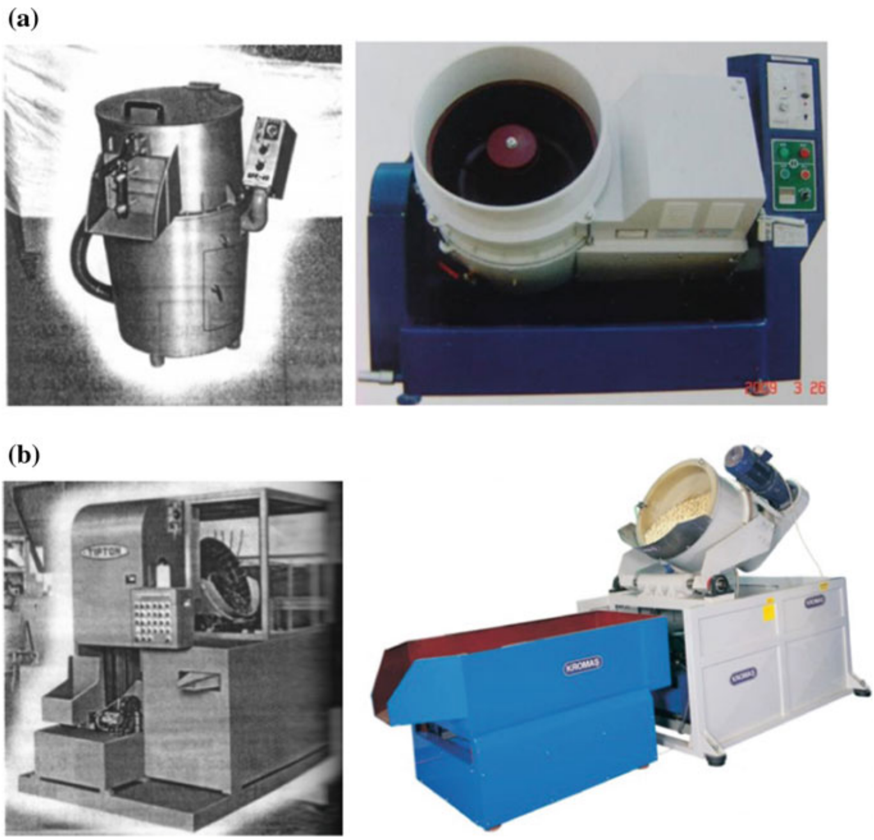


Fig. 2.20 Photographs of whirling barrel finishing equipment. **a** Small equipment; **b** full-automatic equipment

2.5 Centrifugal Barrel Finishing

The centrifugal barrel finishing is the combination of workpieces, abrasive blocks, and liquid medium, which are put into a sealed barrel according to certain proportioning. The barrel undergoes the planetary motion. Under the action of the inertia force, the forced flow of the media in the barrel causes the collision, rolling, and micro-grinding of abrasive blocks onto the workpieces surface to be generated. The surface finishing of the workpieces is achieved [8].

Since the centrifugal barrel finishing process has greatly changed the motion pattern, it overcomes the defects of the rotary barrel finishing process, such as poor finishing quality, low efficiency. This process with centrifugal action results in a very fast, highly controllable operation, and maintains a smooth rubbing action with little or no workpiece impingement, making it possible to produce fine finishes on precision and fragile parts. Another important advantage is its capability to impart high compressive stresses in the surface layer.

2.5.1 *Finishing Principle and Characteristics*

1. Finishing principle

Figure 2.21a is the schematic diagram of the centrifugal barrel finishing principle. Several barrels revolve around one fixed shaft (the speed is N) and rotate actively round its own shaft (the speed is n); therefore, the planetary motion can be formed. When $N \neq 0$ and $n = 0$, the mixture in the barrel can form one curved surface of radius R_1 (Fig. 2.21b), and the mutual rolling between the workpieces and abrasive blocks can generate at a given positive pressure, but cannot form the

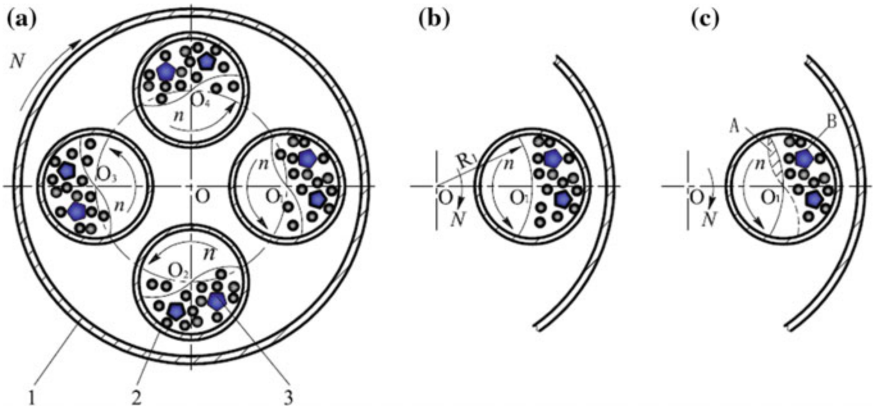


Fig. 2.21 Schematic diagram of the centrifugal barrel finishing principle. **a** Principle diagram; **b** $N \neq 0$ and $n = 0$; **c** $N \neq 0$ and $n \neq 0$

forced flow. When $N \neq 0$ and $n \neq 0$, the barrel does both the revolution motion and the rotation motion, and the mixture in the barrel can form one new curved surface (shown by the dotted line in Fig. 2.21c). The mixture in the barrel tries to return to its original position under the action of the centrifugal force. The forced sliding flow layer can be formed from A to B in the figure. The relative slipping motion between the workpieces and abrasive blocks can be generated. By the result of the positive pressure and the forced flow, the mutual collision, rolling, and micro-grinding are forced to form among the workpieces and abrasive blocks [30–32].

2. Dynamics analysis

(1) Magnitude of inertia force and its influence

In centrifugal barrel finishing process, the collision, rolling, and micro-grinding among the workpieces and abrasive blocks result from the joint effects of the inertia force, the counterforce, the gravity, and the friction during their movement. If ignoring the influence of gravity, the forced condition of one particle among the mixture in the barrel is shown in Fig. 2.22. The counterforce F of the barrel wall acting on the mixture can be separated into two component forces: One is the constraining force F_r which has the same size of the inertia force F_i of the particle doing the planetary motion, and has the opposite direction of the inertia force. It forces the particle doing the planetary motion with the barrel; the other is a sliding component force F_s, and it is combined with the friction F_f to form the thrusting force F_t which forces the particle doing the relative movement with respect to the barrel. Among the above forces, the sizes of F and F_r depend on F_i. Therefore, in centrifugal barrel finishing process, F_i is an important parameter. For one particle in the wall of the barrel, F_i is

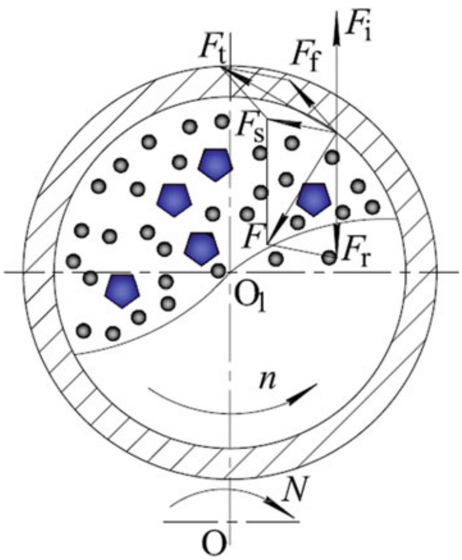


Fig. 2.22 Force analysis of one particle among the mixture in the barrel

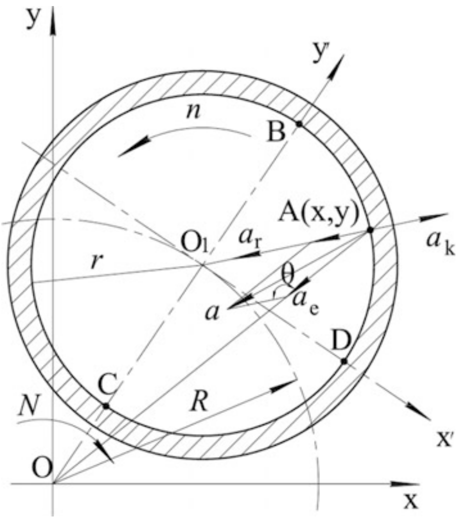


Fig. 2.23 Acceleration analysis of one particle among the mixture in the barrel

$$F_i = ma \tag{2.9}$$

where m is the mass of the particle and a is the absolute acceleration of the particle.

Figure 2.23 is the acceleration analysis chart of one particle among the mixture in the barrel, and the absolute acceleration a of Point A in the barrel can be computed according to Fig. 2.23. In the figure, R and r are the revolution and rotation radius of the barrel; the convected acceleration a_e, the relative acceleration a_r, and the Coriolis acceleration a_k of Particle A are

$$a_e = OA \cdot \omega_N^2 = \sqrt{x^2 + y^2}(2\pi N)^2 \tag{2.10}$$

$$a_r = O_1A \cdot \omega_n^2 = r(2\pi n)^2 = \left(r\frac{n^2}{N^2}\right)(2\pi N)^2 \tag{2.11}$$

$$a_k = 2\omega_N \cdot V_A = \left(2r\frac{n}{N}\right)(2\pi N)^2 \tag{2.12}$$

$$a^2 = (a_r + a_k)^2 + a_e^2 + 2(a_r + a_k)a_e \cos\theta \tag{2.13}$$

$$\cos\theta = \left(r^2 + x^2 + y^2 - R^2\right)\Big/2r\sqrt{x^2 + y^2} \tag{2.14}$$

where R and r are the revolution and rotation radius of the barrel (mm) and N and n are the revolution and rotation velocity of the barrel (r/min); ω_N is the revolution angular velocity of Particle A (rad/s); ω_n is the rotation angular velocity of Particle A (rad/s); V_A is the circumferential velocity of Particle A relative to O_1 (m/s).

From Eqs. (2.10)–(2.14), the absolute acceleration of the particle van bet obtained and it is

$$a = (2\pi N)^2 \left[\left(x^2 + y^2\right)\left(1 + \frac{n}{N}\right)^2 + r^2\left(1 + \frac{n}{N}\right)^2 \left(2 + \frac{n}{N}\right)\frac{n}{N} - R^2\left(2 + \frac{n}{N}\right)\frac{n}{N} \right]^{1/2} \tag{2.15}$$

When the particle position is Point B which is the furthest point from Center-point O, the absolute acceleration a is

$$a = (2\pi N)^2 \left[R + r\left(\frac{n}{N} + 1\right)^2 \right] \tag{2.16}$$

When the particle position is Point C which is the nearest point from Center-point O, the absolute acceleration a is

$$a = (2\pi N)^2 \left[R - r\left(\frac{n}{N} + 1\right)^2 \right] \tag{2.17}$$

When the particle position is Point D which is on the center line of the barrel, the absolute acceleration a is

$$a = (2\pi N)^2 \left[R^2 + r^2\left(\frac{n}{N} + 1\right)^4 \right]^{1/2} \tag{2.18}$$

Known from Eqs. (2.15)–(2.18), a is related to N, n/N, R, r, and the particle position, the maximum appears on Point B, and the minimum appears on Point C. If $n/N = -1$, the value of a always is

$$a = (2\pi N)^2 R \tag{2.19}$$

This shows that the inertia forces of the particle are the same regardless of the positions. Through quantitative graphic methods, the absolute acceleration direction of one particle in the barrel is parallel to the connecting line between the revolution center and the rotation center of the barrel.

(2) Formation of forced flow

The forced flow is relative to the natural flow. In the rotary barrel finishing process, when the barrel rotates at a certain speed, the mixture in the barrel lifts up with a rotation direction along the wall of the barrel, under the action of gravity, centrifugal force, and friction. When the mixture lifts up to a certain height, it will lose the balance, and the mixture of the surface layer will slide down naturally. In the centrifugal barrel finishing process, the barrel does both revolution and rotation; the mixture in the barrel has relatively lifting effect along the wall of the barrel; meanwhile, the mixture of surface layer is forced to slide down. This forced slipping is the forced flow [33].

Known from the foregoing analysis, the barrel must do rotation to form the forced flow into the centrifugal barrel finishing process, that is

$$n \neq 0 \tag{2.20}$$

According to Eq. (2.17), when $\frac{n}{N} > \sqrt{\frac{R}{r}} - 1$ or $\frac{n}{N} < -\left(\sqrt{\frac{R}{r}} + 1\right)$, the acceleration α of the mixture at Point C is negative, and the mixture rotates with the barrel, attaches evenly to the wall of the barrel, and remains relatively motionless. This cannot form the force flow. Therefore, in the process of centrifugal barrel finishing, in order to obtain satisfactory machining effects, n/N should satisfy

$$\sqrt{\frac{R}{r}} - 1 > \frac{n}{N} > -\left(\sqrt{\frac{R}{r}} + 1\right) \tag{2.21}$$

At this point, the mixture in the barrel does both the planetary motion with the barrel and the forced flow relative to the barrel under the action of constraining force F_r and thrusting force F_t [34].

On the basis on Eqs. (2.19) and (2.21), in order to make the workpiece well-proportioned by the force in process, $n/N = -1$ is the best selection. This can guarantee the stability of machining quality and benefit the strength designing of the equipment structure.

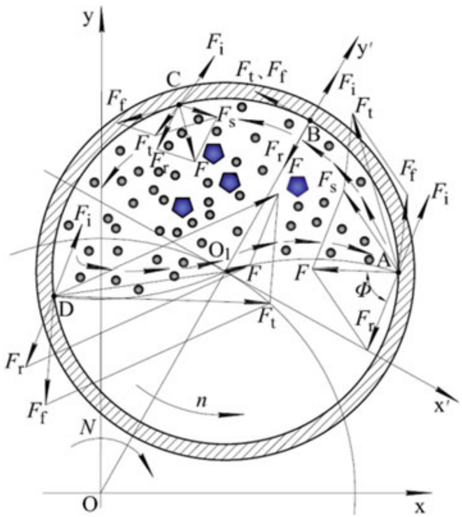


Fig. 2.24 Force status of the mixture in the barrel at every point

When $n/N = -1$, the force status of the mixture in the barrel at every point is shown in Fig. 2.24. At Point A, for the counterforce F of the barrel wall acting on the particle, its direction is perpendicular to the wall of the barrel. F can be separated into F_r and F_s, and the constraining force F_r maintains the planetary motion of the particle; the sliding component force $F_s = \left(F^2 + F_r^2 - 2FF_r \cos \varphi\right)^{1/2}$. F_s and the friction F_f of the barrel wall acting on the particle are combined to the thrusting force F_t which pushes the particle to do the relative movement with respect to the barrel. In Area *AB* along the barrel wall, the thrusting force F_t helps the medium to have a motion along the barrel wall in accordance with the rotation direction of the barrel. But in Area *BCD*, the magnitude and direction of F_t can change with the increase of angle Φ; therefore, the mixture in the barrel tries to do it with its own forced flow relative to the barrel under the action of the thrusting force. The mixture in the inner layer is acted upon the thrusting force from the surrounding mixture, the relative sliding between different mixtures is blocked, the velocity of the relative sliding is slower, and it is in a dynamic balance on the whole and remains to be relatively still. The finishing capacity in this case is very weak. The mixture in the surface layer Area *DA* is acted upon small thrusting force from the surrounding mixture; the fast relative sliding between the mixtures is generated along the action direction of F_t, and the forced flow is intense. The finishing capacity in this case is good [1, 35].

The related forced flow process is shown in the high-speed photography of Fig. 2.25. Two hexagon barrels are installed symmetrically on the centrifugal barrel finishing equipment. The white part of the barrel is the mixture of the workpieces and the medium. The factors are as follows: $N = 280$ r/min, $n/N = -1$,

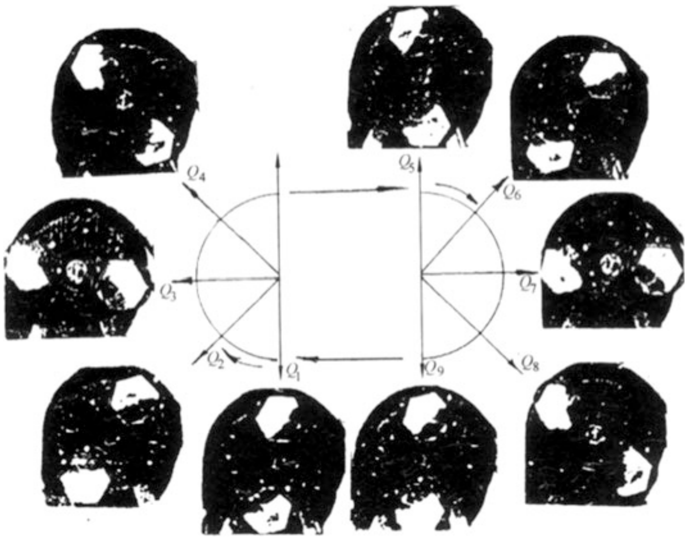


Fig. 2.25 High-speed photography of related forced flow process

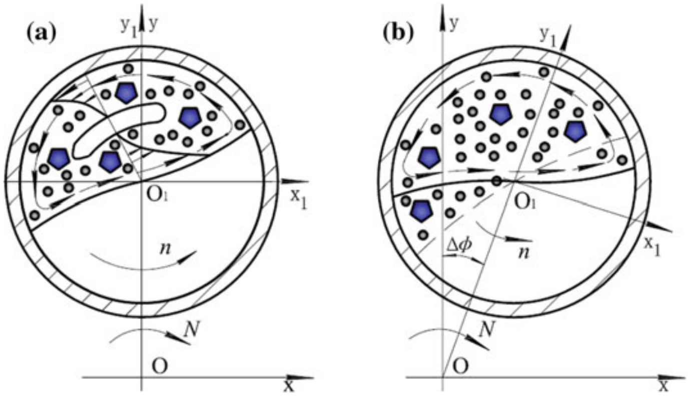


Fig. 2.26 Analysis of forced flow process of the mixture. **a** Forced flow situation; **b** forced flow process

R = 110 mm, r = 42.5 mm, and the photograph speed of high-speed camera (Model Pentezent-16) is 600 times/s.

The forced flow situation of the mixture in the barrel at the instantaneous moment is shown in Fig. 2.26a. The mixture in the barrel can be divided into three kinds: The mixture in inner layer rotates with the barrel, and it is in a dynamic balance on the whole; the mixture in surface layer does the forced flow in a direction opposite to the rotational direction of the barrel under the action of the thrusting force; the middle area is acted upon the friction torque of the mixture in inner layer and surface layer and can generate core-annulus peristalsis. When the revolution of the barrel reaches $\Delta\Phi$ (Fig. 2.26b), the mixture transforms force fully from the dashed status to the solid-line status. In the process of the forced transition, the relative motion exists not only in the interlayer, but also within the layer due to the differences in the shape, size, and quality of the workpieces and abrasive blocks.

3. Flow field simulation

Based on the motion course of the mixture in the barrel, the corresponding two-phase flow model and its control equations are established. The dynamic process of the mixture motion is simulated and numerically studied using fluid dynamics software Fluent, and the distributing characters of the mixture concentration, velocity, and pressure in the course of the barrel-running are obtained. The impact of various machining conditions (such as barrel shapes, motion parameters, characteristic parameters of abrasive blocks) to the motional behavior of the mixture is analyzed. This supplies theory base for the structure design of this finishing technology and the reasonable selection of the constructional parameters.

In centrifugal barrel finishing process, the barrel contains the mixture of parts and a certain amount of abrasive blocks and liquid medium. When the volume of the abrasive blocks and the parts makes up above 10% of the total volume of the barrel, the interaction among abrasive blocks, parts, and liquid medium can have a non-negligible impact on the movement feature. The liquid medium and abrasive blocks should be taken as a continuous medium, and the motion process of abrasive blocks should be described by Euler method [36].

It's supposed that no physiochemical process, such as dissolution and crystallization, occurs among the abrasive particle phase, the part phase and the liquid phase during establishing and simplifying the model. That is to say, the mass and heat exchangers between any two phases will not be considered, and the pressures among these phases are equal. Based on the mass conservation and the momentum conservation in two-phase flow continuum theory and k-ε turbulence law, the dynamical equations of the material and the liquid are established. The boundary conditions and the parameter conditions are unified, and the motion model of the mass material is obtained for analyzing the effect of its movement flow on the processing effect.

Setting the volume fraction of the liquid and the material particle are α_{f} and α_{k}, respectively, then

$$\alpha_{\mathrm{f}} + \alpha_{\mathrm{k}} = 1 \tag{2.22}$$

And the mass concentration distributions of the particles are

$$n_{\mathrm{k}} = \alpha_{\mathrm{k}} \rho_{\mathrm{k}} \tag{2.23}$$

where n_{k} is the mass concentration distributions of the particles (kg/m^3) and ρ_{k} is the material density of the particles (kg/m^3).

Since there is no mass exchanger between the two phases, the mass conservation equations of the liquid phase and the particle phase are

$$\begin{cases} \frac{\partial}{\partial t}(\alpha_{\mathrm{f}}\rho_{\mathrm{f}}) + \nabla \cdot (\alpha_{\mathrm{f}}\rho_{\mathrm{f}}\vec{V}_{\mathrm{f}}) = 0 \\ \frac{\partial}{\partial t}(\alpha_{\mathrm{k}}\rho_{\mathrm{k}}) + \nabla \cdot (\alpha_{\mathrm{k}}\rho_{\mathrm{k}}\vec{V}_{\mathrm{k}}) = 0 \end{cases} \tag{2.24}$$

where ρ_{f} is the material density of the liquid (kg/m^3) and v_{f} and v_{k} are the velocity distributions of the liquid phase and the particle phase (m/s).

The motion of the particles in the fluid medium is a consequence of the resistance of the liquid acting on the particles, and these particles experience centrifugal force and gravity. The fluid resistance is the combined force of the pressure difference resistance and the frictional resistance acting on the particles when the particles move at constant speed in the motionless viscous liquid. Then, the movement of the liquid phase and the particle phase satisfied the following momentum conservation equations

$$\begin{cases} \frac{\partial}{\partial t}(\rho_{\mathrm{f}}\vec{V}_{\mathrm{f}}) + \nabla \cdot (\rho_{\mathrm{f}}\vec{V}_{\mathrm{f}}\vec{V}_{\mathrm{f}}) = -\nabla P + \nabla \cdot \bar{\tau}_{\mathrm{f}} + \vec{R}_{\mathrm{kf}} + \vec{F}_{\mathrm{gf}} \\ \frac{\partial}{\partial t}(\alpha_{\mathrm{k}}\rho_{\mathrm{k}}\vec{V}_{\mathrm{k}}) + \nabla \cdot (\alpha_{\mathrm{k}}\rho_{\mathrm{k}}\vec{V}_{\mathrm{k}}\vec{V}_{\mathrm{k}}) = -\nabla P + \nabla P_{\mathrm{k}} + \nabla \cdot \bar{\tau}_{\mathrm{k}} + \vec{R}_{\mathrm{fk}} + \vec{F}_{\mathrm{gk}} \end{cases} \tag{2.25}$$

where F_{gf} and F_{gk} are the combined force of the gravity, the centrifugal force and the Coriolis force acting on the liquid medium and the particles (N); P_k is the solid phase pressure of the granular fixing abrasive (N); R_{fk} and R_{kf} are the interactive force between the liquid phase and the particle phase, and their sizes are equal; their directions are opposite; $\overline{\tau}_f$ and $\overline{\tau}_k$ are the shear stress tensors of the liquid phase and the particle phase, and they are

$$\begin{cases} \overline{\tau}_k = \mu_k(\nabla\vec{V}_k + \nabla\vec{V}_k^{\mathrm{T}}) + \left(\lambda_k - \frac{2}{3}\mu_k\right)\vec{V}_k\nabla\cdot\overline{I} \\ \overline{\tau}_f = \mu_f\left(\nabla\vec{V}_f + \nabla\vec{V}_f^{\mathrm{T}}\right) + \left(\lambda_f - \frac{2}{3}\mu_f\right)\vec{V}_f\nabla\cdot\overline{I} \end{cases} \tag{2.26}$$

where μ_f, μ_k and λ_f, λ_k are the first viscosity coefficients and the second viscosity coefficients of the liquid phase and the particle phase and $\overline{I}$ is the unit tensor.

When N = 158 r/min and n = −21 r/min, the cloud diagram of the volume fraction for particles flow in the barrel over one revolution cycle is shown in Fig. 2.27. As shown in Fig. 2.27, light color represents that the particle density is big enough, and dark color represents that the particle density becomes smaller. They respond to the concentration distribution characteristics of the particles, and this indicates that the interface shapes in different rotation degrees are generally similar. As the centrifugal force moves around periodically, the positions of the interfaces present similar periodic change [37].

4. Discrete element modeling

3D DEM model of centrifugal barrel finishing is constructed on the basis of the Hertz–Mindlin (no slip) contact model. In this model, the normal force component

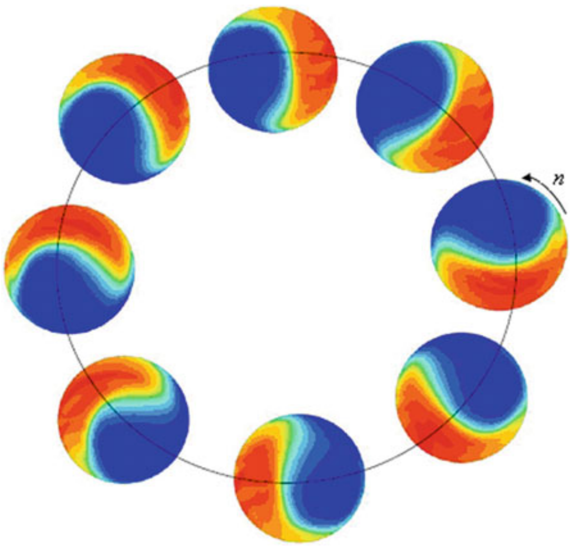


Fig. 2.27 Cloud diagram of the volume fraction for particles flow in the hexagon barrel

is based on Hertzian contact theory. The tangential force model is based on Mindlin–Deresiewicz work. Both normal and the tangential forces have damping components where the damping coefficient is related to the coefficient of restitution. The tangential friction force follows the Coulomb law of friction model. The rolling friction is implemented as the contact independent directional constant torque model.

The normal force F_n and damping force F_n^d are given by Eqs. (2.27)–(2.28).

$$F_n = \frac{4}{3} E^* \sqrt{R^* \delta_n^3} \tag{2.27}$$

$$F_n^d = -2\sqrt{\frac{5}{6}} \beta \sqrt{S_n m^*} \upsilon_n \overrightarrow{\mathrm{rel}} \tag{2.28}$$

where E^*, R^*, δ_n, m^*, $v_n^{\overline{\mathrm{rel}}}$, S_n are the equivalent Young's modulus, the equivalent radius, the normal overlap, the equivalent mass, the normal component of the relative velocity, the normal stiffness, respectively, which are calculated by Eqs. (2.29)–(2.33).

$$\frac{1}{E^*} = \frac{(1-\upsilon_i^2)}{E_i} + \frac{(1-\upsilon_j^2)}{E_j} \tag{2.29}$$

$$\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j} \tag{2.30}$$

$$\frac{1}{m^*} = \frac{1}{m_i} + \frac{1}{m_j} \tag{2.31}$$

$$\beta = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}} \tag{2.32}$$

$$S_n = 2E^* \sqrt{R^* \delta_n} \tag{2.33}$$

The tangential force, F_t, the tangential damping F_t^d, and the Coulomb friction is given by Eqs. (2.34)–(2.36).

$$F_t = -S_t \delta_t \tag{2.34}$$

$$F_t^d = -2\sqrt{\frac{5}{6}} \beta \sqrt{S_t m^*} \upsilon_t \overrightarrow{\mathrm{rel}} \tag{2.35}$$

$$F_s = \mu_s F_n \tag{2.36}$$

where δ_t is the tangential overlap and S_t is the tangential stiffness.

$$S_t = 8G^* \sqrt{R^* \delta_n} \tag{2.37}$$

Here, G^* is the equivalent shear modulus and is calculated as

$$\frac{1}{G^*} = \frac{2 - \upsilon_i^2}{G_i} + \frac{2 - \upsilon_j^2}{G_j} \tag{2.38}$$

For centrifugal barrel finishing in which rolling friction is important, a torque is applying to the contacting surfaces.

$$T_i = -\mu_r F_n R_i \omega_i \tag{2.39}$$

where μ_r is the coefficient of rolling friction; R_i is the distance of the contact point from the center of mass; ω_i is the unit angular velocity vector of the abrasive particle at the contact point.

The material properties and the contact parameters given in Tables 2.7 and 2.8, and the geometry parameters and motion parameters provided in Table 2.9 are used in these simulations. About 5000 particles are introduced to the DEM at the speed

Table 2.7 Material properties used in the DEM simulations

Material parameters	Material	Poisson's ratio	Shear modulus (Pa)	Density ($kg \cdot m^{-3}$)
Abrasive blocks	Al_2O_3	0.21	1.24e + 11	2675
Barrel	Nylon 66	0.28	3.2e + 09	1150

Table 2.8 Contact parameters of abrasive particles and the barrel

Interaction parameters	Coefficient of restitution	Coefficient of static friction	Coefficient of rolling friction
Particle–particle	0.55	0.3	0.3
Particle–barrel	0.36	0.15	0.15

Table 2.9 Geometry parameters and motion parameters

Parameters	Value/mm
Bore diameter of drum/mm	118
Height of drum/mm	125
Thickness of drum/mm	5
Revolution radius/mm	135
Transmission ratio	−1
Radius of abrasive blocks/mm	3

of 10,000 particles per second when the simulation runs, with the packed weight 50%, and freely falls with the initial velocity 2 m/s. Then, the drum begins to do planetary motion from 1 to 2 s. When simulating, abrasive particles are randomly generated by particle factory from 0 to 1 s (generation rate is 10,000 particles per second) and generate 5000 particles.

The gravity center and the velocity of abrasive blocks group can be obtained from Eqs. (2.40) and (2.41).

$$(x, y, z) = \left(\frac{\sum x_i}{n}, \frac{\sum y_i}{n}, \frac{\sum z_i}{n}\right) \tag{2.40}$$

$$\left(v_x, v_y, v_z\right) = \left(\frac{\sum v_{xi}}{n}, \frac{\sum v_{yi}}{n}, \frac{\sum v_{zi}}{n}\right) \tag{2.41}$$

where n represents the total number of the abrasive blocks and i represents serial number of the abrasive blocks.

Figure 2.28 shows the gravity center change of the abrasive blocks group with $i = -1$. As shown in Fig. 2.28, the z-axis of the gravity center of the abrasive blocks group keeps unchanged. In addition, the gravity center trajectory of the abrasive blocks group is a closed circle with the circle center (0, 0). The gravity center trajectory of the abrasive blocks group is same as the revolution center of centrifugal barrel finishing equipment can be obtained.

The velocity variation of gravity center of the abrasive blocks group with time is shown in Fig. 2.29. It can be seen that the gravity center velocity of the abrasive

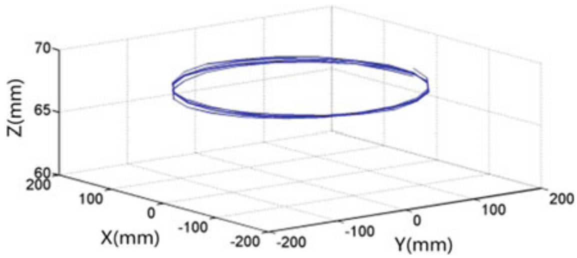


Fig. 2.28 Position change of the center of gravity of abrasive particles

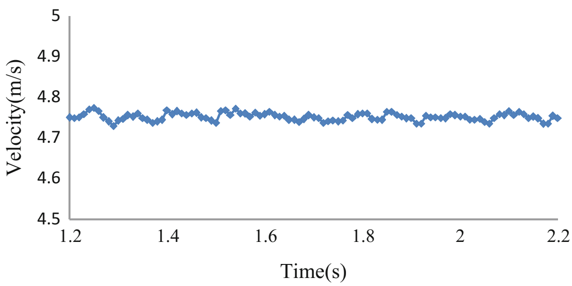


Fig. 2.29 Gravity center velocity of the abrasive particles group versus time

blocks group ranges from 4.7 to 4.8 m/s, and the average velocity is 4.752 m/s. The deviation of simulation results to theoretical analysis is 0.04%.

The instantaneous distribution of abrasive blocks in the barrel is shown in Fig. 2.30 with simulation time being 2 s. At this time, the instantaneous gravity center coordinates and instantaneous velocity of the abrasive blocks group are (149.577, −23.1086, 65.1121) and (0.730, 4.697, 0.003), respectively. The flow path of abrasive blocks is also shown in Fig. 2.10. When the supportive force and the friction force cannot provide sufficient velocity and acceleration to keep them attached to the wall of the barrel surface, the abrasive blocks move toward the center of gravity and far from the barrel wall, thereby forming a forced flow layer.

When the barrel rotates clockwise, the abrasive blocks rotate together with it because of the friction between the inner wall of the barrel and the adjacent abrasive blocks. When the revolution takes part in, and the centrifugal force formed by revolution is larger than that of formed by rotation, the abrasive blocks separate from the wall of the barrel and move toward the upper right as in Fig. 2.30.

The abrasive blocks in the barrel should be rotary motion relative to the center of gravity under the action of the friction torque. So, the velocity relative to the gravity from the center of the abrasive blocks is proportional to the distance between the gravity center and the abrasive blocks. Therefore, all abrasive blocks velocity is derived. The velocity distribution of abrasive blocks that minus the revolution velocity vector is shown in Fig. 2.31. Specific operation method includes the

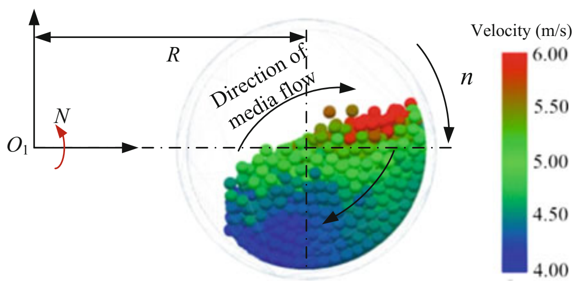


Fig. 2.30 Instantaneous velocity distribution of abrasive particles within the barrel at 2 s

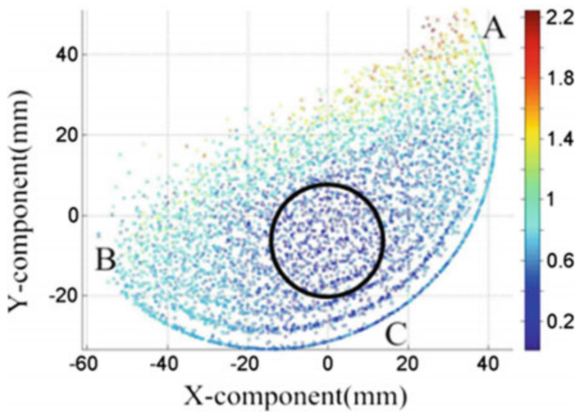


Fig. 2.31 Velocity distribution of abrasive particles relative to its center of gravity at 2 s

following: Using EDEM ANALYST, export the position and velocity component of all abrasive particles at 2 s, and derive rotation velocity of all abrasive particles, and then the velocity distribution is drawn with the coordinate system of position component in the *x*, *y* direction and rotation velocity using MATLAB software.

Figure 2.31 shows that the velocity of abrasive blocks is the smallest at the center of gravity, and the peripheral velocities are relatively large. Abrasive blocks in region A is far from the center of the barrel, moving to region C and forming gradually decelerating centripetal motion caused by rotation torques. Then, continue to move to region B and form gradually accelerating eccentric motion. Finally, the velocity reaches the critical value and separates from the wall of the drum surface, close to region A.

Due to the velocities of abrasive blocks in the barrel are different in the macroscale, it is very difficult to describe using conventional methods. Therefore, Maxwell velocity distribution law for large amounts of gas molecular motion state is attempted to the use of describing the abrasive particles motion from the statistics perspective. According to its definition, velocity distributions relative to the center of gravity were classified in the barrel, as shown in Fig. 2.32. It can be seen that the percentage of the abrasive blocks with different velocity range in total amount of abrasive blocks counts is almost at a constant during different moments; this indicates that the velocity distribution follows Maxwell velocity distribution law. Through the use of velocity distribution rules of abrasive blocks in the barrel, it can effectively help designers by revolutionizing the velocity to study velocity distribution of abrasive blocks in the barrel [38, 39].

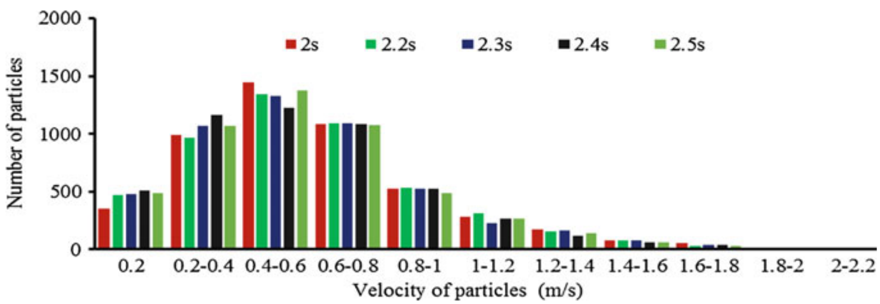


Fig. 2.32 Number of abrasive particles with different velocity range

5. Function characteristics and applicable scope

The finishing efficiency of the centrifugal barrel finishing process is high, and it is appropriate for the deburring and finishing of small- or medium-sized parts with multiple variety and large number of productions. It can be used for removing the oxide layer and the small flashes on the surface of stamping or casting parts in rough processing, and precision machining before electroplating. It can enhance the surface quality and the surface roughness, with degree of the finished parts that can increase up to 1–2 grades. It can improve the physical–mechanical properties of the part surface layer, increase the surface hardness, and change the surface residual stress. Otherwise, it can also have other advantages such as decreased cost, reduced working intensity [1, 15–17, 20, 40–42].

2.5.2 Main Factors Affecting Finishing Effects

In centrifugal barrel finishing process, many factors can influence its finishing quality and efficiency. The factors mainly include the workpiece conditions, finishing equipment, finishing medium, and finishing process [41]. Only through coordinating the matching relationship properly among these four aspects, the barrel finishing process can be completed excellently, efficiently, and beneficially [43]. Figure 2.33 shows the flowchart of the centrifugal barrel finishing process. Once the machined workpiece and the finishing requirements are determined, the factors influencing finishing quality and efficiency become finishing equipment, finishing medium, and various parameters in the course of finishing [44]. The influence of the finishing medium will be expatiated in Sect. 2.8 of this chapter.

1. Kinematic parameters of equipment
   Based on the analysis of finishing principles, the kinematic parameters with the most influence on finishing effects include n/N and N.

   (1) n/N
   Based on the principle analysis, n/N has to satisfy the following condition:

$$\sqrt{\frac{R}{r}} - 1 > \frac{n}{N} > -\left(\sqrt{\frac{R}{r}} + 1\right), \quad \text{and } n \neq 0$$

   Depending upon the analysis of kinematics research, if $n/N < 0$ (i.e., revolution moves in the opposite direction of rotation), the flow direction of the forced flow layer is basically the same with the orientation of the particle motion, the flow resistance is low, and the sliding speed between abrasive blocks and the workpieces is fast; this is beneficial to improve the finishing efficiency and guarantee the finishing quality. On the contrary, if $n/N > 0$, the sliding speed is slow, and the finishing effects are poor.

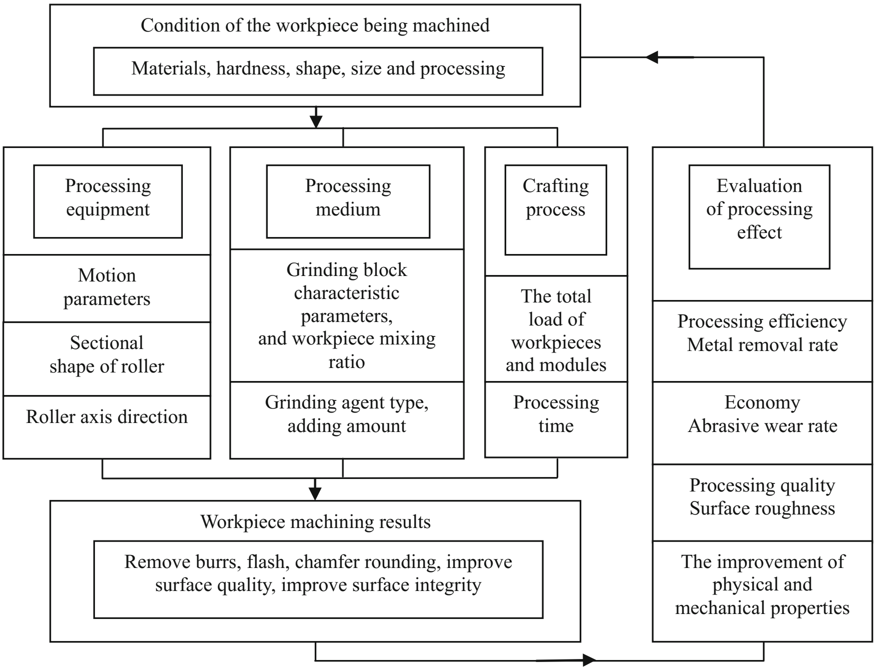


Fig. 2.33 Flowchart of centrifugal barrel finishing process

For further study of the optimal value of n/N, taking $n/N = -1, -1.5$, and -2 as samples, the tests are carried out on four hexagonal prism barrels with the total volume of 60 L (15 L × 4), $N = 180$ r/min, $R = 235$ mm, and $r = 150$ mm. The test results are shown in Table 2.10. The test conditions are found as follows: The specimen is cylinder (135 cases) with $45^{\#}$ steel, Φ10 mm × 30 mm, Φ30 mm × 10 mm, Φ20 mm × 5 mm; abrasive blocks used for rough processing are white alumina, oblique triangle prism with 15 mm × 15 mm × 15 mm, and the granularity is $180^{\#}$; abrasive blocks used for precision processing are aluminum oxide, sphere Φ5 mm, and the granularity is $280^{\#}$; compounds solution is LC-10, and the load is appropriate; the processing time is 60 min; the temperature in the barrel before finishing is 18 °C.

Known from experimental results, the forced flow of the workpieces and abrasive blocks in the barrel is intensified, and thus the metal removal of the workpiece and the wear of abrasive blocks become much more, and the scratches on the workpieces surface increase. From the economic perspective (the wear of abrasive blocks), the ratio of material removal rate to the wear rate of abrasive blocks is the highest and the economical efficiency is the best during rough processing and precision processing as n/N is -1.

Table 2.10 Records and results of rough machining tests and precision machining tests

	Roughness processing			Precision processing		
n/*N*	−1	−1.5	−2	−1	−1.5	−2
Total mass of the workpiece/g	4067.790	4083.925	4094.960	4130.500	4114.190	4043.660
Material removal amount/g	24.130	35.520	63.050	1.745	3.040	3.238
Material removal rate/(g/kg·h)	5.932	8.698	15.397	0.4225	0.7389	0.8008
Total mass of abrasive blocks/g	7982.925	7665.570	7982.480	7958.320	7935.430	7951.760
Wear amount of abrasive blocks/g	317.355	670.345	1176.215	6.560	13.930	43.930
Wear rate of abrasive blocks/(g/kg·h)	39.754	87.449	147.350	0.824	1.755	5.525
Material removal rate/Wear rate of abrasive blocks	1:6.70	1:10.05	1:9.57	1:1.95	1:2.38	1:6.89
The temperature in the barrel after finishing/°C	44	49	73	47	63	69

(2) N

When n/N is −1, the absolute acceleration α of any particle in the barrel is $(2\pi N)^2R$. This is the inertia force of the particle, which performs the planet motion in the barrel, and it is determined by the two parameters N and R. Since the value of R is determined by structure design, the value of R directly determines the magnitude of the inertia force.

If the value of N is too large, the inertia force of the mixture in the barrel will be very large, and the forced flow will be vigorous, thus causing the colliding and scoring among abrasive blocks and the workpieces to be serious. This can cause the scratching and bumping on the workpiece surface, an increase in the surface roughness value, a breakage of the abrasive blocks, and so on. If the value of N is too small, the inertia force of the mixture in the barrel will become very small, and the forced flow will be slow, thus causing the normal action of rolling and scoring between the workpieces and abrasive blocks to be weakened, which can ultimately decrease the finishing efficiency.

Based on a large number of experiments, the recommended revolution speed N is

$$N = K/\sqrt{D}(\text{r/min}) \tag{2.42}$$

Table 2.11 Values range of *K* under different conditions

Conditions	The workpiece of medium or large hardness			The workpiece of low hardness		
	Rough processing	Self-finishing process	Finishing processing	Rough processing	Self-finishing process	Finishing processing
K	5200–6000	4500–5200	3800–4500	4700–5500	4000–4700	3200–4000

where *D* represents the revolution radius of the barrel (mm) and *K* represents the coefficient, and $K = 3000$–6000. The value range of *K* under different conditions is shown in Table 2.11.

N is restricted by the workpiece hardness and finishing requirements, and it can also affect the surface quality of the workpiece and the finishing efficiency.

2. Geometrical parameters of equipment

The revolution radius *R* and the rotation radius *r* of the barrel are determined by the structure design. In general case, the value of n/N is determined by the value of R/r. Under the condition of $n/N = -1$, the magnitude of *R* directly affects the inertia force of the mixture in the barrel, and the magnitude of *r* responds directly to the size of the barrel volume. At a constant *R* and *r*, the geometric parameters influencing the finishing effects include the shape of the barrel section and the axis direction of the barrel.

(1) Shape of barrel section

The shapes of the barrel section used in the centrifugal barrel finishing process have two general types: circle and regular polygon. Different section shapes can cause variety of the force and forced flow of the mixture in the barrel, and further affect the finishing effects.

On the testing finishing equipment with the same parameters, the movements of the mixture in the barrels with circle and hexagon section are observed by means of high-speed camera. Results show that the forced flow of the workpieces and abrasive blocks in the barrel with circle section is relatively slow, and there is an obvious core-annulus peristaltic area between the workpieces and abrasive blocks. The forced flow of the mixture in the barrel with hexagon section is vigorous, and the core-annulus peristaltic area disappears; the acting force between the workpieces and abrasive blocks increases at that moment, the contacting times between each other increase, and the collision, rolling, and micro-grinding effects are evident. These benefit the improvement of the finishing efficiency, but will also bring scratches to the workpieces surface. If the edge number of the barrel section shape reduces to three or four sides, the forced flow will be intensified, but the finishing efficiency will decrease as the length of the slipping zone becomes shorter. The experimental results are shown in Fig. 2.34.

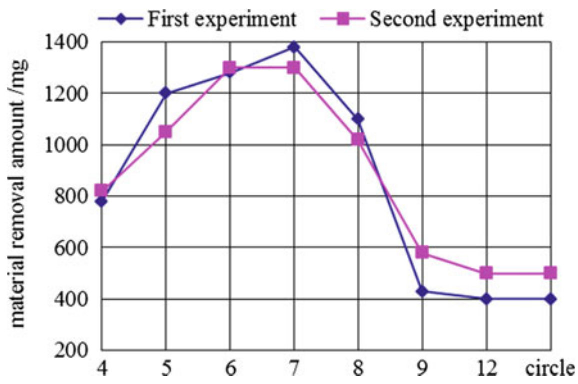


Fig. 2.34 Impact of barrels section shape on finishing efficiency

Therefore, the finishing requirements of the workpieces should be considered when choosing the edge number of the barrel section shape. When the workpiece surface demands higher quality and no scratches are allowed, the circular section is a better choice; when the workpiece needs higher finishing efficiency and is less likely to show scratches, regular hexagon or octagon section are better choices.

(2) The axis direction of the barrel

On the premise of the axis direction of the barrel is horizontal, if the geometric axis is consistent to the rotary axis, the mixture in the barrel only shows the forced flow in the section perpendicular to the rotary axis (i.e., two-dimensional forced flow). As shown in Fig. 2.35, if the axis direction of the barrel sets at an angle α to the rotary axis, the counterforce F of the mixture in the barrel from barrel wall has two components when the barrel does a planetary motion: One component is Fr, which forces the workpiece to do a planetary motion following the barrel. Meanwhile, to execute a circumferential forced flow relative to the barrel, the other component Fs forced the mixture to do an axial motion relative to the barrel, and the flow proceeds to the opposite direction when the barrel rotates over 180°. In the whole process of processing, the mixture in the barrel executes ∞-shaped

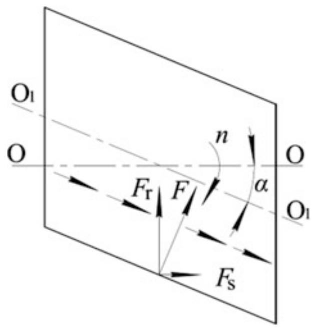


Fig. 2.35 Impact analysis of the axis direction of the barrel on finishing effects

comprehensive flow (i.e., three-dimensional forced flow), and this can increase the relative motion between the workpieces and abrasive blocks, which improve the finishing efficiency.

3. Process parameters

   (1) Load of the mixture
   The load of the mixture is the percentage of the total volume of the mixture loaded in the barrel to the total volume of the barrel. In barrel finishing processes, the loading capacity has a greater influence on the flowing layer length of the mixture in the barrel than the relative sliding velocity and the number of interactions between abrasive blocks and the workpieces. So, the loading capacity would affect the material removal rate, the surface roughness value, deformation degree of the workpiece, and so on.
   For the appropriate loading capacity (Fig. 2.36a), the local relative stationary status will not be formed in the mixture center. A large relative sliding velocity and a longer flowing layer will be obtained in the sliding flowing layer, and then the times of the relative sliding and scoring between abrasive blocks and workpieces will increase, which will lead to high finishing efficiency.
   If the loading capacity is too large (Fig. 2.36c), the core-annulus peristaltic area in the mixture center will increase, abrasive blocks and workpieces in the area will be in the moderate flow state, and the finishing action will be small. Meanwhile, the length of flowing layer is very short, which leads to lower finishing efficiency.
   Based on a lot of experimental results, the influence and the adaptation situation of different loading capacity are summarized, shown in Table 2.12.

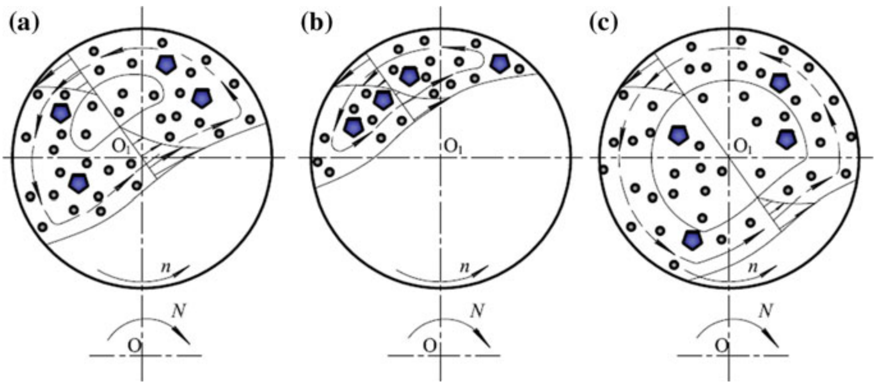


Fig. 2.36 Flow status analysis of the mixture in the barrel with different loading capacity. **a** 60% loading capacity; **b** 30% loading capacity; **c** 90% loading capacity

Table 2.12 Influence and adaptation situation of different loading capacities

Loading capacity (volume ratio)/%	Material removal rate	Decreasing of surface roughness value	Deformation degree of the workpiece	Adaptation situation
<50	Low	Low	Large	No using generally
50–65	Large	Moderate	Moderate	Heavy cutting, difficult deformation parts
65–90	Low	High	Low	Easy-deformed flat parts, thin bars, and low stiffness parts

(2) Mixing ratio

The mixing ratio of abrasive blocks and the workpieces is the mass or volume ratio of abrasive blocks to workpieces loaded in the barrel. If mixing ratio is low, it indicates that there are more workpieces in the barrel, the abrasive blocks are reduced, and the barrel finishing efficiency is low. As more workpieces are added, the possibility of mutually collision and pounds among the workpieces is enhanced, the deformation often happens in finishing the easy-deformed flat parts, thin bars, or soft material workpieces, and this can affect surface quality. If the mixing ratio is large, it indicates that there are fewer workpieces in the barrel, and the abrasives are more. This can not only impact the finishing efficiency, but also aggravate the actions of abrading and collision among abrasive blocks, and the finishing economy will be poor.

Experimental results show that the mass mixing ratio of abrasive blocks to workpieces between 1:1 and 2:1 is suitable. The mixing ratio can be chosen according to the workpiece material, shape, size, and finishing requirements.

(3) Finishing time

The length of the barrel finishing time directly affects the finishing quality, finishing efficiency, and economy. The barrel finishing process can be divided into three stages (Fig. 2.37):

Intense finishing stage: This is the preliminary stage of the process; the burrs, sharp corners, and profile peaks of the workpieces surface are removed effectively by the actions of forced collision, rolling, and grinding of abrasive blocks to the workpieces, and the surface roughness value is reduced significantly. In this stage, the material removal rate of the workpiece is large, and accordingly the wear rate of abrasive blocks is also large.

Uniform finishing stage: In this stage, the action of abrasive blocks to the workpiece is mainly sliding. The profile peaks on the workpieces surface are continually smoothed and grinded, and the concave–convex surface is not found. The relationship of material removal rate and the surface roughness value versus the finishing time appears to be linear. This is a stable and uniform finishing process.

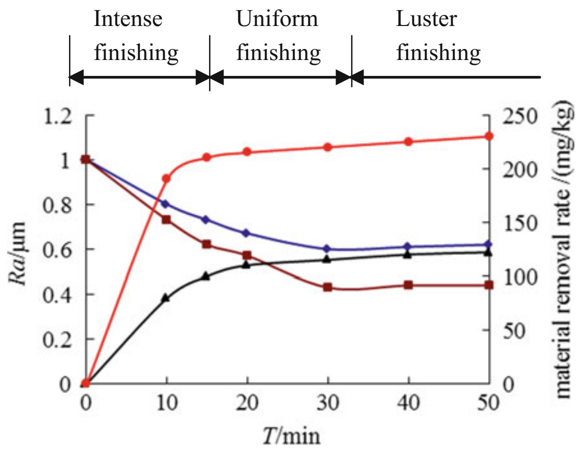


Fig. 2.37 Impact rules on finishing effects of different finishing time

Luster finishing stage: In this stage, the original profile peaks completely disappear, the contact area between abrasive blocks and the workpieces surface increases, the pressure is lower (that means the cutting force per unit area decreases), the material removal amount of the workpiece decreases significantly, and the decrease of the surface roughness value is no longer significant. Therefore, this stage only exists with the luster finishing effect. In the luster finishing stage, the surface stress distribution would be improved and the surface hardness would be enhanced (the workpieces surface would gain cold hardening effect) as the abrasive blocks have this intense rolling effect on the workpieces surface. The surface roughness value no longer decreases and remains a relatively stable value during this finishing stage. The workpieces surface is considered to have reached the ultimate roughness value (Ra_j), that is to say, the ultimate roughness value always exists with certain finishing conditions.

For different materials, shapes, finishing requirements of workpieces, and abrasive blocks, the finishing time of these three stages mentioned above is different. Large amount of experimental results demonstrates that the removing burrs, flashes, oxide skins, and other similar rough processing needs 40–60 min; removing edges and corners, chamfering, and other similar rough processing needs 30–40 min; semi-finishing processing of various workpieces needs about 30 min; finish processing of various workpieces needs about 15 min [45].

2.5.3 Equipment Types and Design

1. Equipment types

Figure 2.38 shows the basic structure diagram of the centrifugal barrel finishing equipment ($n/N = -1$). When finishing, abrasive blocks, workpieces, and liquid medium (water and compounds) are put into sealed barrel 8 with a certain proportion, and tie-rod belt wheel 3 generates rotation by means of the belt transmission and the motor. The barrel not only rotates around central shaft 4 (speed N), but also makes retrograde motion around its shaft (speed n) through planetary driving wheel system comprised of tie-rod belt wheel 3, center belt wheel 5, and planetary belt wheel 6. Figure 2.39 is the three-dimensional model generated by Pro/E software.

The classification of centrifugal barrel finishing equipment is shown as follows:

(1) They can be classified into horizontal type and vertical type, based on the installed direction of the barrel shaft. Generally, horizontal type equipment is the most applied, and vertical barrel is often used on the small equipment in which the volume of single barrel is less than 2L (vertical type has advantage of high automation, such as the mixture loading or unloading).
(2) They can be classified into coaxial type and tilting type, based on the relationship between the geometric axis of the barrel and its rotational axes.
(3) They can be classified into circular barrel type and regular polygon barrel type, based on the cross-sectional shape of the barrel. The regular polygon type is most commonly chosen to be regular hexagon and regular octagon barrel.
(4) They can be classified into double-barrel type, triple-barrel type, quadruple-barrel type, and hexa-barrel type, based on the number of barrels. The number of the barrels is usually an even number, thereby ensuring dynamic balance in processing.
(5) They can be classified into belt-driven type, chain-driven type, and gear-driven type, based on the mode of transmission. Gear-driven is compact in structure, but its lubrication condition is poor, and it has a great noise. Belt-driven and chain-driven have to set tensioning mechanism.
(6) They can be classified into constant-speed type and change-speed type, based on the change of revolution speed. Change-speed type is achieved by adopting gearbox, adjustable speed motor, and stepless speed regulation device. During the time of the start-up and the finishing termination, the revolution speed will have a sudden increase or decrease. This can cause violent collision and affect the finishing effect. In the design of finishing equipment, it is very necessary to implement measures for achieving slow-start and slow-stop.
(7) They can be classified into stationary barrel type and detachable barrel type, based on the operating mode of the barrel. Considering the discharging requirements, stationary barrel type must add discharging mechanism, so that the barrel can achieve rotations, but cannot obtain revolutions, which pouring the workpieces and abrasives out by its rotation.

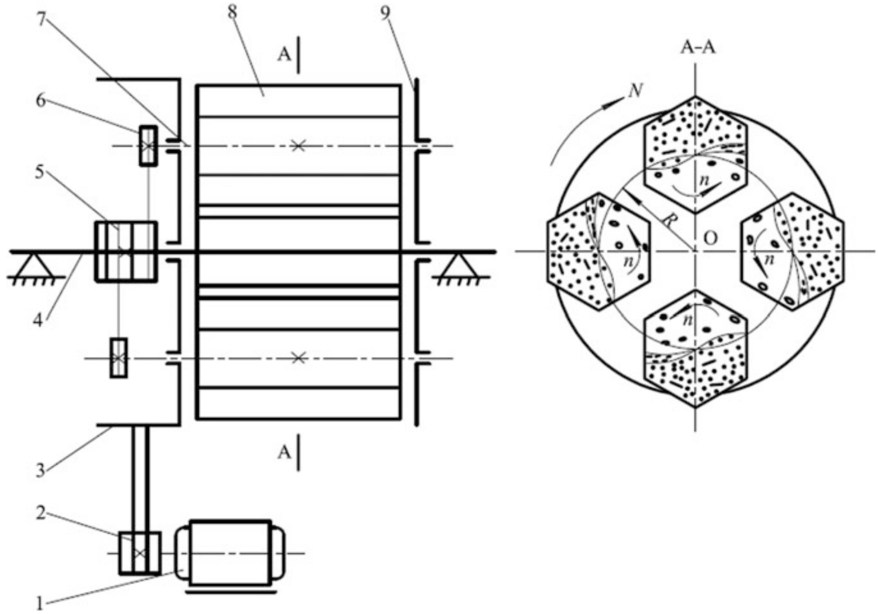
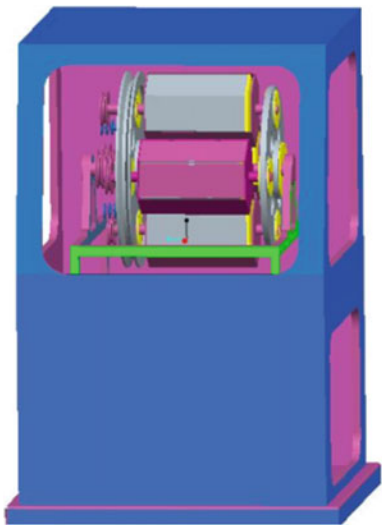


Fig. 2.38 Basic structure diagram of centrifugal barrel finishing equipment. 1—Motor; 2—motor belt wheel; 3—tie-rod belt wheel; 4—central shaft; 5—center belt wheel; 6—planetary belt wheel; 7—rotary shaft of the barrel; 8—barrel; 9—tie-rod

Fig. 2.39 Three-dimensional model of centrifugal barrel finishing equipment



(8) They can be classified into single support type (cantilever structure) and double support type, based on the supporting form of the central shaft. Single support type is only suitable for low-volume barrels.

(9) They can be classified into stationary central shaft type and detachable central shaft type, based on the fixation of central shaft or not. Stationary central shaft type (Fig. 2.38) needs a large-scale tie-rod belt wheel, and this can consume less speed reducers and other speed reducing mechanisms, but becomes difficult when changing the driving belt. Detachable central shaft type usually adopts a small-scale tie-rod belt wheel which is placed besides the support, and the driving belt is convenient to exchange, but the speed reducing mechanism must be added.

As planetary mechanism has great inertial motion after finishing, the brake device should be also be set. Based on the difference in the structural form, the brake device can be mechanical type and electromagnetic type. For the barrel operating (barrels or mixtures loading/unloading) reliability, it is necessary to set the position with a locking mechanism.

Otherwise, the revolution-driven and rotation-driven of the equipment will be separated. The double driving structure diagram is shown in Fig. 2.40.

2. Equipment design

(1) Structure of critical component

Among centrifugal barrel finishing equipment, the barrel not only is the loading container of the mixture, but also is the carrier which realizes the finishing process.

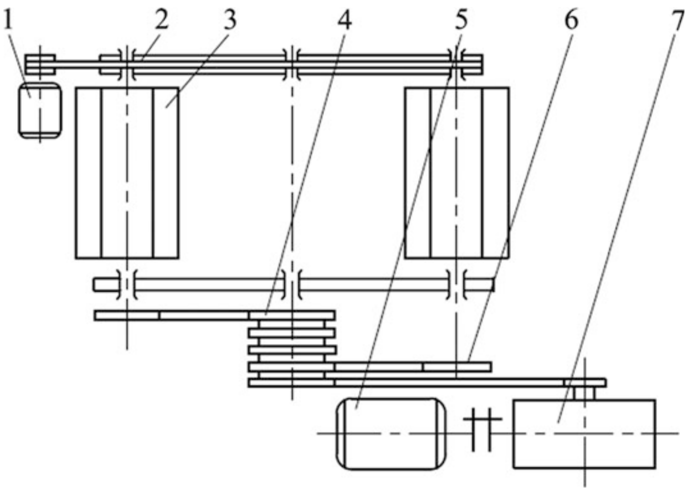


Fig. 2.40 Double driving structure diagram. 1—Revolution control motor; 2—tie-rod belt wheel; 3—barrel; 4—primary belt wheel of rotation; 5—rotation control motor; 6—barrel belt wheel; 7—speed reducing mechanism

During the finishing process, the barrel carries the mixture (workpieces, abrasive blocks, and liquid medium) to make the planetary motion at the high speed, and the following is the requirements for the barrel.

(1) It must have good sealing property.
(2) The lining on the inner wall should resist corrosion and wear, and has a big coefficient of friction acting on the mixture.
(3) A single barrel and a set of barrels of the same equipment should have a good rotary balance.

The barrel component is mainly composed of barrel body, barrel cover, and pressing mechanism. The barrel body mainly includes the shell and the lining. The shell of the barrel body can employ cast iron materials or welded structure, and the method of the rotating counterweight should be considered in the structure. The best way to process the shell of the barrel body is with a welded structure, which is corrected after the aging treatment. The lining of the barrel body can adopt complete sulfide rubber or combined rubber. The effect of sulfide barrel body is good, but the cost is high; therefore, the combining way can be used generally. Besides, the lining of the barrel body can also adopt polyurethane coating. The pressing mechanism should be safety, reliability, and easy operating.

(2) Parameters determination

When determining parameters, the following factors should be considered.

(1) Total volume of the barrels reflects the maximum working capacity of the centrifugal barrel finishing equipment.
(2) Number of the barrels and the volume of single barrel determine the structure of the finishing equipment.
(3) Structure size of single barrel (diameter d and length L): If no special requirements are present, d/L can be about 0.618; this makes a more harmonious shape. In case of the special requirements, the specialization should be satisfied.
(4) Determination of barrel orbital diameter D can guarantee the structure compactness.
(5) Design of planet transmission mechanism: It should guarantee $\frac{n}{N} = -1$ or $\sqrt{\frac{R}{r}} - 1 > \frac{n}{N} > -\left(\sqrt{\frac{R}{r}} + 1\right)$.
(6) Determination of revolution speed N: Coefficient K should be reasonably selected based on $N = K/\sqrt{D}$.

3. Equipment shapes

Figure 2.41 shows the photographs of two centrifugal barrel finishing equipment [46, 47]. Figure 2.42 shows the photographs of different centrifugal barrel finishing equipments produced by Langfang Beifang Tianyu Mechanical and Electrical Technology Co., Ltd.

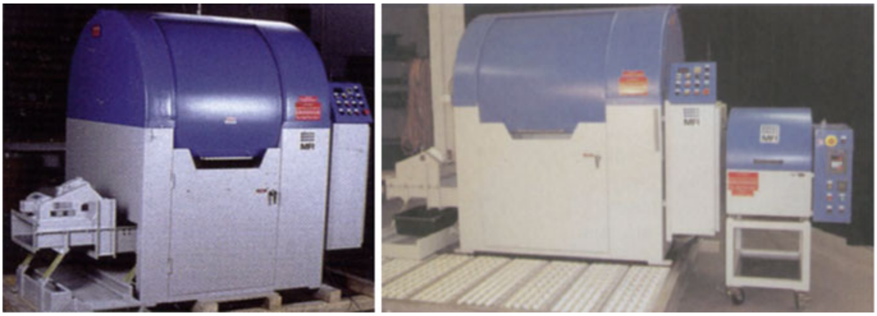


Fig. 2.41 Photographs of centrifugal barrel finishing equipment

Fig. 2.42 Photographs of centrifugal barrel finishing equipment produced by Beifang Tianyu

2.6 Vertical Spindle Barrel Finishing

The vertical spindle barrel finishing is that the workpieces installed on the spindle are inserted into the barrel with media (abrasive blocks, compounds, and water) vertically or at a tilting angle to a vertical direction. The relative motion and interactions between the abrasive blocks and the workpiece surface can be generated by the rotational motion of the spindle and the barrel or the revolution and the rotation of the spindle, and then the deburring process or the surface finishing of the workpieces is achieved.

2.6.1 Finishing Principle and Characteristics

1. Finishing principle

Figure 2.43 shows the schematic diagrams of several typical spindle barrel finishing ways. In Fig. 2.43a, the barrel revolves at N, the spindle revolves at n, and the rotating axis of the spindle is parallel to the rotating axis of the barrel. In Fig. 2.43b, the barrel is fixed, the spindle revolves along N and rotates along n, and

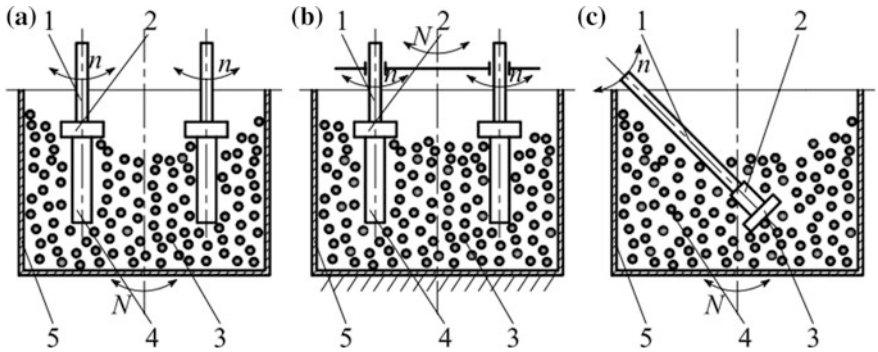


Fig. 2.43 Schematic diagrams of several typical spindle barrel finishing ways. **a** Parallel spindle type I; **b** parallel spindle type II; **c** intermeshing spindle type. 1—Spindle; 2—holding device; 3—medium; 4—parts; 5—barrel

the revolution axis of the spindle is parallel to the rotation axis. As shown in Fig. 2.43a, b, both types are collectively called parallel spindle barrel finishing. In Fig. 2.43c, the barrel revolves at N, the spindle revolves at n, and the rotating axis of the spindle is laid crosswise to the rotating axis of the barrel, and this situation is called intermeshing spindle barrel finishing.

When $N \neq 0$, as shown in Fig. 2.43a, b, a certain amount of the medium in the barrel produces centrifugal force under the action of the revolution, due to the mass exists. The abrasives form a rigid staging area in a certain range of the barrel wall due to the centrifugal force. In Fig. 2.43b, the medium in the barrel is free-depositional incompact status.

When $N \neq 0$ and $n = 0$, the workpiece surface facing at the direction of the abrasive blocks flow is subjected to the impacting action (or barrier action) of the abrasive blocks, and the rolling force and the friction of the abrasive blocks to the workpiece surface are produced during the impacting (barrier) process. Under the action of these forces, the phenomenon of eccentrically worn occurs on the surface of the workpiece. Comparing between Fig. 2.43a, b, the machining range in Fig. 2.43a is in the rigid staging area, and the machining range in Fig. 2.43b is in incompact status, so the action force on the workpiece in Fig. 2.43a is larger than that of in Fig. 2.43b when the revolution speed N and the revolution radius of the workpiece are the same. This can cause more severe eccentrically worn phenomenon.

When $N \neq 0$ and $n \neq 0$, various places over the workpiece surface are under the action of the above several forces. Given the machining medium, the finishing effects depend heavily on the complexity of the relative movement between the abrasive blocks and the workpiece surface.

2. Kinematic analysis

(1) Kinematic analysis of parallel spindle barrel finishing

Kinematic analysis of parallel spindle barrel finishing is shown in Fig. 2.44. The rotating speed of the barrel is set to N; the rotating speed of the workpiece is n; v_N is the velocity of the abrasive blocks at Moving-point A because of the rotation (N) of the barrel; v_n is the relative velocity of the abrasive blocks at Moving-point A because of the rotation (N) of the workpiece; v is the resultant velocity (i.e., cutting velocity) of the abrasive blocks relative to the workpiece at Moving-point A; q is the distance from Moving-point A to the rotating axis of the workpiece; Q is the distance between the rotating axis of the barrel and the rotating axis of the workpiece; θ is the angle between the connecting line from Moving-point A to the center of the workpiece and the connecting line between the two center points; $\theta = 0°$ is at the intersection of the extension of line OO′ and the surface of the workpiece; the size of angle θ is in the counterclockwise direction; φ is the acute angle (cutting angle) between the cutting velocity direction of the arbitrary points on the outside circle surface of the workpiece and the tangent line of that point, when θ is in the range of 0°–180°, φ is positive, when θ is in the range of 180°–360°, φ is negative.

Based on the equation of velocity synthesis,

$$v = v_N + v_n \tag{2.43}$$

Through the analysis, calculation, and sorting of the geometric relationship, it can obtained that

$$v = 2\pi N\left[q^2\left(1-\frac{n}{N}\right)^2 + Q^2 + 2Qq\left(1-\frac{n}{N}\right)\cos\,\theta\right]^{1/2} \tag{2.44}$$

$$\varphi = \arcsin\frac{-2\pi NQ\,\sin\,\theta}{v} \tag{2.45}$$

The cutting velocity v and the cutting angle φ of certain point on the workpiece surface can be calculated by substituting N, n, q, Q, and θ into Eqs. (2.44) and (2.45).

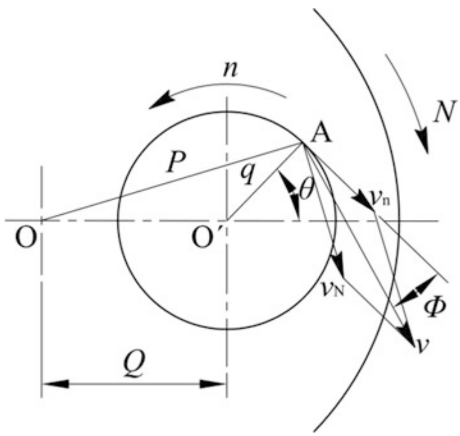


Fig. 2.44 Kinematic analysis of parallel spindle barrel finishing

The higher the cutting velocity v is, the longer the relative friction of the cutting route per unit time is. The removal thickness of the workpiece is related not only to the cutting velocity v but also to the size of the cutting angle. It is for this reason that the workpiece cannot achieve excellent effects [26, 27].

(2) Kinematic analysis of intermeshing spindle barrel finishing

Kinematic analysis of intermeshing spindle barrel finishing is shown in Fig. 2.45. In the figure, OO' (O_1O') is the rotating axis of the barrel; O_2O_3 is the rotating axis of the workpiece; N is the rotating speed of the barrel; n is the rotating speed of the workpiece; O_2O_3 is in Plane P_1, OO' (O_1O') is in Plane P_2, and P_1 // P_2; OO' (O_1O') is in Plane P_3, and $P_3 \perp P_2$; Plane P_3 and O_2O_3 meet in Point O_2; O_3 is the end plane center of the workpiece; q is the rotating radius of the workpiece about O_2O_3; Q is the distance between Plane P_1 and Plane P_2, that is the shortest distance (O_1O_2) between Line O_2O_3 and Line OO' (O_1O'); β is the angle (spindle swinging angle) between Line O_2O_3 and the horizontal plane; L is the distance between O_2 and O_3.

(1) Establishment of moving point trajectory equations

As shown in Fig. 2.45, considering the characteristic and requirements of keeping invariable relative motion and postulating to the barrel stops, the workpiece rotates on axis O_2O_3 at rotational speed n. Meanwhile, the spindle axis O_2O_3 used for clamping the workpiece rotates on axis OO' opposite to the original rotation direction of the barrel, and its rotating speed is N. The kinematic analysis model of the abrasives relative to one point on the workpiece surface is shown in Fig. 2.46.

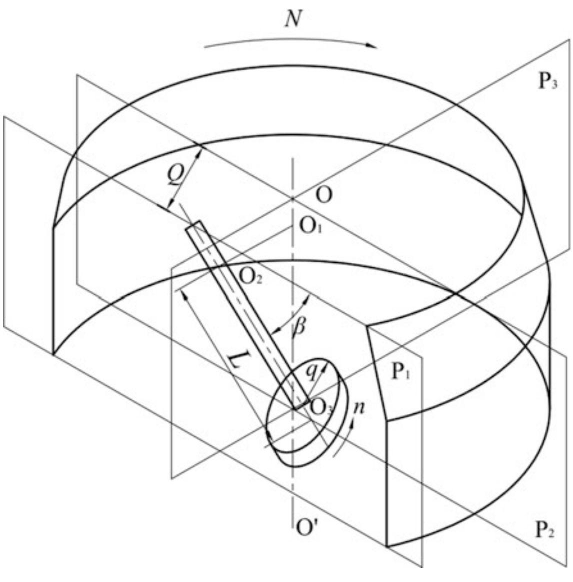


Fig. 2.45 Kinematic analysis of intermeshing spindle barrel finishing

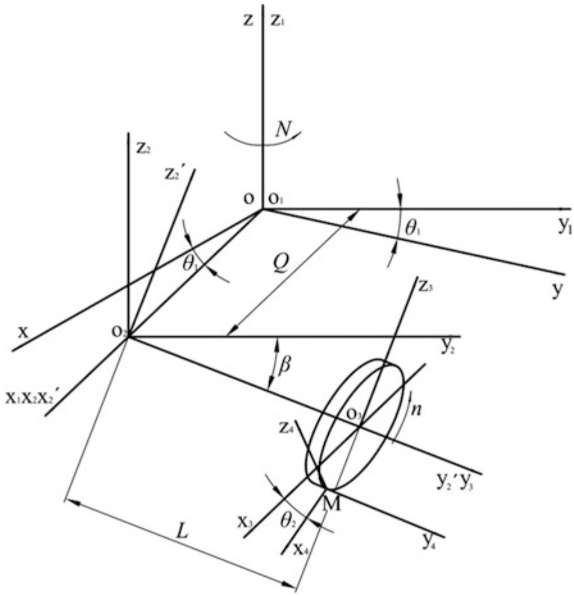


Fig. 2.46 Kinematic analysis model of intermeshing spindle barrel finishing

For Moving-point M on the outer circumference of the workpiece end face, geometric transformation coordinates shown in Fig. 2.46 are built, and its transformation processes are as follows:

$$\mathrm{O}xyz \xrightarrow{\text{Going } \theta_1 \text{ around the } z \text{ axis}} \mathrm{O}_1\, x_1\, y_1\, z_1 \xrightarrow{\text{Translating } Q \text{ along } x_1} \mathrm{O}_2\, x_2\, y_2\, z_2$$

$$\xrightarrow{\text{Going } \beta \text{ around the } x_2 \text{ axis}} \mathrm{O}_2\, \mathrm{x}_2'\, \mathrm{y}_2'\, \mathrm{z}_2' \xrightarrow{\text{Translating } L \text{ along } y_2'} \mathrm{O}_3\, x_3\, y_3\, z_3$$

The corresponding geometric transform relation is

$$\begin{vmatrix} x \\ y \\ z \end{vmatrix} = \begin{vmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} x_1 \\ y_1 \\ z_1 \end{vmatrix} \tag{2.46}$$

$$\begin{vmatrix} x_1 \\ y_1 \\ z_1 \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} x_2 \\ y_2 \\ z_2 \end{vmatrix} + \begin{vmatrix} Q \\ 0 \\ 0 \end{vmatrix} = \begin{vmatrix} Q + x_2 \\ y_2 \\ z_2 \end{vmatrix} \tag{2.47}$$

$$\begin{vmatrix} x_2 \\ y_2 \\ z_2 \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & \cos\,\beta & \sin\,\beta \\ 0 & -\sin\,\beta & \cos\,\beta \end{vmatrix} \begin{vmatrix} x_2' \\ y_2' \\ z_2' \end{vmatrix} \tag{2.48}$$

$$\begin{vmatrix} x_2' \\ y_2' \\ z_2' \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} x_3 \\ y_3 \\ z_3 \end{vmatrix} + \begin{vmatrix} 0 \\ L \\ 0 \end{vmatrix} = \begin{vmatrix} x_3 \\ L + y_3 \\ z_3 \end{vmatrix} \tag{2.49}$$

In the $O_3x_3y_3z_3$ coordinate system, the position of Moving-point M changes with θ_2. θ_2 is defined as the angle between the line from the outside point on the workpiece to O_3 and the line from M to O_3, then

$$\begin{vmatrix} x_3 \\ y_3 \\ z_3 \end{vmatrix} = \begin{vmatrix} q \cos \theta_2 \\ 0 \\ -q \sin \theta_2 \end{vmatrix} \tag{2.50}$$

Through the deduction of inversion equation, it can be obtained that

$$\begin{vmatrix} x \\ y \\ z \end{vmatrix} = \begin{vmatrix} Q \cos \theta_1 + q \cos \theta_1 \cos \theta_2 - L \sin \theta_1 \cos \beta + q \sin \beta \sin \theta_1 \sin \theta_2 \\ Q \sin \theta_1 + q \sin \theta_1 \cos \theta_2 + L \cos \theta_1 \cos \beta - q \sin \beta \cos \theta_1 \sin \theta_2 \\ -L \sin \beta - q \cos \beta \sin \theta_2 \end{vmatrix} \tag{2.51}$$

Since θ_1 and θ_2 vary simultaneously with time t, and $\theta_1 = 2\pi Nt$, $\theta_2 = 2\pi nt$ are substituted to Eq. (2.51), there is

$$\begin{vmatrix} x \\ y \\ z \end{vmatrix} = \begin{vmatrix} Q \cos(2\pi Nt) + q \cos(2\pi Nt) \cos(2\pi nt) - L \sin(2\pi Nt) \cos \beta + q \sin \beta \sin(2\pi Nt) \sin(2\pi nt) \\ Q \sin(2\pi Nt) + q \sin(2\pi Nt) \cos(2\pi nt) + L \cos(2\pi Nt) \cos \beta - q \sin \beta \cos(2\pi Nt) \sin(2\pi nt) \\ -L \sin \beta - q \cos \beta \sin(2\pi nt) \end{vmatrix} \tag{2.52}$$

Equation (2.52) is the movement trajectory equation of Moving-point M.

(2) Velocity component of Moving-point M and the resultant cutting velocity in cylindrical coordinates

Taking the trajectory Eq. (2.52) of Moving-point M in the Oxyz coordinate system as a research object, the derivative of both sides is taken, and the velocity component of M in the Oxyz coordinate system is obtained, that is

$$\begin{vmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{vmatrix} = \begin{vmatrix} -2\pi[NQ \sin(2\pi Nt) + Nq \sin(2\pi Nt) \cos(2\pi nt) + nq \cos(2\pi Nt) \sin(2\pi nt) + NL \cos(2\pi Nt) \cos \beta \\ \quad + Nq \sin \beta \cos(2\pi Nt) \sin(2\pi nt) - nq \sin \beta \sin(2\pi Nt) \cos(2\pi nt)] \\ 2\pi[NQ \cos(2\pi Nt) + Nq \cos(2\pi Nt) \cos(2\pi nt) - nq \sin(2\pi Nt) \sin(2\pi nt) - NL \sin(2\pi Nt) \cos \beta \\ \quad + Nq \sin \beta \sin(2\pi Nt) \sin(2\pi nt) - nq \sin \beta \cos(2\pi Nt) \cos(2\pi nt)] \\ -2\pi nq \cos \beta \cos(2\pi nt) \end{vmatrix} \tag{2.53}$$

The velocity component of M in the $O_1x_1y_1z_1$ coordinate system is making the above-mentioned component do counterclockwise rotation $2\pi Nt$ about the Z-axis, and there is

$$\begin{vmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{z}_1 \end{vmatrix} = 2\pi \begin{vmatrix} q(N\sin\beta - n)\sin(2\pi nt) - NL\cos\beta \\ q(N - n\sin\beta)\cos(2\pi nt) + NQ \\ -nq\cos\beta\cos(2\pi nt) \end{vmatrix} \tag{2.54}$$

Since the transformation of $O_1x_1y_1z_1 \rightarrow O_2x_2y_2z_2$ is the translation along x_1-axis, so

$$\begin{vmatrix} \dot{x}_2 \\ \dot{y}_2 \\ \dot{z}_2 \end{vmatrix} = \begin{vmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{z}_1 \end{vmatrix} = 2\pi \begin{vmatrix} q(N\sin\beta - n)\sin(2\pi nt) - NL\cos\beta \\ q(N - n\sin\beta)\cos(2\pi nt) + NQ \\ -nq\cos\beta\cos(2\pi nt) \end{vmatrix} \tag{2.55}$$

The velocity component of M in the $O_2x'_2y'_2z'_2$ coordinate system is making the velocity component in $O_2x_2y_2z_2$ coordinate system to do clockwise rotation β about the x_2-axis, and there is

$$\begin{vmatrix} \dot{x}'_2 \\ \dot{y}'_2 \\ \dot{z}'_2 \end{vmatrix} = 2\pi \begin{vmatrix} q(N\sin\beta - n)\sin(2\pi nt) - NL\cos\beta \\ N\cos\beta[q\cos(2\pi nt) + Q] \\ N\sin\beta[q\cos(2\pi nt) + Q] - nq\cos(2\pi nt) \end{vmatrix} \tag{2.56}$$

Since the transformation of $O_2x'_2y'_2z'_2 \rightarrow O_3x_3y_3z_3$ is the translation along y'_2-axis, so

$$\begin{vmatrix} \dot{x}_3 \\ \dot{y}_3 \\ \dot{z}_3 \end{vmatrix} = \begin{vmatrix} \dot{x}'_2 \\ \dot{y}'_2 \\ \dot{z}'_2 \end{vmatrix} = 2\pi \begin{vmatrix} q(N\sin\beta - n)\sin(2\pi nt) - NL\cos\beta \\ N\cos\beta[q\cos(2\pi nt) + Q] \\ N\sin\beta[q\cos(2\pi nt) + Q] - nq\cos(2\pi nt) \end{vmatrix} \tag{2.57}$$

With this, if M is set as the origin, the direction of O_3M is x_4 axle, y_4 axle is parallel to y_3, and rectangular coordinate system $Mx_4y_4z_4$ is set up. Under this coordinate system, the velocity component of moving point is making the velocity component in the $O_3x_3y_3z_3$ coordinate system do counterclockwise rotation $2\pi nt$ about the y_3-axis, and there is

$$\begin{vmatrix} \dot{x}_4 \\ \dot{y}_4 \\ \dot{z}_4 \end{vmatrix} = 2\pi \begin{vmatrix} -NL\cos\beta\cos(2\pi nt) - NQ\sin\beta\sin(2\pi nt) \\ N\cos\beta[q\cos(2\pi nt) + Q] \\ q(N\sin\beta - n) - NL\cos\beta\sin(2\pi nt) + NQ\sin\beta\cos(2\pi nt) \end{vmatrix} \tag{2.58}$$

According to the composition equation of velocity, if the cutting speed is v, there is

$$\begin{aligned} v^2 &= \dot{x}^2 + \dot{y}^2 + \dot{z}^2 = \dot{x}_1^2 + \dot{y}_1^2 + \dot{z}_1^2 = \dot{x}_2^2 + \dot{y}_2^2 + \dot{z}_2^2 = \dot{x}_2'^2 + \dot{y}_2'^2 + \dot{z}_2'^2 \\ &= \dot{x}_3^2 + \dot{y}_3^2 + \dot{z}_3^2 = \dot{x}_4^2 + \dot{y}_4^2 + \dot{z}_4^2 \end{aligned} \tag{2.59}$$

The results calculated, derived, and arranged based on different components are the same, and $2\pi nt$ is recorded as θ_2; then,

$$v = 2\pi N\left\{q^2\left(\sin\beta - \frac{n}{N}\right)^2 + Q^2 + 2Qq\left(\sin\beta - \frac{n}{N}\right)\sin\beta\cos\theta_2 + \cos\beta\left[q^2\cos\beta\cos^2\theta_2 + 2Qq\cos\beta\cos\theta_2 - 2qL\sin\beta\sin\theta_2 + 2qL\frac{n}{N}\sin\theta_2 + L^2\cos\beta\right]\right\}^{1/2} \tag{2.60}$$

(3) Cutting angle at certain point on the workpiece cylindrical surface, and the axial end surface

To better describe machinability at a certain point on the workpiece, it is not enough to only consider the value of its cutting speed, and the direction of the cutting speed v relative to special machined surface should also be considered. During crossed spindle barrel finishing process, the surface of the workpiece finished by the abrasive blocks includes the workpiece cylindrical surface and the axial end surface.

For cylindrical surface, the acute angle between the defined direction of the cutting speed v at Moving-point M and the tangent plane across the workpiece is the cutting angle (symbolized by φ_{r}) of the cylindrical surface; for the axial end surface, the acute angle between the defined direction of the cutting speed v at M and the axial end surface of the workpiece is the cutting angle (symbolized by φ_0) of the axial end surface.

In the M$x_4y_4z_4$ coordinate system, the cutting angle φ_0 of the cylindrical surface is the angle between the direction of the cutting speed v and coordinate plane Mx_4y_4; the cutting angle φ_0 of the axial end surface is the angle between the direction of the cutting speed v and coordinate plane Mx_4z_4. If these information is presented in the form of cosine, there are

$$\cos\varphi_r = \sqrt{\dot{y}_4^2 + \dot{z}_4^2}/v \tag{2.61}$$

$$\cos\varphi_o = \sqrt{\dot{x}_4^2 + \dot{z}_4^2}/v \tag{2.62}$$

If this information is presented in the form of sine, there are

$$\sin\varphi_r = \dot{x}_4/v \tag{2.63}$$

$$\sin\varphi_o = \dot{y}_4/v \tag{2.64}$$

It can be derived from Eqs. (2.61)–(2.64) that

$$-90^\circ \le \varphi_{\mathrm{r}} \le 90^\circ - 90^\circ \le \varphi_0 \le 90^\circ$$

$\dot{x}_4$, $\dot{y}_4$ are plugged separately into Eqs. (2.63) and (2.64), it can be obtained that

$$\varphi_r = \arcsin \frac{-2\pi N(L \cos \beta \cos \theta_2 + Q \sin \beta \sin \theta_2)}{v} \tag{2.65}$$

$$\varphi_o = \arcsin \frac{2\pi N \cos \beta(q \cos \theta_2 + Q)}{v} \tag{2.66}$$

For special cases, if $\beta = 90°$, then the workpiece spindle is parallel to the revolving axis of the barrel, and Eqs. (2.60) and (2.65) are equivalent to Eqs. (2.44) and (2.45). It can be seen that the axial end surface cannot be processed properly from Eq. (2.66), when $\varphi_0 = 90°$.

It can be seen from Eqs. (2.60), (2.65), and (2.66) that, when $\beta \neq 90°$, and N, n, Q, q, L, β, and θ_2 are given, the cutting speed v, the cutting angle φ_r of the cylindrical surface, and the cutting angle φ_0 of the axial end surface at arbitrary point on the workpiece surface can be obtained. This illustrates that the workpiece can carry out surface finishing for both the cylindrical surface and the axial end surface.

(4) Impacts of every parameter on the cutting speed and the cutting angle

It can be seen from Eqs. (2.60), (2.65), and (2.66) that the cutting speed v and the cutting angle φ_r, φ_0 are affected by parameters such as n/N, N, Q, q, L, β, and θ_2. When θ_2 is in the range of 0°–360°, the effect condition of every parameter on v, φ_r, and φ_0 can be analyzed.

① Impacts of n/N on v, φ_r, and φ_0

The preparing conditions of Fig. 2.47 are $N = 50\,\text{r/min}$, $\beta = 60°$, $Q = 0.3\,\text{m}$, $L = 0.3\,\text{m}$, and $q = 0.05\,\text{m}$, as shown in the figure.

Within the range of 360° on the cylindrical surface of the workpiece, the cutting angles φ_r in the 180° range are negative. That is, there are no finishing effects; within the range of 360° on the axial end surface of the workpiece, all of the cutting angles φ_r are positive value, and that is there are finishing effects for every degree.

In all of those areas, there are finishing effects, and the change of the average value of v is smaller with n/N, that is n/N has less effect upon finishing. It could also be said that the value of n has less effect upon machining at a constant N.

When $n/N = 0$, the phenomenon of non-uniformity finishing will occur on the workpiece.

② Impacts of N on v, φ_r, and φ_0

The preparing conditions of Fig. 2.48 are $n/N = -2$, $\beta = 60°$, $Q = 0.3\,\text{m}$, $L = 0.3\,\text{m}$, and $q = 0.05\,\text{m}$, as shown in the figure.

The change of N does not affect the cutting angles φ_r and φ_0 in terms of other conditions unchanged. The key to representing the strength of process ability is the cutting speed.

With the increase of the value of N, the cutting speed v increases linearly. So, to improve finishing efficiency, the value of N can be increased.

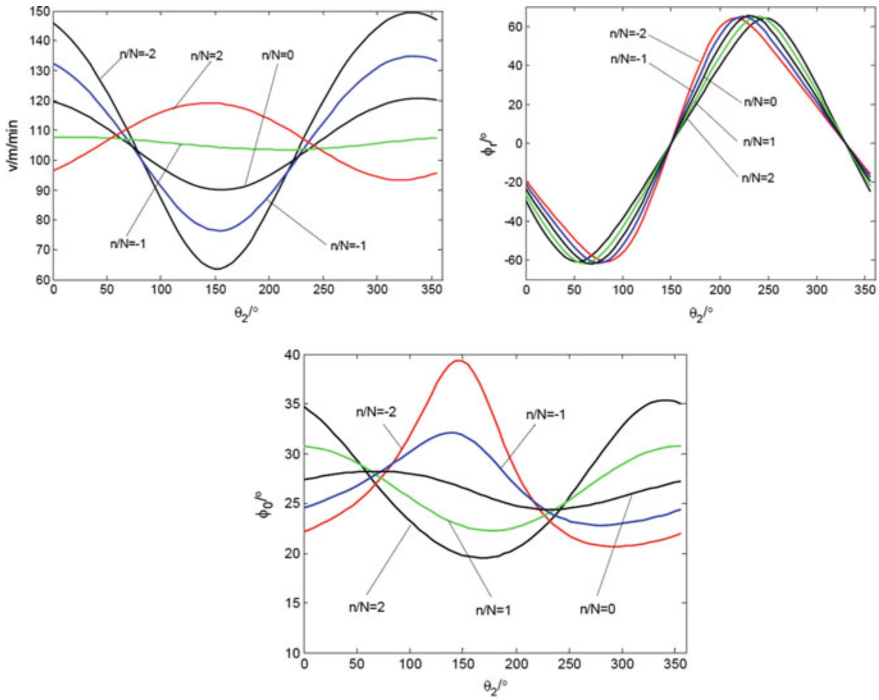


Fig. 2.47 Impacts of n/N on v, φ_r, and φ_0

③ Impacts of β on v, φ_r, and φ_0

As shown in the figure, which is drawn by the condition of $n/N = -2$, $N = 50\,\text{r/min}$, $Q = \sqrt{0.16 - L^2\cos^2\beta}$, $L = 0.3\,\text{m}$, and $q = 0.05\,\text{m}$.

Comparing $\beta \neq 90°$ with $\beta = 90°$, the change of the cutting speed is small, but the cutting angle changes greatly.

When $\beta = 90°$, the maximum value of φ_r is 90° and $\varphi_0 = 0°$. This shows that there are obvious collision points on the cylindrical surface, and the axial end surface does not obtain any finishing effects during parallel spindle barrel finishing.

④ Impacts of Q on v, φ_r, and φ_0

As shown in the figure which is drawn by the condition of $n/N = -2$, $N = 50\,\text{r/min}$, $\beta = 60°$, $q = 0.05\,\text{m}$, and $L = \sqrt{0.16 - Q^2}/\cos\beta$.

The average value of v increases along with increasing Q, and the maximum value of φ_r decreases along with increasing Q. Overall, a large Q is good for the finishing effect of the cylindrical surface.

When $Q = 0$, the value of φ_0 has negative territory, and the value of φ_0 in positive territory is no remarkable. This shows that the finishing effect of the axial end surface is poor when $Q = 0$.

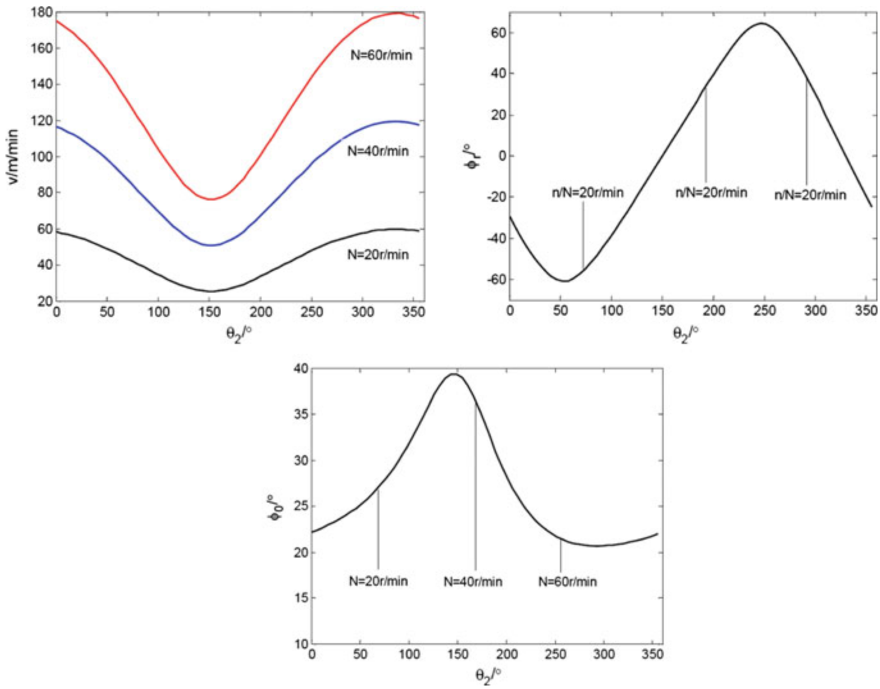


Fig. 2.48 Impacts of N on v, φ_{r}, and φ_0

⑤ Impacts of L on v, φ_{r}, and φ_0

As shown in the figure which is drawn by the condition of $n/N = -2$, $N = 50\,\mathrm{r/min}$, $\beta = 60°$, $q = 0.05\,\mathrm{m}$, and $Q = \sqrt{0.16 - L^2\cos^2\beta}$.

The processing effect of L on the effective finishing area is not very obvious. Note that the value of L has a smaller effect, then the possibility of the cylindrical surface can be plumped, and it may occur to the cylindrical workpiece during barrel finishing.

⑥ Impacts of q on v, φ_{r}, and φ_0

As shown in the figure which is drawn by the condition of $n/N = -2$, $N = 50\,\mathrm{r/min}$, $\beta = 60°$, $Q = 0.3\,\mathrm{m}$, and $L = 0.3\,\mathrm{m}$.

Increasing with q, the machinability of the cylindrical surface is basically stable. Increasing with q, the machinability of the axial end surface has the change, and therefore the adjustment of other parameters should be noticed when finishing disk parts with high requirements on the axial end surface [48].

3. Functional characteristics and application scope

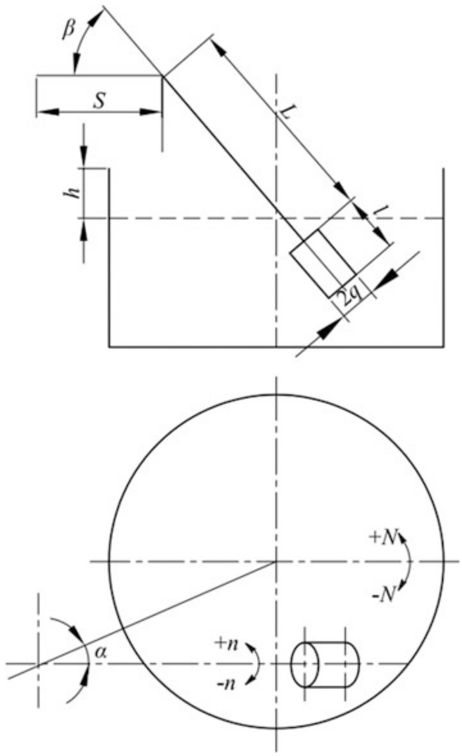
Vertical spindle barrel finishing belongs to the surface barrel finishing that the workpiece is in a non-free state. Compared with the surface barrel finishing technology, the workpiece is in a free state, and it can effectively avoid the knocking and scratch between workpieces.

Parallel spindle barrel finishing, including vertical spindle type and planetary vertical spindle type, mainly applies to finishing small-sized axis parts or the peripheral surface of disk parts. Because its finishing depth along the axial direction is inconsistent, the axial machining uniformity of the parts is not very ideal when finishing large medium-sized parts. Intermeshing spindle barrel finishing is mainly used to the finishing of disk parts end surface and can also implement the finishing of the peripheral surface. It applies to finishing the surface of small- and medium-sized axis/disk parts.

2.6.2 Main Factors Affecting Finishing Effects

According to the analysis of finishing principle, the influence factors of the intermeshing vertical spindle barrel finishing are more than the parallel vertical spindle barrel finishing, including kinematic parameters, geometric parameters, and finishing time. In order to illustrate the factors of intermeshing vertical spindle barrel finishing, the schematic diagram of its variable basic parameters is described in Fig. 2.49. In the figure, the anticlockwise of the roller in vertical view is positive

Fig. 2.49 Schematic diagram of variable basic parameters



(+N), and the clockwise of that is negative ($-N$); the anticlockwise of the projection direction from the truncation spindle to workpiece is positive (+n), and the clockwise of that is negative ($-n$). In addition, h is the distance between the horizontal plane of solid medium in static roller and the upper edge of roller mouth, L can be adjusted using a flexible spindle jig, α is spindle deflection angle, corresponding to the angle between the roller axis and rotation axis in the previous machining principle analysis, and β is spindle oscillating angle.

1. Kinematic parameters of equipment

In the finishing process of the intermeshing vertical spindle barrel, the equipment kinematic parameters consist of the revolving speed and direction of a barrel and that of a spindle. Theoretical results demonstrate that the kinematic parameters affecting cutting speed and angle are the revolving speed of a barrel N, and the ratio between the spindle speed n and the revolving speed of a barrel n/N. The variation curves under different test conditions are shown in Figs. 2.50, 2.51, 2.52, 2.53, and 2.54.

Figures 2.50 and 2.51 show, respectively, the different thickness curves of surface material removals, as the spindle is fixed under conditions of $\alpha = 25°$, $\beta = 60°$, $N = -50$ r/min, $S = 490$ mm, $L = 485$ mm, $h = 230$ mm, and the processing time is 15 min. θ is arranged from 0 to 360. At $\theta = 0$, the farthest distance of the processing plate far away from the central position of the roller can reach to the maximum. All angles are subject to the rule that the direction of a spindle $-n$ rotates to the rotational direction.

Further, from Figs. 2.50 and 2.51, the finishing inhomogeneous can be observed as the spindle is fixed, which fits theoretical calculations well.

Figure 2.52 shows variation curves of surface material removal in thickness versus n and $|n/N|$ under conditions of $\alpha = 25°$, $\beta = 60°$, $N = -50$ r/min, $S = 490$ mm, $L = 485$ mm, $h = 230$ mm, and the time is 20 min. As shown in Fig. 2.52, when N is fixed, the less effect of n and $|n/N|$ on surface material removal in the thickness and the more the power variation can be found. What is more, the thickness of axial end surface material removal is much higher than that of cylindrical surface material removal. It is caused by different cutting angles of different surface materials. For a cylindrical surface within 360°, only half of its surface can be regarded as a processing zone, but for an axial end surface, the whole surface is a processing zone. Thus, with the view of improving thickness of surface material removal, the spindle speed is not too high.

Figure 2.53 shows variation curves of surface material removal in thickness versus N, as the spindle speed is fixed under conditions of $\alpha = 25°$, $\beta = 60°$, $n = 88$ r/min, $S = 490$ mm, $L = 485$ mm, $h = 230$ mm, and the time is 20 min. From Fig. 2.53, it can be seen that with the increase of roller rotation speed, whatever for axial end surface or cylindrical surface, the thickness of surface material removal can be increased, and the non-load power and test load power are also increased. Moreover, the thickness variation of axial end surface material removal is more obvious than that of the cylindrical surface. Thus, to obtain a good variation

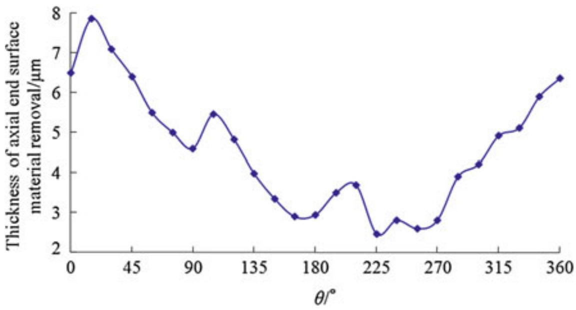


Fig. 2.50 Thickness distribution curves of axial end surface material removal, as the spindle is fixed

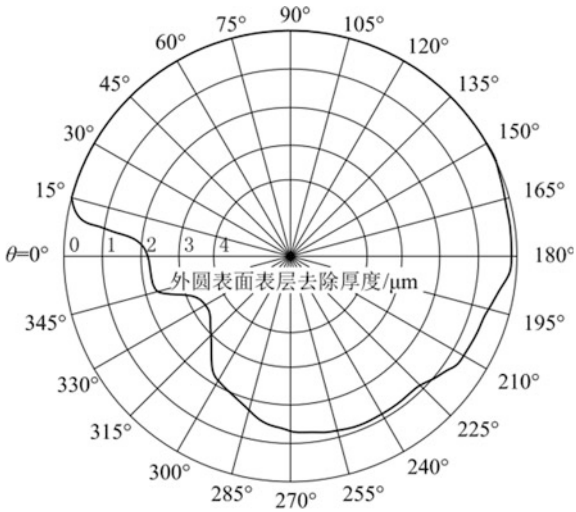


Fig. 2.51 Thickness distribution curves of cylindrical surface material removal, as the spindle is fixed

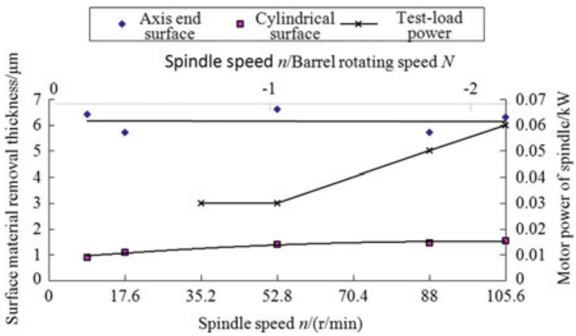


Fig. 2.52 Variation curves of surface material removal in thickness versus n and $|n/N|$, as the revolving speed of a barrel is fixed

consistency, the rotation direction of the roller needs to be adjusted periodically during the whole processing. Furthermore, the revolving speed of the roller must be selected as high as possible in design under the consideration of the equipment ultimate reliability.

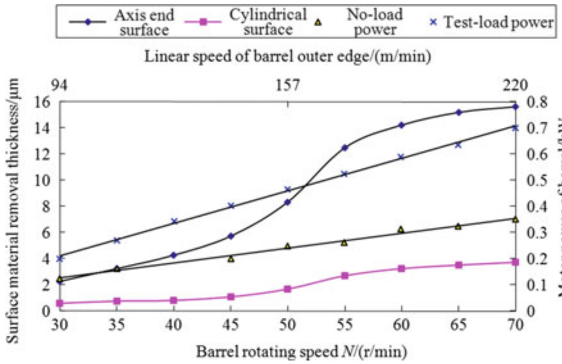


Fig. 2.53 Variation curves of surface material removal in thickness versus *N*, as the spindle speed is fixed

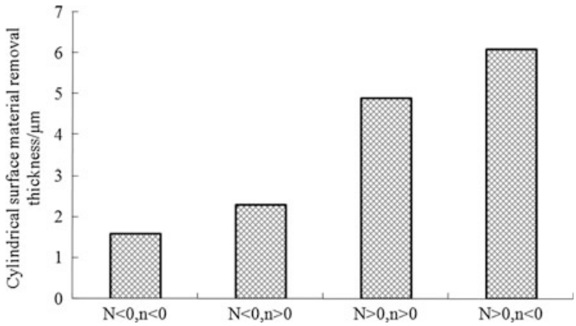


Fig. 2.54 Effect of the roller and spindle rotation direction on the thickness of cylindrical surface material removal

Figure 2.54 shows effect of the roller and the spindle rotation direction on the thickness of cylindrical surface material removal under conditions of $\alpha = 25°$, $\beta = 45°$, $|N| = 50$ r/min, $|n| = 88$ r/min, $S = 490$ mm, $L = 485$ mm, $h = 230$ mm, and the time is 50 min. As shown in Fig. 2.54, the thickness of surface material removal of counterclockwise rotary of the barrel ($N > 0$) is significantly greater than that of clockwise rotary ($N < 0$). This is mainly stems from spindle inclination. When $N > 0$, the flow direction of the solid medium impacting the sample cylindrical surface moves toward the bottom of the barrel. Owing to the fact that the bottom of the barrel is filled with solid medium, the momentum of effective solid medium mainly consumed in removal of metal sample surface. When $N < 0$, the flow direction of the solid medium impacting the sample cylindrical surface moves toward the top of the barrel. On account to the top of the barrel being a blank space, some of the momentum of the effective solid medium may have been released, and then the remaining momentum is used to remove the metal material. When the rotation direction of the barrel is fixed, contrary to that of the spindle, the thickness of surface material removal is slightly greater than both of the same rotation directions. It is the result of the different cutting speed of a solid medium on sample. For example, when the rotation direction of the barrel is contrary to the spindle, the entire linear velocity of the solid medium on the outside of a sample is much larger and vice versa.

Therefore, from Figs. 2.53 and 2.54, it is entirely possible that the average thickness of cylindrical and an axial end surface material removal can keep a good variation consistency, by adjusting the rotation direction of the barrel and spindle periodically.

2. Geometrical parameters of equipment

Figure 2.55 shows the effect of the spindle deflection angle α on the thickness of sample surface material removal under conditions of $\beta = 60°$, $N = -50$ r/min, $n = 88$ r/min, $S = 490$ mm, $L = 485$ mm, $h = 230$ mm, and the time is 30 min.

In Fig. 2.55, in view of the thickness of sample axial end surface material removal, compared with the calculation results of $\alpha = 0$, the result of $\alpha \neq 0$ is much better. This is mainly influenced by the cutting angle. However, for a cylindrical surface, the results of the thickness of material removal of $\alpha \neq 0$ are slightly inferior to that of $\alpha = 0$. This situation is also caused by the cutting angle.

Figure 2.56 shows the effect of the spindle oscillating angle β on the thickness of sample surface material removal under conditions of $\alpha = 25°$, $N = -50$ r/min, $n = 88$ r/min, $S = 490$ mm, $L = 485$ mm, $h = 230$ mm, and the time is 30 min.

From Fig. 2.56, it can be seen that for an axial end surface, the results of the thickness of material removal of $\beta \neq 90°$ are obviously less than that of $\beta = 90°$. This is to say, due to the existing cutting angle, the effect of the intersection vertical spindle barrel finishing is superior to the parallel vertical spindle barrel finishing.

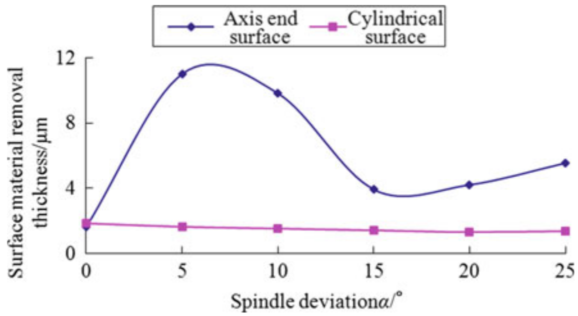


Fig. 2.55 Effect of the spindle deflection angle α on the thickness of sample surface material removal

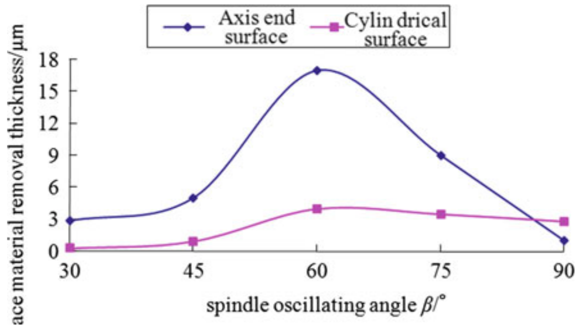


Fig. 2.56 Effect of the spindle oscillating angle β on the thickness of sample surface material removal

For a cylindrical surface, the difference of the results of the thickness of material removal of $\beta \neq 90°$ and $\beta = 90°$ is not clear, but the situation of $\beta = 60°$ is much better than $\beta = 90°$.

The results of theoretical and experiment results demonstrate that by increasing the effective radius of the roller during processing, the thickness of material removal of the axial end surface of the parallel vertical spindle and the axial end and cylindrical surface of the intersection vertical spindle can increase. Thus, when the structure size of a barrel is fixed during finishing, for improving the cutting velocity effectively, the distance between the sample position and the center of the barrel needs to be as far as possible. Furthermore, in the process of special equipment design, the diameter of the barrel should be taken into account big enough.

In view to the improvement of the applied force of the barrel finishing or enhancing the momentum of the effective solid medium, the results show that as the effective thickness of the barrel is increased, the cylindrical surface of the parallel vertical spindle and the axial end surface of the intermeshing vertical spindle can increase. Thus, in the equipment design, the effective thickness of the barrel, which is the height of the loaded solid medium, should also be considered. This can cause the thickness non-uniformity of workpiece material removal along the surface of the principal axis. As a result, this method is just fit for shaft parts or short axis. For processing precision long axis, the method of the horizontal spindle barrel finishing or adjusting turning processing of the vertical spindle barrel finishing again can be used.

3. Technological parameters

Figure 2.57 shows the effect of time on the thickness of sample surface material removal and surface roughness under conditions of $\alpha = 25°$, $\beta = 45°$, $N = -50$ r/min, $n = 88$ r/min, $S = 390$ mm, $L = 630$ mm, and $h = 230$ mm.

Experimental results show the continuation of processing after working for 15 min, and the value of surface roughness Ra has changed a little, whatever for the cylindrical or the axial end surface material of the sample. That means the value of

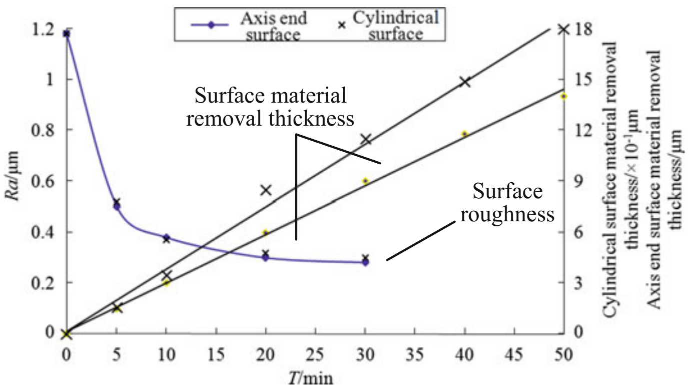


Fig. 2.57 Effect of time on the thickness of sample surface material removal and surface roughness

surface roughness *Ra* can tend to be stable after processing at a certain time T_j, when employing specific barrel medium. At this point, the value *Ra* can be referred to as the limit surface roughness under certain conditions. As processing time increases, thickness of the sample surface material removal is increased steadily. In addition, as shown in Fig. 2.57, compared to the cylindrical surface, the thickness of sample surface material removal of the axial end surface has greater differences. In order to solve this problem, some solutions such as adjusting the values of α, β, or transforming the rotating direction of the barrel and spindle by the automatic cycle can be used [49].

Moreover, the time has large influence on the surface topography, physical, and mechanical properties of the workpiece. The surface topography of the sample before and after the barrel finishing is presented using scanning electron microscope KYKY1000B, as shown in Fig. 2.58. From Fig. 2.58, before barrel finishing, the ups and downs change of the material surface can be found and material surface texture can be identified clearly. However, after the barrel finishing, the material surface topography can be refined, which illustrates that the barrel finishing can refine the surface topography and improve the surface integrity of materials.

The side of the sample (i.e., the sample section) was firstly polished metallographically and then corroded with nitric acid of 4%. The surface thickness of the denatured layer of the sample was recorded using scanning electron microscope (see Table 2.13), and further the denatured layer was observed which is described

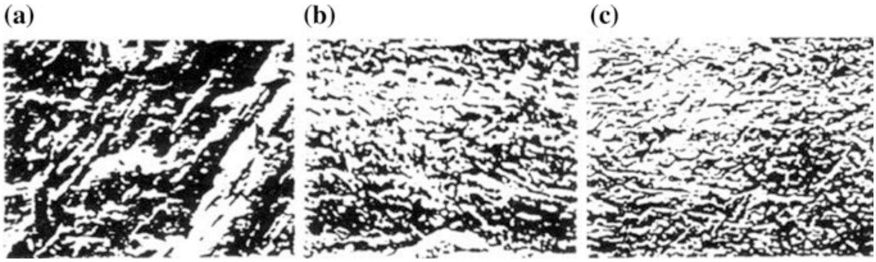


Fig. 2.58 Surface topography of the sample HT before and after the barrel finishing (200×). **a** Before finishing (traditional grinding); **b** barrel finishing for 15 min (cylindrical surface); **c** barrel finishing for 15 min (axial end surface)

Table 2.13 Observation data of denatured surface layer thickness

Specimen material	Finishing time/min	Denatured surface layer thickness of specimen with axis end surface/μm	Denatured surface layer thickness of specimen with cylindrical surface/μm
Q235	0	<5	<5
	15	42	24
	45	56	66
	Over 5 h	26	30
HT	0	<5	<5
	15	34	26

in Fig. 2.59. Experimental results show the barrel applied force of the flow medium on the workpiece during the barrel finishing can make the material surface enact plastic deformation and then form the structural skin layer (denatured layer). In the process of formation of the denatured layer, it must be accompanied by lattice movement, dislocation, and compression of metal crystal, which has an important value for improving the abrasive resistance, the corrosion resistance, and the fatigue strength.

The surface micro-hardness of the sample before and after barrel finishing is observed using a micro-hardness tester HVS-1000. The results indicate that the micro-hardness of the sample is increased by 8–15 HV on average.

The values of surface residual stress of the sample before and after barrel finishing can be obtained using X-ray stress measurement method (see Table 2.14). The results show improvement of surface residual stress of the sample, corresponding to the time when other conditions are invariable. At time of 15 min in finishing, the surface residual stress of the sample is obviously increased, and the increment value can reach −300 MPa. At time of finishing 45 min, the surface

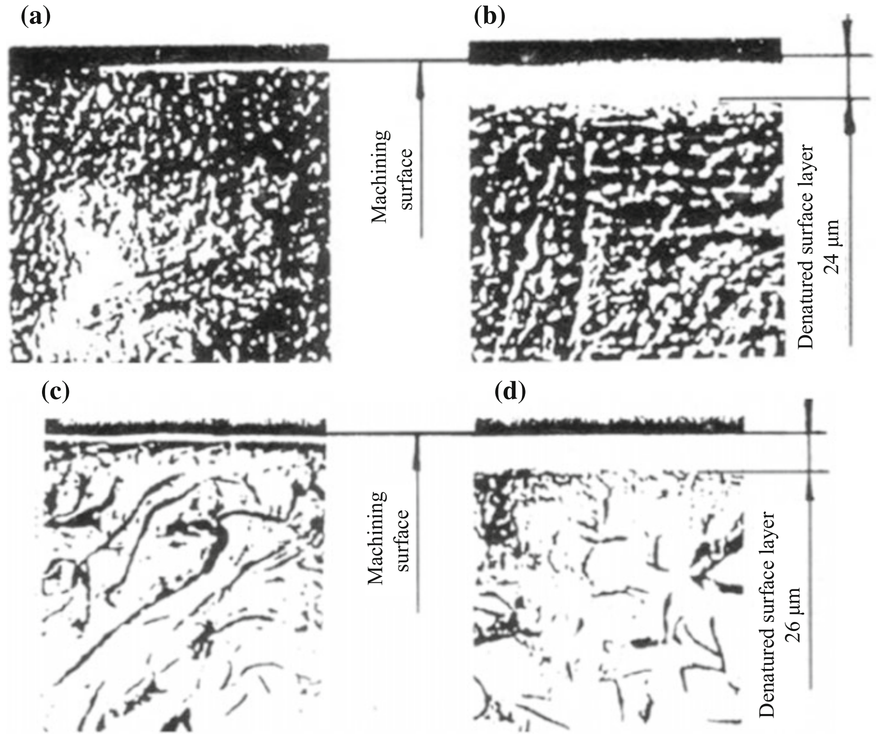


Fig. 2.59 Denatured surface layer of workpiece before and after barrel finishing (200×). **a** Before finishing (Q235 common grinding); **b** finishing 15 min (Q235 excircle surface); **c** before finishing (HT common grinding); **d** finishing 15 min (HT excircle surface)

Table 2.14 Observation data of the surface residual stress under different conditions

Processing condition of specimen	Surface stress measurements of specimen cylindrical surface/MPa	Surface stress measurements of specimen axis end surface/MPa
Before finishing (common grinding)	–	−52
Finishing 15 min	−304	−349
Finishing 45 min	−386	−424
Finishing over 5 h	−326	−376

residual stress of the sample can still increase, but the increment value is smaller. When the time is longer than 5 h, the surface residual stress of the sample begins to decrease. This is caused by serious wear of the sample surface in barrel finishing with long life. The degree of wear of the sample can be confirmed by the measurement date of the surface thickness of the denatured layer [50].

2.6.3 Equipment Types and Design

1. Equipment types and structure

According to whether the barrel is fixed or not, the vertical spindle barrel finishing equipment can be divided into rotary barrel type and fixed barrel type; according to the position of the spindle axis, it can be divided into parallel spindle type, crossed spindle type, and intermeshing spindle type.

Figure 2.60 shows the general structural schematic diagram of the parallel spindle barrel finishing equipment, which consists primarily of the spindle reducer-rotary assembly, the slider, the vertical base, the base, the barrel reducer-rotary assembly, the barrel, the work-holding assembly, and et al. There are multiple spindles which can do positive or counter revolution movement to spindle box 1. The spindle box is fixed on slider 2, and the slider is installed on framework 3 along the guide rail for reciprocating motion. Turntable 7 is installed on base 5. Barrel 9 is fixed on the turntable and does the positive or counterrevolution movement with the turntable. Holding device 4 connects into the spindle.

Figure 2.61 shows the general structural schematic diagram of the intermeshing spindle barrel finishing equipment, which consists primarily of the base, the vertical base, the spindle deflection angle adjusting assembly, the spindle shifting assembly, the spindle reducer-rotary assembly, the spindle swing angle adjusting assembly, the work-holding assembly, the barrel, the barrel reducer-rotary assembly. Its most distinctive feature is that the spindle is three-dimensional adjustable structure. That is to say, the rotation axis of the spindle and the rotation axis of the vertical barrel can be adjusted to three states: parallel, crossing, and intersection for suiting different workpieces and different processing requirements.

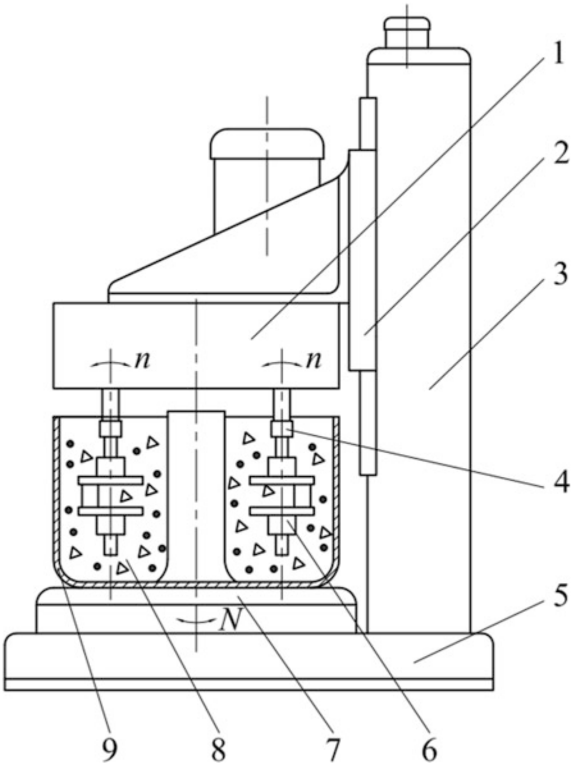


Fig. 2.60 General structural schematic diagram of parallel spindle barrel finishing equipment. 1—Spindle reducer-rotary assembly; 2—slider; 3—vertical base; 4—work-holding assembly; 5—base; 6—workpiece; 7—barrel reducer-rotary assembly; 8—processing medium; 9—barrel

In addition to the essential functions (main functions) of realizing workpiece processing, the above two equipments should have the following functions:

(1) Processing safety and reliability considered, the barrel does the high-speed rotating in processing, and the safety protection devices are needed. The structure of the safety protection device can be fixed and remain active.
(2) Improving machining efficiency considered, pneumatic or hydraulic control work-holding assembly, increasing the number of the spindle, and other measures can be adopted.
(3) Ensuring the processing quality should be considered, and liquid medium (grinding compound and water) as processing medium can automatically recycle throughout the progressive processing. The filter is set in the re-circulating device, and this can efficiently reduce the impact of the processing impurities in the processing quality. When setting the liquid medium to re-circulate the device, the feature of the liquid medium movement with the rotating barrel should be considered fully for good match between the liquid medium re-circulating device and the barrel.

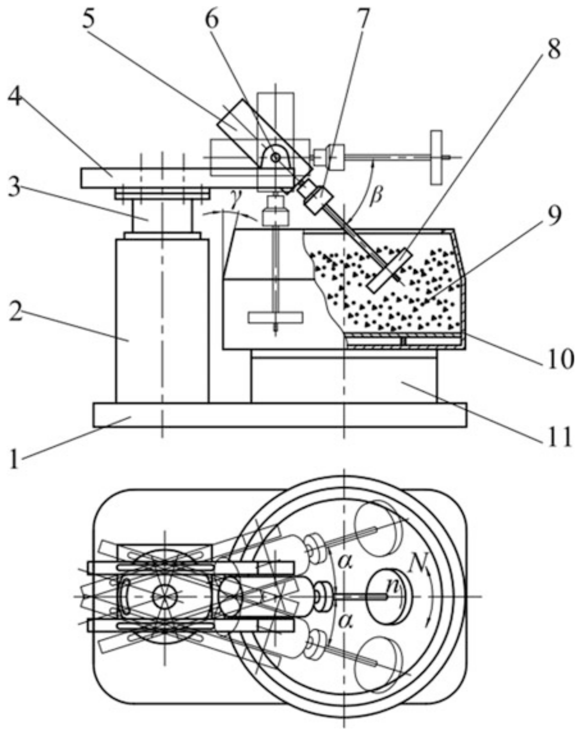


Fig. 2.61 General structural schematic diagram of intermeshing spindle barrel finishing equipment.
1—Base; 2—vertical base; 3—spindle deflection angle α adjusting assembly; 4—spindle shifting assembly; 5—spindle reducer-rotary assembly; 6—spindle swing angle β adjusting assembly; 7—work-holding assembly; 8—workpiece; 9—processing medium; 10—barrel; 11—barrel reducer-rotary assembly

(4) Improving processing adaptability should be considered; the rotating speed adjustments of the spindle and the barrel are quite necessary. This can be realized through method that sets frequency conversion speed regulator.

2. Equipment design

(1) Design of barrel

The design of the barrel bases is the simplest of mechanical principle. When the abrasives are rotating in the barrel, certain centrifugal force can generate due to the presence of the abrasives own quality. The abrasives group can generate discrete flow away from the rotating axis under the action of the centrifugal force. The abrasives group can self-climb along the barrel wall during the flow as a result of the restrictions imposed by the limited barrel wall. The number of the abrasives at the center position of the barrel reduces accordingly, and then one revolution paraboloid that exists a minimum value forms on the abrasives-boundary. In case of the packed weight of the abrasives limited, as the rotating speed of the barrel is improving, the minimum value of the revolution paraboloid on the abrasives-boundary becomes smaller. Limited by the height dimensions of the barrel, the degree of the abrasives group self-climbing along the barrel wall will become more intense, which even results the abnormal circumstances that the abrasives are thrown out. Even if the abnormal phenomenon does not occur, the circumstance that the abrasive splashes can occur during the processing. Given the above analysis, the vertical structural barrel that is used during parallel spindle barrel finishing must have a certain height. During intermeshing spindle barrel finishing, the whole structure of the barrel can be designed into two parts: The lower part is designed into regular twelve-prime structure; the upper part is designed into upper reentrant regular twelve-prismatic table structure. As a result, the lower part has a larger rotating radius in favor of workpiece processing for ensuring productivity; the upper reentrant form of the upper part can efficiently reduce the climbing and splash of the abrasives group during processing.

The whole structure of the barrel often adopts welded steel plate. There should be a certain thickness of polyurethane or vulcanized rubber anti-corrosive coating on the barrel inner wall. This can not only avoid the corrosion of the bottom and the wall of the barrel, but also increase the friction property between the barrel and the abrasives as appropriate for the purpose of the effective rotating of the abrasives in the barrel.

The result that the abrasives process of the workpiece must make a part of metal particle and burrs on the workpiece surface comes off during barrel finishing. Meanwhile, there are also some tiny abrasive falling off the surface of the abrasives. These metal micro-powders, burrs, and abrasive particles are mixed in the barreling medium during sustaining processing, and even some can adhere to the surface of the abrasives. This can affect not only the processing efficiency, but also the processing quality. In order to reduce or eliminate the influence of these micro-contaminant, a partition with one groove about 1 mm wide is added on the bottom of the barrel. One depositing chamber is formed between the partition and the bottom of the barrel. There are two symmetrical sewage outlets on the wall of the depositing chamber for easy periodic cleaning. Otherwise, dewatering equipment can be designed on the wall or at the bottom of the depositing chamber because of the cleaning of the abrasives and the replacement problem of the liquid medium during sustaining processing.

(2) Design of barrel reducer-rotary assembly

The barrel reducer-rotary assembly serves two functions: One is to ensure the implementation of the barrel rotating speed; the other is to guarantee the stationary of the barrel motion process with large diameter.

The effective working linear velocity of the barrel is typically in 80–280 m/min. under the condition to maintain the rotating speed of the barrel. The adoptive transmission route is as follows: electromotor—belt driving—cylindrical worm-driven reducer—rotary table (barrel). In order to guarantee the stationarity of the barrel rotating motion, the major diameter rotary table should be connected to the output end of the cylindrical worm-driven reducer, and the lower end surface of the rotary table should be supported on the hoop-type guide rails of the rotary table base.

(3) Design of finishing automatic cycle process

The technological process of the vertical spindle barrel finishing is shown in Fig. 2.62. Whereby, special attention should be paid to the determination and the transformation of the spindle rotating direction (n) and the barrel rotating direction (N) during barrel finishing. For the ordinary uniform workpiece with cylindrical surface, no matter what directions n and N take, the full surface finishing of the workpiece can achieve. Based on the theoretical analysis and the experimental study, the situation of $n/N < 0$ is better than the situation of $n/N > 0$; for the workpiece with non-uniform cylindrical surface such as gear and cam, the direction of the spindle rotating (n) must be changed during finishing in order to ensure that the full surface of the workpiece can be processed; furthermore, the continuous uniform processability of the finished surface considered, the automatic circulation process of the spindle rotating (n) and the barrel rotating (N) is adopted. And

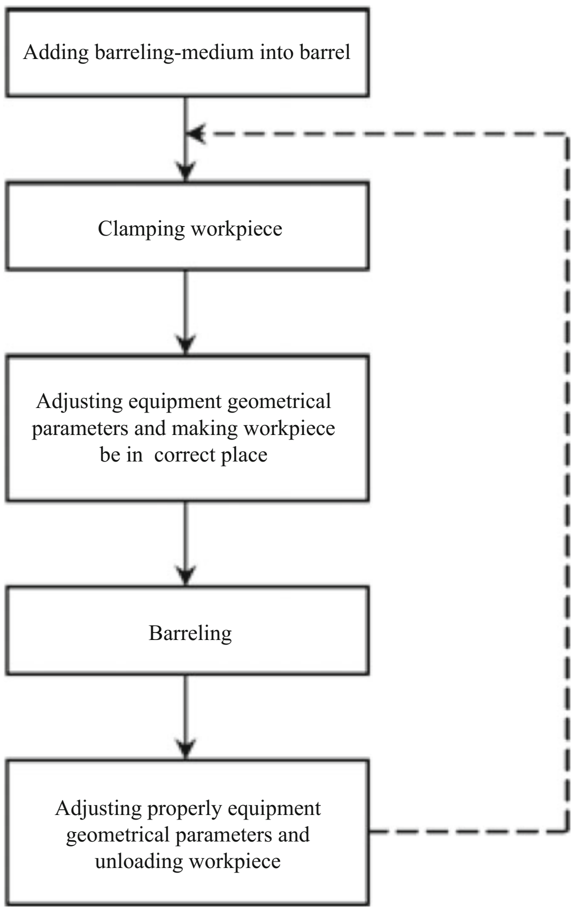


Fig. 2.62 Technological process of vertical spindle barrel finishing

$$(N, -n, t) \Leftrightarrow (0, 0, \Delta t) \Leftrightarrow (-N, n, t)$$
$$\text{or } (N, n, t) \Leftrightarrow (0, 0, \Delta t) \Leftrightarrow (-N, -n, t)$$

In the above circulation process, t is the circulating half period, usually 1–2 min, and Δt is controlled by electrical appliance, usually 5–7 s.

(4) Equipment shape

Figures 2.63 and 2.64 show the photographs of the parallel spindle and the intermeshing spindle barrel finishing equipment which are produced by Langfang Beifang Tianyu Mechanical and Electrical Technology Co., Ltd.

2.7 Horizontal Spindle Barrel Finishing

2.7.1 Finishing Principle and Characteristics

Fig. 2.63 Photograph of parallel spindle barrel finishing equipment

Fig. 2.64 Photograph of intermeshing spindle barrel finishing equipment

1. Finishing principle

Based on design request, crankshafts should have good machining precision, and its surface quality and integrality are also important. At present, crankshafts are finished mostly by abrasive cloth and manual steel brush, which is not ideal on finishing quality, efficiency, and cost, and especially cleanness degree does not meet design and using request. Therefore, a new process, horizontal spindle barrel finishing, is developed.

Figure 2.65 shows the principle diagram of horizontal spindle barrel finishing. Parts like crankshaft rotate round their axes of main journal in opposite direction. Reciprocating motion of the container (slot barrel), which is the loaded machining medium (abrasive blocks, compounds, water included), is driven by crank and slider mechanism. With rotary motion and reciprocating motion, the abrasive blocks have the action of colliding, extruding, and the micro-grinding (scraping and scoring) against the crankshaft surface. Consequently, it has effects of finishing crankshafts, increasing surface quality, and improving the physical–mechanical properties [51, 52].

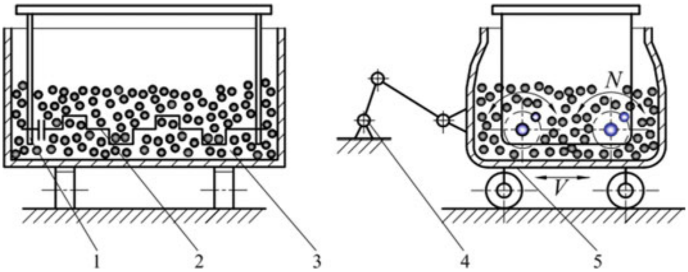


Fig. 2.65 Principle diagram of horizontal spindle barrel finishing. 1—Gearing; 2—crankshaft; 3—machining medium; 4—driven mechanism; 5—slot barrel

The acting force is necessary to achieve horizontal barrel finishing. But, under certain circumstances of the machining medium, the impact of the acting force mainly depends on the complex motion condition between the abrasive blocks and the workpiece surface.

2. Motion analysis

According to the characteristic and request of relative motion invariability, model diagram of motion analysis for arbitrary point M of connecting rod journal surface is set up, as shown in Fig. 2.66, where O is the rotary center of crankshaft (main journal), O_1 is the center of connecting rod journal, l is the distance between the center of main journal and connecting rod journal, r is radius of connecting rod journal, n is rotational speed of crankshaft, S and f are the reciprocating amplitude and frequency.

In the course of finishing ($\theta = 2\pi nt$), the velocity component of the abrasive block to the arbitrary point M ($\theta_1 \in [0, 2\pi]$) on the connecting rod journal is

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} 2\pi n(l \sin\theta + r\sin(\theta + \theta_1)) \pm v_1 \\ 2\pi n(l\cos\theta + r\cos(\theta + \theta_1)) \end{bmatrix} \tag{2.67}$$

where

$$v_1 = 2Sf \tag{2.68}$$

According to the equation of velocity composition, composite velocity v can be obtained [53].

Under certain circumstances of the machining medium, finishing effects of horizontal spindle barrel finishing have relations with composite velocity v. From Eq. 2.67, influencing factors on composite velocity include n, S, f, r, l, θ_1. Their specific impacts are analyzed through the MATLAB software as follows.

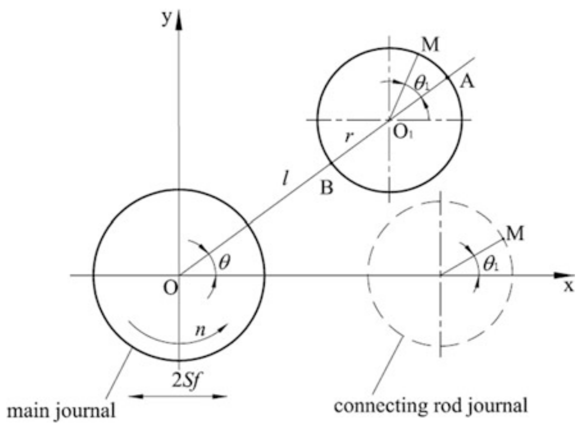


Fig. 2.66 Motion analysis diagram of connecting rod journal surface

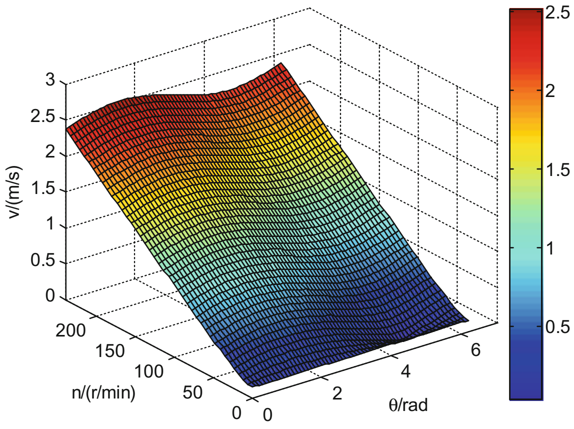


Fig. 2.67 Effect curve of composite velocity with different rotational speeds

(1) Effects of different rotational speed n. Under the conditions of $r = 0.0345$ m, $l = 0.06$ m, $\theta_1 = 0°$, $S = 0.08$ m, $f = 60$ times/min, $n = 108$ r/min, Fig. 2.67 shows effect curve of composite velocity with different rotational speeds. With the increase of n, v increases, so they are helpful to improve efficiency.
(2) Effect of different reciprocating amplitudes S and frequencies f. Under $n = 108$ r/min and other same conditions, Fig. 2.68 shows effect curves of composite velocity with different reciprocating amplitudes and frequencies. With the increase of S and f, v increases, so they are helpful to improve efficiency. S and f have similar rule to v. In view to improve efficiency, it should increase S or f. But large S leads to large equipment dimension, and the lateral size of the container increases at least by $2(S_2 - S_1)$.

Additionally, too large f would form instantaneous empty field between the crankshaft and particles according to the barrel finishing mechanism, so finishing effect is not ideal. This phenomenon is simulated by Fluent software. Boundary conditions are the velocity inlet of particles with 0.2 m/s and outflow outlet.

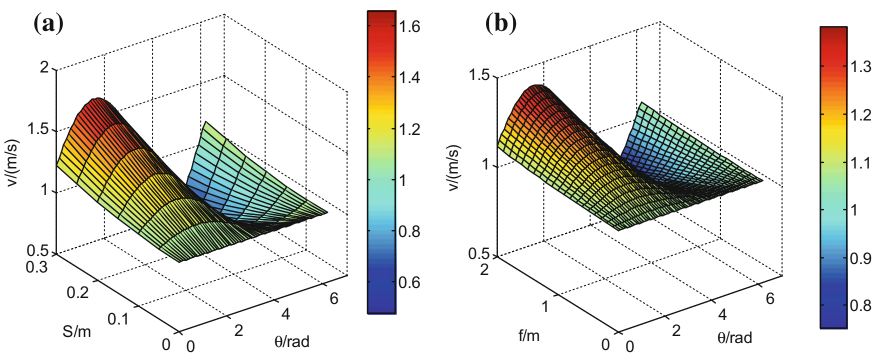


Fig. 2.68 Effect curves of composite velocity with different reciprocating amplitude and frequency. **a** S; **b** f

Crankshaft surface is wall surface condition, and its angular velocity is 11.3 rad/s. The k-ε model is adopted. SIMPLE arithmetic is selected, which can directly compute velocity and pressure field. Simulation results with different reciprocating frequency f are shown in Fig. 2.69. Under constant rotational speed, the crankshaft surface is basically surrounded by abrasive blocks as low reciprocating frequency (such as 50 times/min), and abrasive blocks are driven to rotate a certain scope by crankshaft rotation, which is main proportion to reciprocating motion. With the increase of reciprocating frequency, the velocity of abrasive blocks increases, which leads to untimely surrounded crankshaft, and forms instantaneous empty field. At the same time, the degree and abrasive blocks are driven to rotate, which are relatively weakened, thus affecting finishing effects and efficiency. Therefore, it is proper for the main journal to improve the finishing effect and efficiency by selecting large rotational speed.

(3) Effect of different distance between the center of main journal and connecting rod journal l and radius of connecting rod journal r. Under the other same conditions, Fig. 2.70 shows effect curves of composite velocity with different l and r. With the increase of l or r, v increases. For the specific crankshaft finishing, the structure size is fixed. But there is different productivity for the crankshaft with different size (i.e., different crankshaft should use different processing time).

3. Finishing uniformity analysis

Finishing uniformity is the consistency of processing results on different positions of the part surface. Under conditions of $r = 0.0345$ m, $l = 0.06$ m, $\theta_1 = 0°$, $S = 0.08$ m, $f = 60$ times/min, $n = 108$ r/min, composite velocity curves of all positions on connecting rod journal surface with one rotation cycle are plotted, as

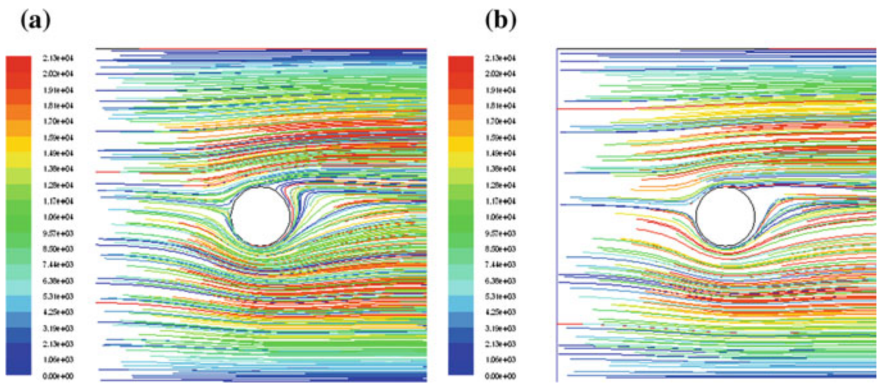


Fig. 2.69 Simulation results with different reciprocating frequency. **a** 50 times/min; **b** 62.6 times/min

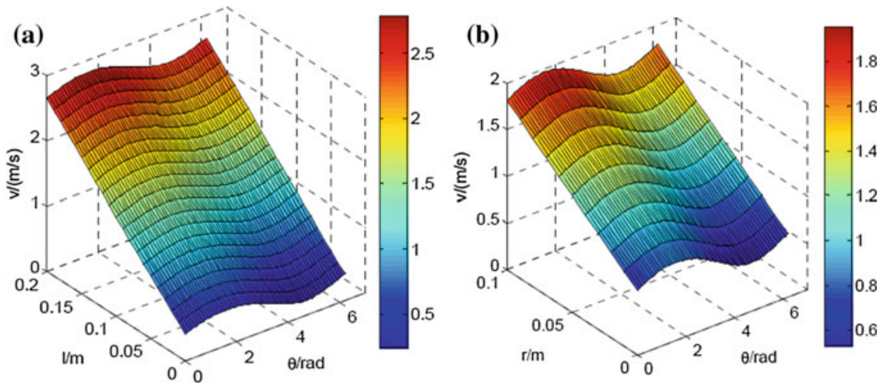


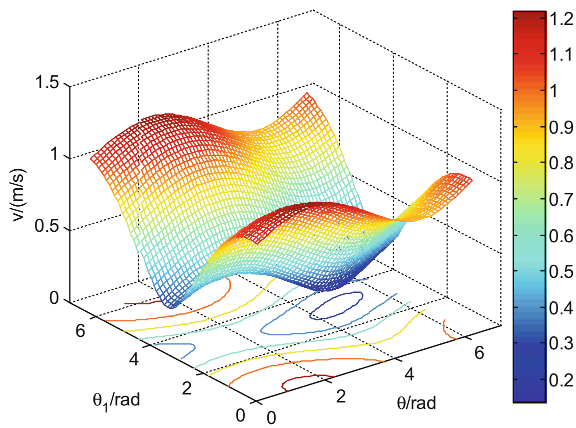
Fig. 2.70 Effect curves of composite velocity with different distance between the center of main journal and connecting rod journal and radius of connecting rod journal. **a** *l*; **b** *r*

shown in Fig. 2.71. The velocity of different points on connecting rod journal surface is changeable. When θ_1 varies from 0 to π, v decreases from the maximum value to minimum value. Similarly, v increases from the minimum value to the maximum value as θ_1 varies from π to 2π. Moreover, finishing depth is also different which leads to different acting force, so that the surface of connecting rod journal is not uniform.

When the distance between the center of main journal and connecting rod journal l is zero, the part is not an eccentric shaft. According to Eq. (2.67), the composite velocity of the abrasive block to the arbitrary point M ($\theta_1 \in [0, 2\pi]$) is

$$v = ((2\pi nr)^2 \pm 2\pi nrv_1 \sin\theta_1 + v_1^2)^{1/2} \tag{2.69}$$

Fig. 2.71 Effect curve of finishing uniformity with different point of connecting rod journal



In the course of finishing ($\theta_1 = 2\pi nt$), the velocity and the processing state are consistent to the different positions of the surface, and only the phase changes, leading to the uniform of the finishing effect. Therefore, the finishing uniformity is for eccentric shaft parts (such as crankshaft, camshaft). For the crankshaft, finishing effect of main journal is basically uniform, and finishing uniformity is mainly aimed at the connecting rod journal.

The composite velocity of different points on the part surface is analyzed as below. According to Fig. 2.66, two most representative points are selected for simplifying analysis that is outside Point A ($\theta_1 = 0°$) and inside Point B ($\theta_1 = 180°$) on connecting rod journal surface.

(1) Finishing uniformity effect with influencing factors

Effect rules of composite velocity v on Point A and Point B with different n are shown in Fig. 2.72. When n is zero (crankshaft does not rotate), v is equivalent of all points to the connecting rod journal surface. With the increase of n, their difference is gradually increasing. Therefore, n should be smaller to improve the uniformity.

Effect rules of composite velocity v on Point A and Point B with different S and f are shown in Fig. 2.73. It is shown that v has same rules of all points to the connecting rod journal surface with different S and f, which shows that large S and f would have good uniformity and efficiency. As shown in Fig. 2.73, velocity difference between Point A and Point B is mainly caused by certain rotational speed.

Effect rules of composite velocity v on Point A and Point B with different l and r are shown in Fig. 2.74. Figure 2.75 shows the effect relationship with different l and r as θ is 0°. Because parameters setting of curve drawing is $l = 0.06$ m and $r = 0.0345$ m, v deceases as l and r increase to 0.06 m and 0.0345 m. Generally, the difference of v, of all points to connecting rod journal surface, is gradually increasing as the l and r *increase* and has the same changing trend. But when l and

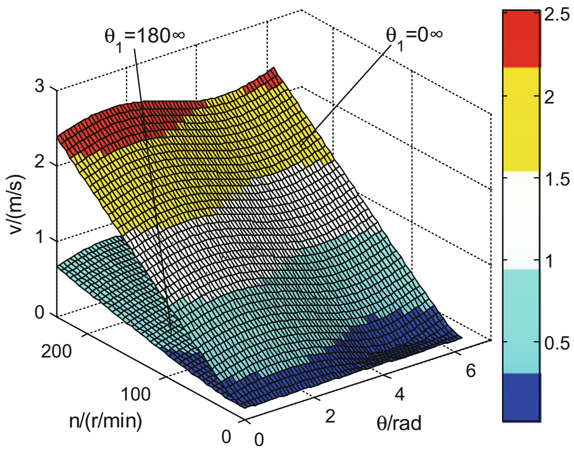


Fig. 2.72 Effect curves of finishing uniformity with different n

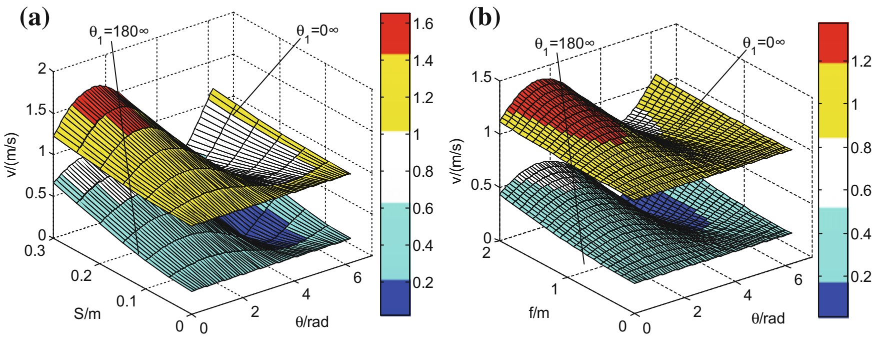


Fig. 2.73 Effect curves of finishing uniformity with different *S* and *f*. **a** *S*; **b** *f*

r are relatively large, the proportion of the rotary motion is increased in the same reciprocating motion, that is,

$$\frac{v - v_1}{v} = 1 - \frac{v_1}{v} \tag{2.70}$$

Therefore, the velocity difference on different points is more significant, and this indicates that finishing uniformity is more important to crankshafts with larger size.

(2) Solving methods

According to the above analysis of the finishing uniformity of the connecting rod journal surface, the different rotating speed, the reciprocating amplitude and frequency, and the crankshaft size will affect finishing uniformity.

For improving uniformity, the composite velocity v of arbitrary point of the connecting rod surface is expected to equality. If the velocity is equal, v can be derived from Eq. (2.67).

$$v = 2Sf \tag{2.71}$$

Equation (2.71) means that n is zero (the workpiece does not rotate), or r is zero (changing into a point), or l is zero (the workpiece is non-eccentric).

For crankshaft, both r and l cannot be zero. From Figs. 2.74 and 2.75, it is known that the uniformity is good as r and l are small. When r and l are relatively larger, the velocity difference of different positions on the connecting rod journal is caused, which leads to the poor finishing uniformity. That is to say, for the small-sized crankshaft, the uniformity of points on the connecting rod journal surface is relatively good, and the key is how to improve the finishing uniformity of large- or medium-sized crankshaft.

If the velocity is equal, n must be zero. But the processing position of connecting rod journal surface is not changeable, and the cutting angle of different points is different, so the finishing effect and uniformity are obviously bad. At this time, we can use the reciprocating motion of the barrel as the main movement, and the

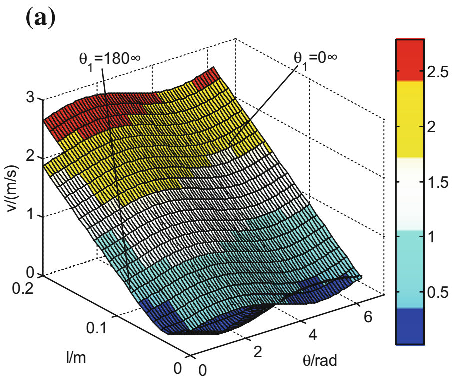


Fig. 2.74 Effect curves of finishing uniformity with different *l* and *r*. **a** *l* ($r = 0.0345$ m); **b** *r* ($l = 0.06$ m)

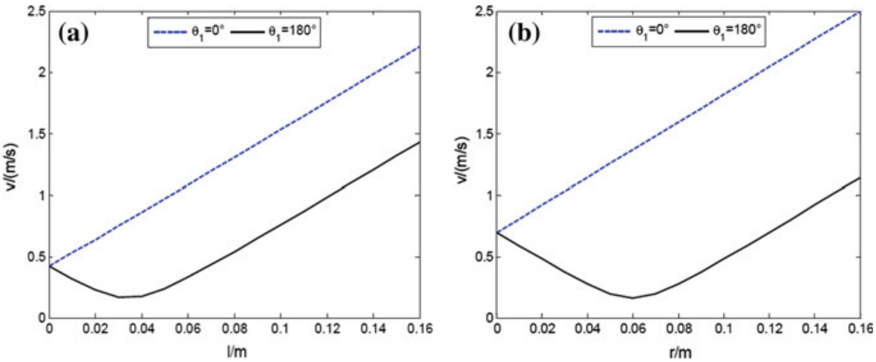


Fig. 2.75 Effect curves of finishing uniformity with different *l* and *r* as θ is 0°. **a** *l* ($r = 0.0345$ m); **b** *r* ($l = 0.06$ m)

periodic intermittent rotary motion of the crankshaft as the feed movement, to reach the goal of finishing uniformity.

According to above analysis, finishing effect of the eccentric shaft cannot be absolutely consistent by this process. But differences can be minimized to meet used requirements and customer needs. The concrete analysis is done as follows.

When the connecting rod journal is located at underside, their equations of composite velocity on Point A and Point B are

$$v_A = -2\pi n(l + r) \pm 2Sf, \ v_B = -2\pi n(l - r) \pm 2Sf \tag{2.72}$$

For definite crankshaft, its size is unchangeable (e.g., $l = 105$ mm, $r = 65$ mm). From Eq. (2.72), under different motion parameters, composite velocities and the sum of their absolute values on Point A and Point B can be computed in a period of reciprocating motion with the same direction of rotation motion, as shown in Table 2.15.

From Table 2.15, the absolute value of the sum of the composite velocity may be equal by choosing suitable parameters. From Eq. (2.72), the condition of velocity equality is

$$-2\pi n(l + r) + 2Sf \geq 0 \tag{2.73}$$

That is,

$$Sf \geq \pi n(l + r) \tag{2.74}$$

So, relations of S, f, and n can be obtained.

Equation (2.73) or (2.74) is the analysis result when the connecting rod journal is located at underside. In the scope of θ in [0, 2π], Sf should be π/2 times with the rule of sine or cosine. In practice, S should be π/2 times, for high frequency is not reasonable. In addition, the value of f/n may as well be decimal fraction, and this is conducive to be similar for the processing state of different points in the statistical sense, which can improve finishing uniformity of connecting rod journal.

The above analysis shows that large rotational speed and certain reciprocating motion speed can be desirable for small-sized crankshaft to achieve the required processing effectiveness and processing efficiency. For medium or large-sized crankshaft, larger reciprocating motion amplitude, certain reciprocating motion frequency, and smaller rotary speed should be chosen to improve finishing uniformity. In a certain finishing depth, through the reasonable selection of motion parameters, surface finishing of the eccentric shafts can be achieved to meet used requirements and customer needs [11, 12].

Table 2.15 Composite velocities and their absolute value sum on point A and point B under the different motion parameters

Motion parameters				*V*/(mm/min)		Absolute value sum/(mm/min)
n/(r/min)	*f*/(times/min)	*S*/mm		+	−	
60	60	80	B	−5460	−24,660	30,120
			A	−54,480	−73,680	12,8160
5	60	80	B	8345	−10,855	19,200
			A	4260	−14,940	19,200
10	60	150	B	15,490	−20,510	36,000
			A	7320	−28,680	36,000
10	45	200	B	15,490	−20,510	36,000
			A	7320	−28,680	36,000
11	40	200	B	13,239	−18,761	32,000
			A	4252	−27,748	32,000

4. Functional characteristics and application scope

Horizontal spindle barrel finishing process is a new technology for the surface finishing problem of the eccentric shafts (including crankshaft, camshaft). By this process, surface roughness value decreases, burrs is removed, surface texture is more isotropic, micro-hardness increases, material ratio of the profile increases, and denatured layer forms. So, the process can improve the geometric, physical and mechanical features of the surface layer, increase the cleanliness of parts (meet requirements of the design and the usage), resulting in improved surface integrity of parts. The specific situations include:

(1) Due to decrease of the surface roughness value, increase of the micro-hardness, and formation of the compressive stress, the fatigue strength increases and the fracture rate reduces, which improves the service life of the parts.
(2) Because of burr removing, non-working surface processing, and the casting or forging residual sand removing, the cleanliness of the whole machine improves, and it is convenient for assembly.
(3) The initial running-in of parts is done while finishing, and this improves the used performance of the whole machine.
(4) After finishing, surface texture tends to be isotropic, and independent micro-pit in part surface is formed, which is conducive to the improvement of storage capacity. Thereby, when the machine starts, the surface wear reduces.
(5) The application of this technology can replace the original four steps for belt polishing, that is aging after shot peening, felt polishing, manual cleaning, and second manual cleaning, so as to reduce the process cost and improve the processing efficiency.

In addition, the labor intensity is reduced, and the production efficiency is improved, which is convenient for realizing mechanization and automation.

Horizontal spindle barrel finishing process is an effective method for eccentric shaft surface finishing and will have a positive impact on the internal combustion engine industry and related parts processing industry, with a wide range of social and economic benefits [54].

2.7.2 Main Factors Affecting Finishing Effects

In experiments, three measuring points are chosen on main journal surface, two points in the direction of 180° and another point with 90°; measuring positions on the connecting rod journal surface are the outside point, the inside point, and the point clockwise 90°. When measuring, the average value of each position, measuring three times, is taken as the surface roughness value to reduce the man-made error in the measurement.

Because the surface roughness of the workpiece is not consistent at different points, the influence of each parameter can be determined by the decrease rate of the surface roughness value.

$$\Delta Ra = \frac{Ra^1 - Ra^i}{Ra^1} \tag{2.75}$$

where ΔRa is the decrease rate of the surface roughness Ra, Ra^1 is the surface roughness Ra before finishing, and Ra^i is the surface roughness Ra as ith measurements.

1. Motion parameters

(1) Rotary motion parameter

Rotary motion parameter is a linear velocity of the part surface. For certain part, it is rotational speed. Under conditions of S = 0.08 m, f = 75 times/min, finishing depth is 240 mm, the shape of abrasive blocks is sphere Φ3 mm, the material is aluminum oxide, compound is LC-10, and decrease rate curves of the surface roughness value Ra on main journal surface, to different rotational speeds, are shown in Fig. 2.76. It shows that ΔRa reached a stable value in 16 min as the rotary speed is 108 r/min; but when the rotary speed is 54 r/min, ΔRa is still in a state of decline in 24 min; while the rotary speed is 0 r/min, the decline is slower and processing time is longer. This indicates that the decrease of the surface roughness value is more rapid as rotational speed increases, which indicates that the rotational speed can improve the finishing efficiency.

Figure 2.77 shows ΔRa curves on connecting rod journal surface with finishing time to different rotational speeds. When n is 54 r/min, ΔRa on the middle point is 16.7% in 4 min, while 9.4% when n is 108 r/min. This indicates that the velocity difference between outside point and inside point at 54 r/min is smaller than 108 r/min, so it is reasonable for improving finishing uniformity. Therefore, in order to improve the uniformity, n should be low; but too small rotational speed will decrease the finishing efficiency, which can be solved by selecting reciprocating motion parameters. In addition, the original surface roughness of the workpiece is

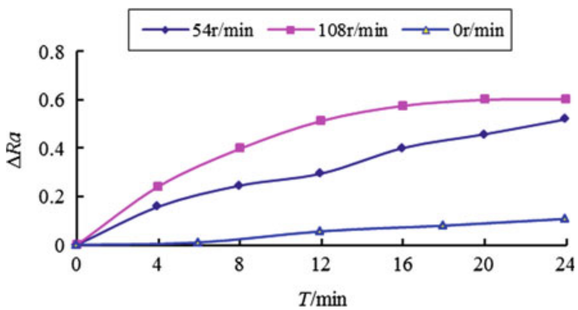


Fig. 2.76 ΔRa curves on main journal surface with finishing time to different rotational speeds

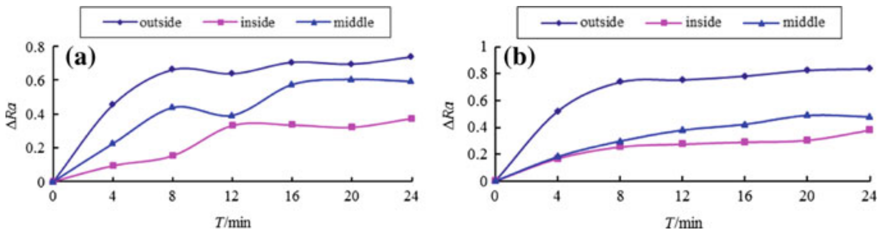


Fig. 2.77 Δ*Ra* curves on connecting rod journal surface with finishing time to different rotational speeds. **a** n = 108 r/min; **b** n = 54 r/min

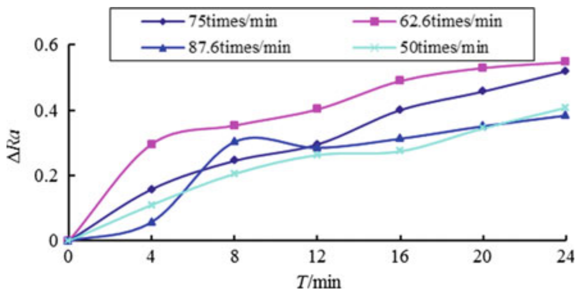
larger, better uniformity than the experimental results can be obtained in a certain finishing time when the original surface roughness value is small.

(2) Reciprocating frequency

Under n = 54 r/min and other same conditions, Δ*Ra* curves on main journal surface with finishing time to different reciprocating frequency are plotted, as shown in Fig. 2.78. With the increase of reciprocating frequency f, opportunities and amounts of collision, rolling, micro-grinding (sliding and scratching) are increased between abrasive blocks and the workpiece surface, the surface roughness value decreases faster, and the finishing efficiency is high at the same processing time. When the reciprocating frequency increased to a certain extent, mutual contact between abrasive blocks and the workpiece surface is not full due to the increment of empty area, and micro-grinding (scratching and scratching) function is not sufficient. Therefore, the decline of the surface roughness value slows down. In a word, there should be a better match between rotational speed and reciprocating frequency for improving the surface roughness.

When n is 108 r/min, Δ*Ra* curves on connecting rod journal surface with finishing time to different reciprocating frequency are shown in Fig. 2.79. Different frequency leads to different uniformity, and *Ra* with reciprocating frequency of 75 times/min is consistent than 62.6 times/min and 87.6 times/min, so the uniformity is good. The main reason is that different reciprocating frequencies lead to different medium flows, different function amounts of collision, rolling, grinding (slip and scratching), and different empty areas.

Fig. 2.78 Δ*Ra* curves on main journal surface with finishing time to different reciprocating frequency



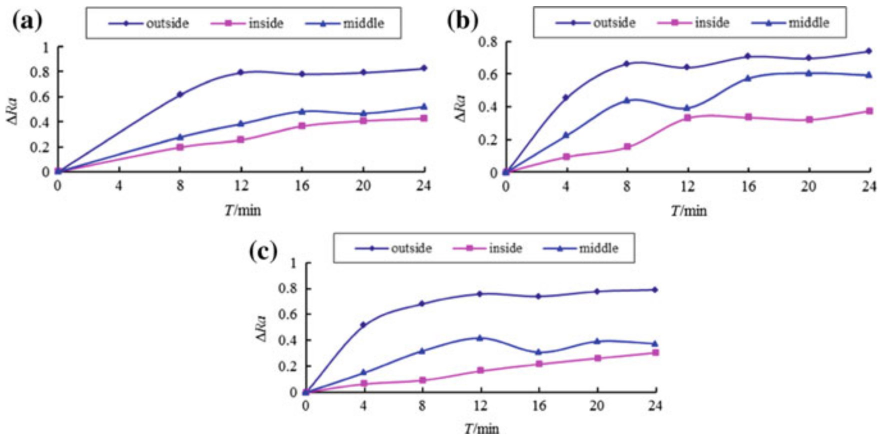


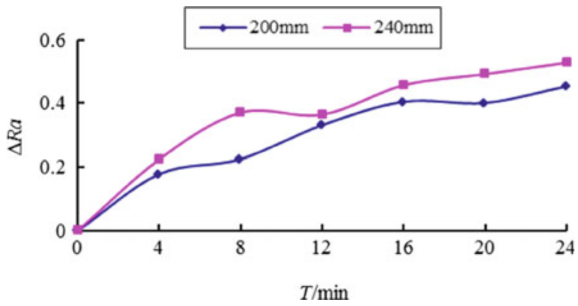
Fig. 2.79 Δ*Ra* curves on connecting rod journal surface with finishing time to different reciprocating frequency. **a** *f* = 62.6 times/min; **b** *f* = 75 times/min; **c** *f* = 87.6 times/min

(3) Reciprocating amplitude

Under conditions of W1600 equipment, *n* = 75.6 r/min, and *f* = 62.6 times/min, Δ*Ra* curves on main journal surface with finishing time to different reciprocating amplitude are plotted, as shown in Fig. 2.80. Experimental results show that Δ*Ra* is larger as reciprocating amplitude is 240 mm than as 200 mm, or that stable value of the surface roughness can be achieved in a relatively short period of time. Due to the increase of the reciprocating amplitude, the amount and length of sliding friction and scratching between abrasive blocks and the workpiece surface will increase, and this is conducive to realize surface micro-machining, to improve the finishing efficiency.

Under conditions of *n* = 75.6 r/min and *f* = 43.8 times/min, Δ*Ra* curves on connecting rod journal surface with finishing time to different reciprocating amplitude are shown in Fig. 2.81. Compared to the reciprocating amplitude of 80 mm, the uniformity of the connecting rod journal surface can be obviously improved as reciprocating amplitude of 200 and 240 mm. When the reciprocating

Fig. 2.80 Δ*Ra* curves on main journal surface with finishing time to different reciprocating amplitude



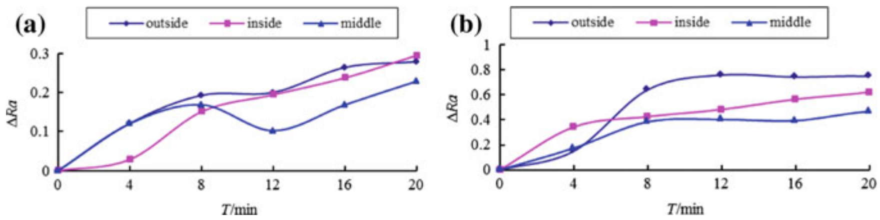


Fig. 2.81 ΔRa curves on connecting rod journal surface with finishing time to different reciprocating amplitude. **a** S = 240 mm; **b** S = 200 mm

amplitude increases, the amount and the length of sliding friction and scratching on different points of connecting rod journal surface are relatively consistent, and empty area between the workpiece and abrasive blocks is weakened, which is helpful to improve the finishing uniformity. Additionally, ΔRa is more obvious at S = 200 mm than S = 200 mm, which indicates that too large reciprocating amplitude may reduce the effective impact of the collision, the rolling, the sliding, and the scratching.

In a word, of processing, the reciprocating amplitude ratio will have a greater effect on improving the finishing uniformity.

2. Process parameters

(1) Finishing depth

Finishing depth is the distance between the rotary axis of the crankshaft and the upper surface of the working medium.

In experiments, ring workpieces are adopted with 40 Cr material, quenching and tempering 28–32 HRC, outer diameter 55 mm, inner diameter 30 mm, length 20 mm. Through measuring weight of ring workpiece before and after finishing, the removal thickness is converted by

$$m_1 = \rho(\pi R_1^2 - \pi(R_1 - h_1)^2)w \tag{2.76}$$

where m_1 is removal mass, R_1 is outer diameter, w is workpiece length, and h_1 is removal thickness.

From Eq. (2.76), the removal thickness can be expressed as

$$h_1 = R_1 - \sqrt{R_1^2 - \frac{m_1}{\rho \pi w}} \tag{2.77}$$

Under conditions of W1300 equipment, n = 108 r/min, f = 75 times/min, and S = 80 mm, removal thickness curves with finishing time to different finishing depth are shown in Fig. 2.82. From Fig. 2.82a, as finishing depth increases, the removal thickness increases in the same time. Figure 2.82b shows the trend of removal thickness variation with different finishing depth as finishing time is

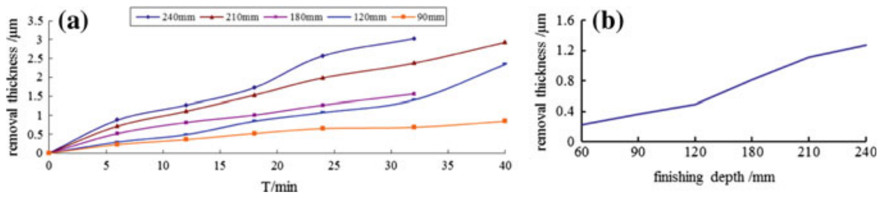


Fig. 2.82 Removal thickness curves with finishing time to different finishing depth. **a** Curves with finishing time; **b** trend curves

12 min, which indicates finishing depth has significant influence to removal thickness. When the depth is up to a certain extent, the increment of the removal thickness is weak. In order to achieve finishing uniformity of connecting rod journal surface, the part should be at a reasonable depth. Additionally, the depth should be determined by considering the equipment structure.

Figure 2.82b shows that the removal thickness is very small when finishing depth is small and is in a slow growth stage; when finishing depth increases to 120 mm, the removal thickness increases significantly with finishing and is in the rapid growth stage; when finishing depth increases to a certain extent (e.g., 210 mm), it is in stable growth stage. Figure 2.83 shows schematic diagram of the influence analysis on the finishing uniformity of connecting rod journal with finishing depth. In Fig. 2.83, three stages of the change of the removal thickness of the surface layer of the workpiece are as follows: the slow growth stage ($<H_1$), the rapid growth stage (between H_1 and H_2), and the stable growth stage ($>H_2$). In the rotary process of the connecting rod journal with rotary center O, finishing depth of each

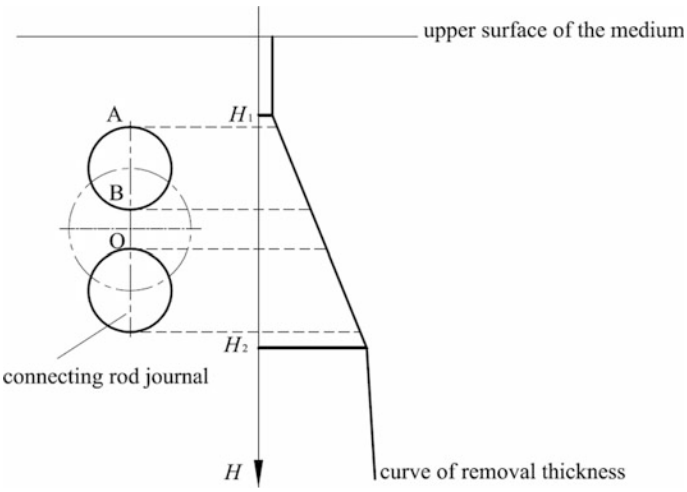


Fig. 2.83 Schematic diagram of the finishing uniformity influence on connecting rod journal with finishing depth

point experiences periodic changes. Two most representative points, Point A and Point B on the connecting rod journal surface are selected for simplifying analysis. When the connecting rod journal is located at the top position, it is more reasonable that Point A is near H_1 or Point B is in the rapid growth stage, so the average value of finishing depth on each point is closer in a rotary cycle, so as to improve the finishing uniformity. If Point B is above H_1, the range of finishing depth and removal thickness is small, therefore, influencing the uniformity. If Point A is under H_2, finishing depth of each point is all in the stable growth stage, the uniformity is relatively good, but the size of finishing equipment also increases significantly.

The above analysis shows that the finishing uniformity of the connecting rod journal is related to the diameter of the connecting rod journal, the distance between the center of the connecting rod journal and the center of the main journal. In the case of certain crankshaft, the finishing uniformity can be improved by selecting the reasonable finishing depth.

(2) Finishing time

Under conditions of W1300 equipment, n = 108 r/min, f = 62.6 times/min, S = 80 mm, and finishing depth 80 mm, the rule of surface roughness value *Ra* with finishing time is shown in Fig. 2.84. The surface roughness value decreases rapidly in initial time, and *Ra* is 0.183 μm when finishing time is 24 min. Then, *Ra* declines lowly in 24–40 min and is essentially unchangeable to 0.15 μm in the last. It indicates that the surface roughness value tends to stabilize in a certain time under certain condition, and the stable *Ra* is also known as the limit surface roughness value.

The surface roughness parameters are tested by Mahr surface roughness instrument, and curves are shown in Figs. 2.85 and 2.86.

From Figs. 2.85 and 2.86, surface roughness value *Ra* can be changed from 0.55 to 0.09 μm. When finishing 8 min, *Ra* decreases obviously and material ratio of the profile also increases significantly; variation trend of surface roughness parameters with finishing time is gradually slow, which also indicates that there exists a limit surface roughness value under certain condition.

By JSM-6700F scanning electron microscope, under the 500 magnification, the surface micro-topography with different finishing time is shown in Fig. 2.87. Before finishing, the workpiece has parallel surface texture, and anisotropy is particularly evident; after finishing 8 min, parallel surface texture disappeared, and

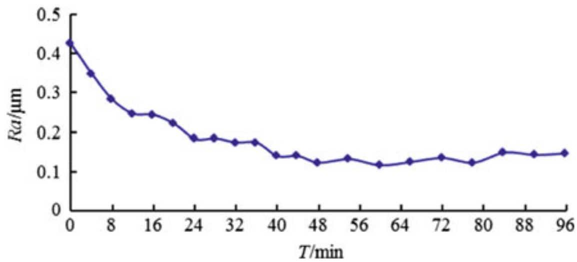


Fig. 2.84 Curve of surface roughness value *Ra* with finishing time

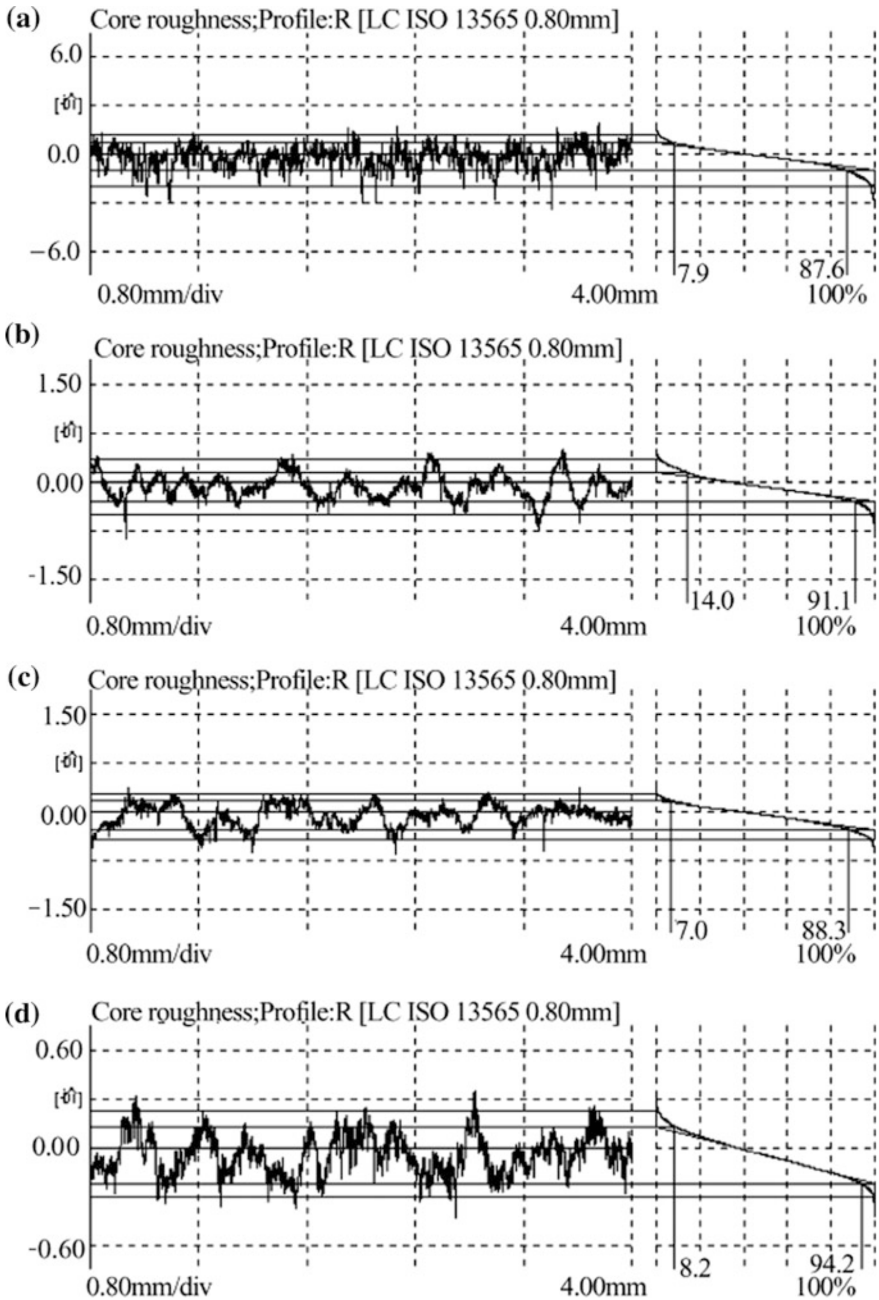


Fig. 2.85 Curves of surface roughness value with finishing time. **a** Before finishing; **b** 16 min; **c** 32 min; **d** 40 min

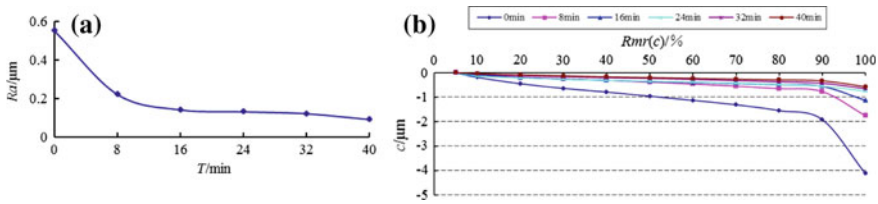


Fig. 2.86 Curves of surface roughness value with finishing time. **a** *Ra*; **b** *Rmr*

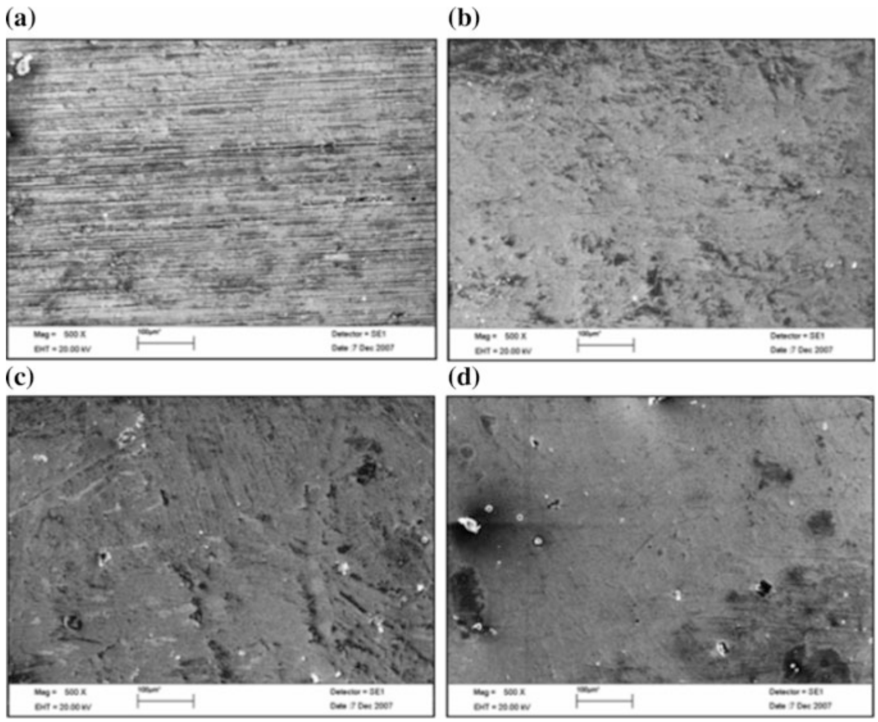


Fig. 2.87 The surface micro-topography with different finishing time under the 500 magnification

the surface morphology refines and has isotropic trend; as the process continues, the surface of isotropic trend is more obvious. In addition, independent micro-pits appear in the workpiece surface, which is beneficial to the storage and reduces the surface abrasion. It is explained that the oil storage capacity of the workpiece can be improved by surface finishing.

Under conditions of n = 108 r/min, f = 50 times/min, S = 80 mm, and finishing depth 80 mm, the crankshaft is finished in long time with one kind of abrasive blocks, and finishing effect is shown in Fig. 2.88. Due to blocking effect of the crank arm, abrasive blocks are arranged in a more orderly manner between two arms and their random motion reduces. Therefore, main journal forms a ring-shaped surface texture after long finishing time. When there are grooves in the surface, it is easier to process the groove and deepen its influence. For the non-eccentric axis, there will be no ring-shaped surface texture because the medium is in a free state. This also shows that the better the flow of the medium is, the better the finishing effect. On the one hand, the solution is to reduce the influence by selecting the appropriate finishing time; on the other hand, it can reduce the orderly manner by selecting a variety of abrasive blocks [55].

3. Structure parameters

Horizontal spindle barrel finishing process mainly depends on the rotary motion of the workpiece and the reciprocating motion of the container to achieve processing. Therefore, structure parameters include realizing rotary motion and reciprocating motion, and structure parameters of the container.

The driven mechanism of rotary motion mainly comprises a spindle frame, a live center frame, and a beam mechanism, and also a motor, a reducer, and a hydraulic system. The spindle frame is fixed on the left end of the beam; the live center frame, clamping the workpiece, is on the axis of the beam on the right end and can do reciprocating motion along the beam by hydraulic system. The motor and the reducer, driving the spindle to rotate through a chain drive, are laid on the beam which supports the spindle frame and the live center frame.

The design of the spindle frame mainly refers to the width and height. The width is equal to the sum of the distance of the two live centers and reserved distance of two sides, and the reserved distance should be greater than the maximum diameter. The height mainly depends on the container height and is approximately equal to the container height plus 200–300 mm, to meet motion range of the live center frame. The live center frame is corresponding to position with the spindle frame, so their width and height are same. But their top structure is slightly different, that is, the spindle frame is bolted to an end of the beam, and the live center frame is sleeve-jointed on the axis of the beam on the right end. The beam mechanism connects the spindle frame with the live center frame, its width is approximately equal to the width of the barrel, and the length is approximately the length of the equipment, so that the whole equipment coordinates each other.

Fig. 2.88 Finishing effect of the crankshaft in long time with one kind of abrasive blocks

The mechanism realizing the reciprocating motion of the container is driven by an electric motor and a reducer, and forms a crank connecting rod mechanism by an eccentric wheel and a connecting rod connected to the container. The length of the crank determines the reciprocating amplitude of the container (the amplitude is equal to 2 l).

According to different types of crankshafts, structure parameters of the container can be determined according to the following equation.

$$L_c = L_1 + 2L_2 + 2s_1 \quad (2.78)$$

$$W_c = 2(l + r + S + s_2) + (q - 1)s_3 \quad (2.79)$$

$$H_c = H + l + r + s_2 + s_4 \quad (2.80)$$

where L_c, W_c, and H_c are longitudinal dimension, transverse dimension, and vertical dimension of the container, respectively (mm); L_1 is the length of the crankshaft (mm); L_2 is the width of the spindle frame clamping the crankshaft (mm); s_1 is the minimum distance between the inside wall of the container and the outside wall of the spindle frame (the principle is to facilitate the lifting of the clamping part, mm); l is the distance between the center of main journal and connecting rod journal (mm); r is radius of connecting rod journal (mm); S is reciprocating amplitude of the container (mm); s_2 is the minimum distance between the inside wall of the container and the workpiece (to determine by the experience or the experiment results, mm); q is the number of parts processed simultaneously; s_3 is the distance of the axis between two workpieces (mm); H is the finishing depth (mm); s_4 is the minimum distance of the top surface between the container and the medium (mm).

According to the experience or experiment results, s_1 and s_2 should be 100–150 mm, to reduce the crushing of abrasive blocks; s_3 should be the sum of l and r, also plus 100–150 mm, to reduce the crushing of abrasive blocks; s_4 should be 100–150 mm, to reduce splashing of the medium. When small-sized parts are finished, q can be selected to 2 or 4; but q can be selected to 1 when using finishing large-sized parts.

2.7.3 Equipment Types and Its Design

1. Equipment design

According to the decomposition principle of the system engineering, the function decomposition is established, which is the function structure diagram (the function tree). Through understanding functions relationship and then combining them, the system plan can be obtained. Figure 2.89 is the function tree of the horizontal spindle barrel finishing equipment.

As a kind of barrel finishing equipment, horizontal spindle finishing equipment has no strict requirement of the stiffness, the accuracy as other barrel finishing equipment, and the design goal is to have good function and comprehensive performance.

Rotary motion and reciprocating motion function are main functions of horizontal spindle finishing equipment. Figure 2.90 shows the assembly diagram of rotary spindle component and reciprocating motion component.

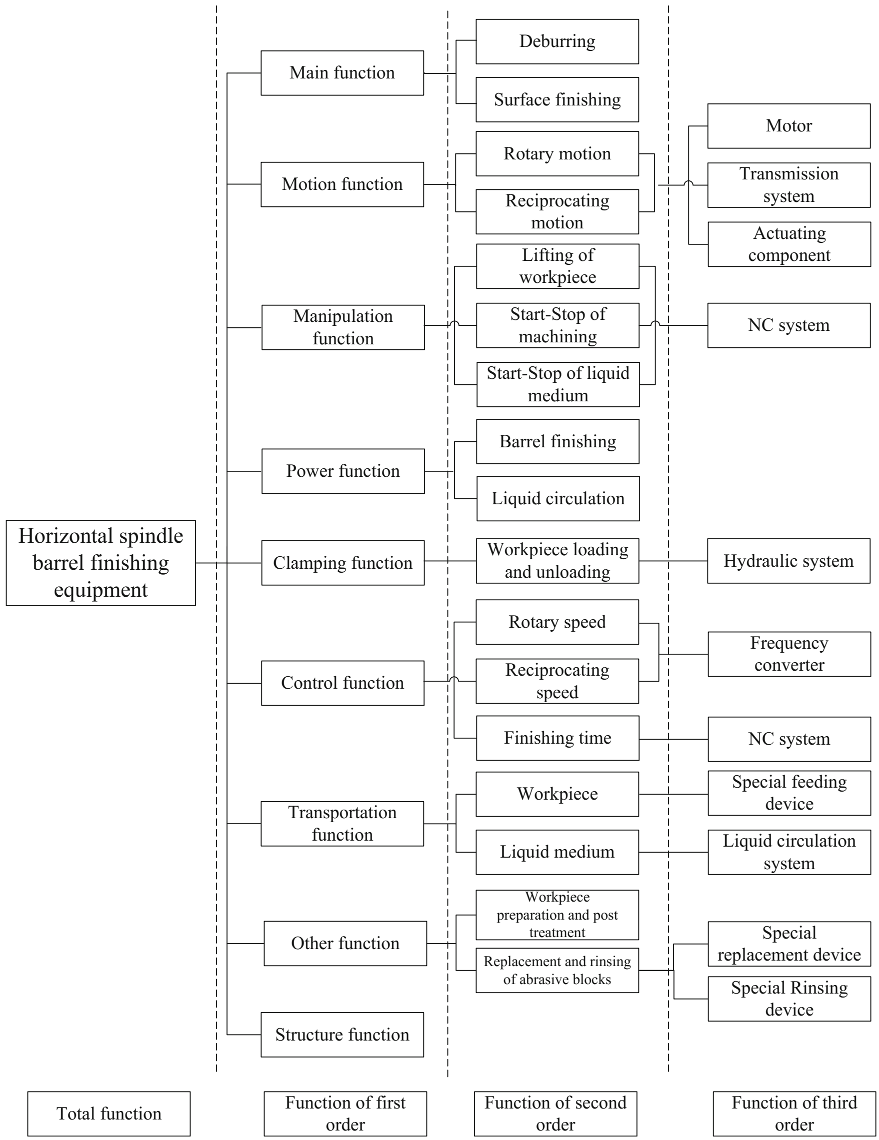


Fig. 2.89 Function tree of the horizontal spindle barrel finishing equipment

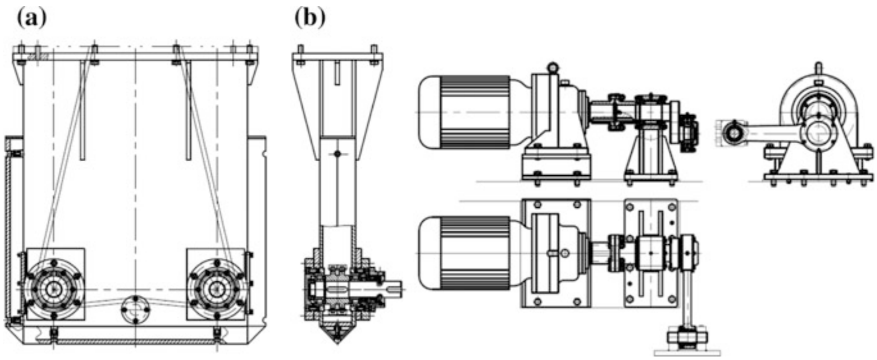


Fig. 2.90 Assembly diagram of rotary spindle component and reciprocating motion component. **a** Rotary spindle component; **b** reciprocating motion component

For a certain processing parts, the range of rotary speed, reciprocating frequency, and amplitude can be determined based on the theoretical analysis and the experimental study, and then overall scheme is selected by analyzing various schemes. Finally, the specific design is done. In addition, in order to meet specific functional requirements, system reliability, compact in structure, stable operation, technological property of the structure, manufacturing economy, and other comprehensive performances are also considered in the schemes election. Finally, the rotary motion is realized through the motor, reducer, and chain transmission mechanism; and the reciprocating motion through the motor, the reducer, and the crank link mechanism.

Through Pro/E software, three-dimensional solid modeling of horizontal spindle finishing equipment is done using the parameterized modeling method, and expected assembly effect can be inspected; assembly process can be reasonably planned. Figure 2.91 shows an assembly drawing of horizontal spindle finishing equipment with W1200 type.

2. Auxiliary device design

The pumping device is mainly used for loading and unloading all kinds of abrasive blocks, which mainly comprises storage tank, cyclone separator, bag filter, centrifugal fan, motor, ash storage box, and electric control components, as shown in Fig. 2.92. Its working principle is as follows: The fan is driven to rapidly rotating after the motor begins to work, so that negative pressure forms in the cyclone separator, and abrasive blocks are inhaled from a feed inlet. When the discharge valve is opened, abrasive blocks are unloaded by the discharge outlet.

The rinsing device is mainly used for rinsing all kinds of abrasive blocks and can be used either alone or in combination with a pumping device. The rinsing device mainly consists of a vibrating screen, water circulation system (main water tank, filter box, paper filter box, water pump, and pipeline), frame body, cover body, and electric control system, as shown in Fig. 2.93. Its working principle is as follows: abrasive blocks vibrate in the vibrating screen according to the predetermined

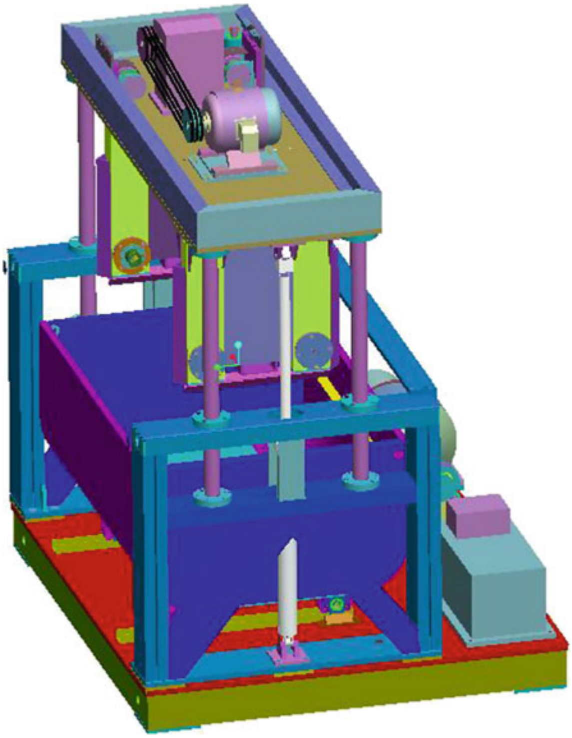


Fig. 2.91 Assembly drawing of horizontal spindle finishing equipment

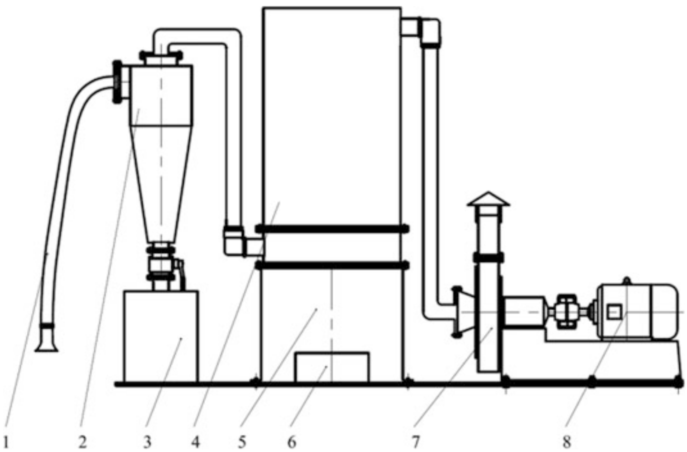


Fig. 2.92 Overall diagram of abrasive blocks pumping device. 1—Inlet; 2—cyclone separator; 3—storage tank; 4—bag filter; 5—ash bucket; 6—ash storage box; 7—centrifugal fan; 8—motor

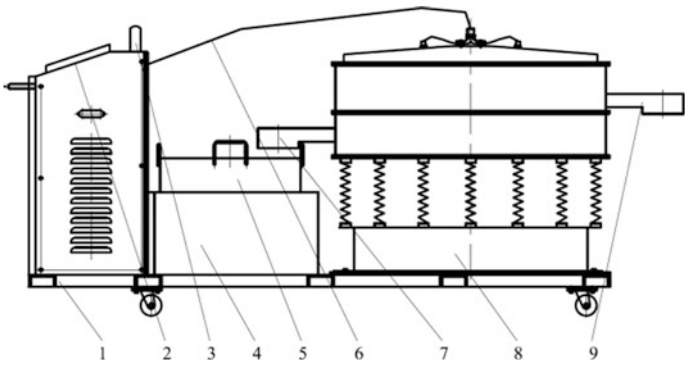


Fig. 2.93 Overall diagram of abrasive blocks rinsing device. 1—Frame body; 2—control panel; 3—alarm lamp; 4—main water tank; 5—filter box; 6—pipeline; 7—water outlet; 8—vibrating screen; 9—discharge outlet

vibration trajectory, broken abrasives in abrasive blocks are filtered and separated, and friction is produced between abrasive blocks. At the same time, rinsing liquid with a certain pressure sprays to the surface of abrasive blocks under the action of the pump, and impurities such as oil are washed away. According to different conditions of abrasive blocks, the purpose of rinsing can be achieved by properly setting washing and vibration time.

The pumping device and rinsing device are mainly suitable for horizontal spindle barrel finishing equipment and have advantages such as compact in structure, strong power, high efficiency, convenient movement, low noise, simple operation, and safe, reliable, and long service life, which can effectively reduce labor intensity and improve production efficiency.

3. Equipment shape

Figure 2.94 shows photographs of horizontal spindle finishing equipment for different types, produced by Langfang Beifang Tianyu Mechanical and Electrical Technology Co., Ltd. Figure 2.95 shows the photograph of abrasive blocks pumping device, and Fig. 2.96 shows the photograph of abrasive blocks rinsing device produced by Langfang Beifang Tianyu Mechanical and Electrical Technology Co., Ltd.

2.8 Finishing Medium

In general barrel finishing processes, the abrasive blocks, compounds, and water, which are used in the barrel finishing, are usually known as the finishing medium. Their features have a great influence on finishing effects of the workpiece.

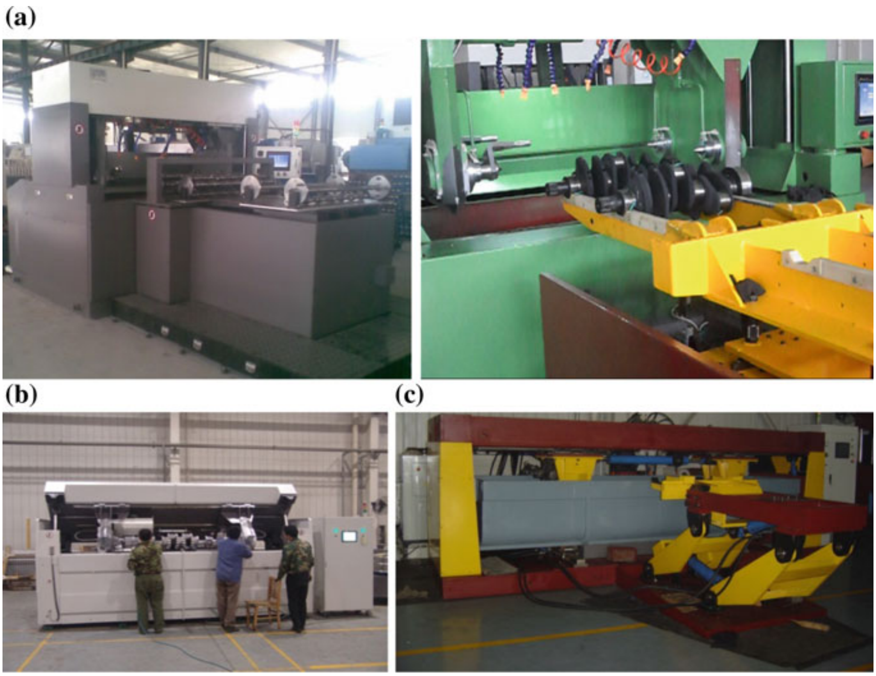


Fig. 2.94 Photographs of horizontal spindle finishing equipment for different types. **a** W900; **b** W2000; **c** W3000

Fig. 2.95 Photograph of abrasive blocks pumping device

Fig. 2.96 Photograph of abrasive blocks rinsing device

2.8.1 Abrasive Blocks

The abrasive tool used for barrel finishing is in various shapes of blocks generally made of abrasives and binders, and referred to as abrasive blocks.

Selection of the proper abrasive blocks for a specific application is critical for optimum deburring and surface finishing results. Major selection factors to consider are composition (type), size, shape, and weight of the abrasive blocks to be used. Other important considerations include the capability, the economy, and the versatility of abrasive blocks. Workpiece material, size and geometry, burr sizes and locations, finishing requirements, finishing equipment used, subsequent operations, and the functions of the parts are also critical factors.

1. Functions and basic requirements of abrasive blocks

(1) Functions of abrasive blocks

As the main finishing medium, abrasive blocks are the main factors for realizing finishing effects.

(2) Condition characteristics and basic requirements of abrasive blocks

Under the action of mechanical transmission, abrasive blocks in the barrel produced a variety of forces, and therefore they (among abrasive blocks, workpieces, and abrasive blocks) present some colliding, rolling effects. This requires that abrasive blocks must be compact, hard, and tough. At the same time, abrasive blocks should be capable of cutting the workpiece and abrasion resistance.

During processing, abrasive blocks and the workpiece have been soaked in a mixture of water and compounds, and the mixture can wash off small chips which plugging in the surface of abrasive blocks. Meanwhile, the chemical reaction between the surface and the mixture is helpful to improve finishing effects. This requires abrasive blocks having characteristics with good compactness, low water absorption, water resistance, oil resistance, and acid alkali resistance.

2. Specifications and performance of abrasive blocks

(1) Types of abrasive blocks

In the development and application of barrel finishing technology, many natural materials often substitute for abrasive blocks in the early period. Table 2.16 lists types and applicability of main substituted abrasive blocks. With the technology development and the application maturity, these abrasive blocks have been unable to meet demand. Therefore, preformed abrasive blocks are produced which can be artificially controlled and have stable processing performance. Table 2.17 lists types, features, and applicability of preformed abrasive blocks.

(2) Manufacture of abrasive blocks

Figure 2.97 shows the manufacture process of sintered abrasive blocks with high temperature. For a variety of abrasive blocks with column shaped, the hole design of extrusion die for extrusion molding is the key factor, and the schematic diagram is shown in Fig. 2.96. From Fig. 2.98, *d* is determined by the shape of green bodies.

Table 2.16 Types and applicability of substituted abrasive blocks

Types		Applicability
Natural stone products	Cobble stone	For the removal of large flash and burr of casting, forging, and stamping parts
	Granite sand	For rounding or polishing of a variety of machined metal parts and die casting parts
	Dolomite	For polishing of softer metal
Agricultural and wood products	Hardwood sawdust	Their cutting capacity is weak, but they not only have a cutting action, but also have good processing effect with the adhesion layer of fine abrasive. These materials can produce a good luster on some workpieces, particularly in the jewelry industry
	Nutshells, ground corncobs, walnuts	
	Leather or blankets flakes	
	Rice nutshells	
Industrial and agricultural used products	Used ceramic	For the removal of small burr of black or nonferrous metal parts; rounding and chamfering of nonferrous metals
	Used wheel	For ferrous metal, casting and forging parts can remove oxide layer, flash and burr efficiently; but the surface roughness is not well
	Used file	
	Glass ball	Cutting capacity is weak, commonly used in metal polishing
	Steel ball	For surface hardening and burnishing of a variety of parts
	Copper ball (powder)	For the removal of small burr and polishing of a variety of parts

Table 2.17 Types, characteristics, and applicability of preformed abrasive blocks

Types		Features	Applicability
Sintered abrasive blocks with high temperature	Ceramic abrasive blocks	Dense microstructure, fine-grain size, high hardness (about 7 degrees), low abrasion, water resistance, oil resistance, acid alkali resistance	For the removal of small burr of black or nonferrous metal parts; polishing of surface roughness requirement
	Fused (crystalline) alumina grinding blocks (pure clay high-temperature alumina crystalline polymer)	Strong cutting ability, high hardness (about 9.3 degrees)	Can remove oxide layer, deburr, round of black metal parts
	Alumina grinding blocks (clay and mixed sintered silicon carbide)	Relatively strong cutting ability, high hardness, good toughness	Commonly used in the removal of a small piece of black metal burrs and polish
	A variety of corundum grinding blocks (corundum, corundum, etc.)	Strong cutting ability	Can be used for a variety of metal parts deburring and polishing
	Silicon carbide abrasive (clay and silicon carbide powder mixed sintering)	High hardness and brittle texture, wear big	For nonferrous metal parts deburring and polishing
	High-hardness abrasive grinding block-based (synthetic diamond, cubic boron nitride, etc.)	Cutting ability, long service life	Because the price is expensive, rarely used
Resin abrasive blocks (bonding abrasives into resin binder by low-temperature mixture)		Lower density, flexible and softer, strong cushioning effect	Well suited for finishing softer metals and fragile parts, achieving pre-plating requirements, and producing smooth finishes; it is also quieter than sintered abrasive blocks
Metallic abrasive blocks		Larger density, good surface conditions, a variety of shapes and sizes	Used primarily for burnishing to achieve maximum luster for decorative purposes, for light deburring applications, and for heavy duty cleaning

When d is less than or equal to 10 mm, take α 12° ~ 13°, and when d is more than 10 mm, take α 17° ~ 20°. In general, d/D can be selected from 1/1.6 to 1/1.3. In order to ensure a smooth surface and uniform quality after green bodies forming, L, known as shaping area, should be 2–2.5 d. If L is small, green bodies will produce elastic expansion, cause transverse cracks, and be easy to swing in the extruding process. Otherwise, green bodies tend to increase the internal stress and produce longitudinal cracks. After determining the structure of the extrusion die hole, the

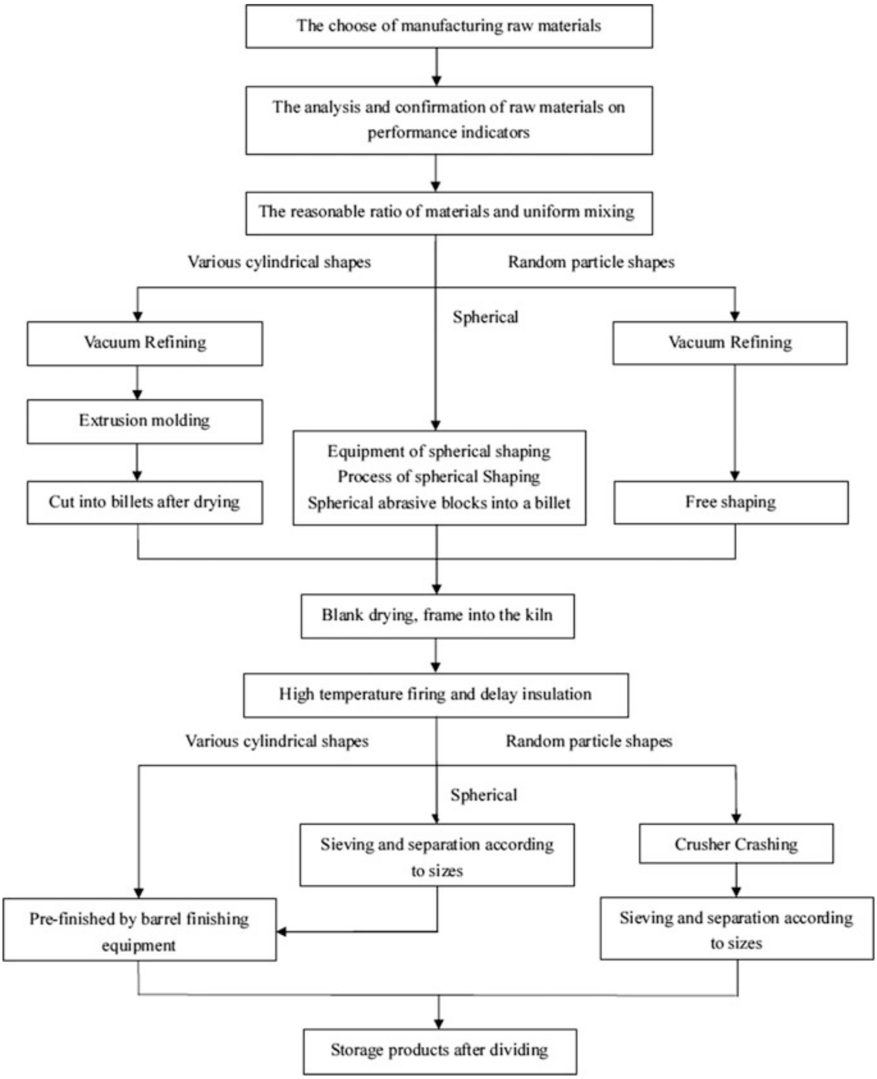


Fig. 2.97 Manufacture process of sintered abrasive blocks with high temperature

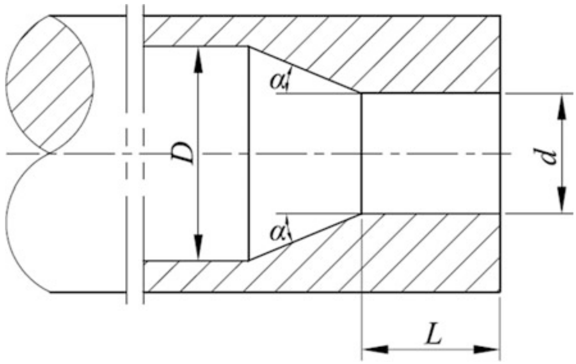


Fig. 2.98 Schematic diagram of the hole design of extrusion die

rate of extrusion should be considered. If this rate is quick, spring back may appear which can lead to deform. When lean materials are used, it needs to add the right amount of binders (polyvinyl alcohol, carboxymethyl cellulose, tung oil or dextrin, and so on). Figure 2.99 shows partial photographs of manufacture process of sintered abrasive blocks with high temperature.

For spherical abrasive blocks, the key is the forming process after the equipment and basic parameters determined, and the control of the raw material and the spray is laid special stress. In addition, the continuous process will go on without adding materials and water after the spherical formation, to increase the density and improve the surface smooth degree. Figure 2.100 shows partial photographs of manufacture process for spherical abrasive blocks.

Various resin abrasive blocks are made of compression metal molding method, and it has special advantages such as apparent angular, accurate edge, small

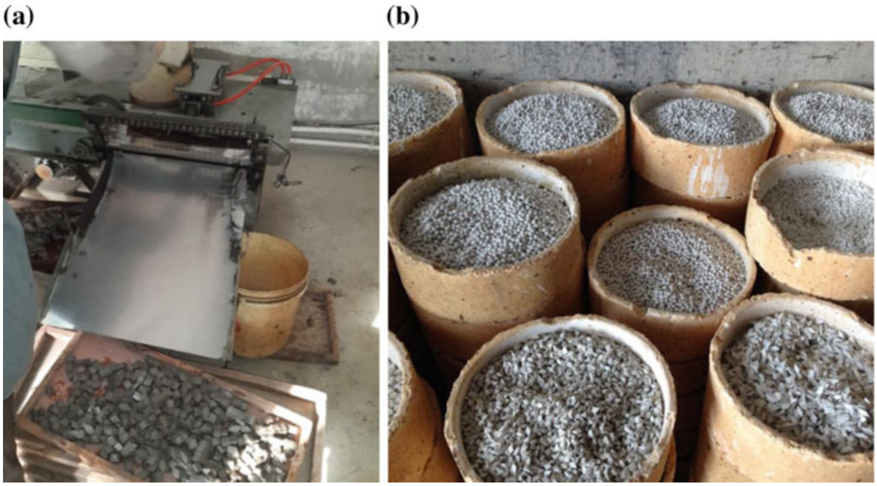


Fig. 2.99 Photographs of manufacture process of sintered abrasive blocks with high temperature. **a** Extrusion forming materials; **b** sintered product

Fig. 2.100 Photographs of manufacture process for spherical abrasive blocks. **a** Spherical forming; **b** screening

shrinkage, and large strength. Figure 2.101 shows photographs of the mold and molded resin abrasive blocks. Casting process is another method for resin abrasive blocks. Figure 2.102 shows partial photographs of casting process for resin abrasive blocks.

(3) Shapes and sizes of abrasive blocks

Preformed abrasive blocks are directly made by using a variety of raw materials, or sintered together by adding binders. Different shapes and sizes of abrasive blocks have advantages for specific applications, primarily depending upon configurations of workpieces. Table 2.18 lists shapes and sizes of sintered abrasive blocks with high temperature. Table 2.19 lists shapes and sizes of resin and metallic abrasive blocks. Figure 2.103 lists a variety of abrasive blocks.

(4) Performance of abrasive blocks

At present, there is JB/T10153-2013 including partial performance and test methods of abrasive blocks in China. Based on many years of theoretical study and experimental analysis, the performance is tested referring similar products, and this plays a positive role for production guiding and the usage of abrasive blocks. Table 2.20 lists performance indexes and test standards of abrasive blocks. According to lots of testing results, the hardness is more than 115HRA, the

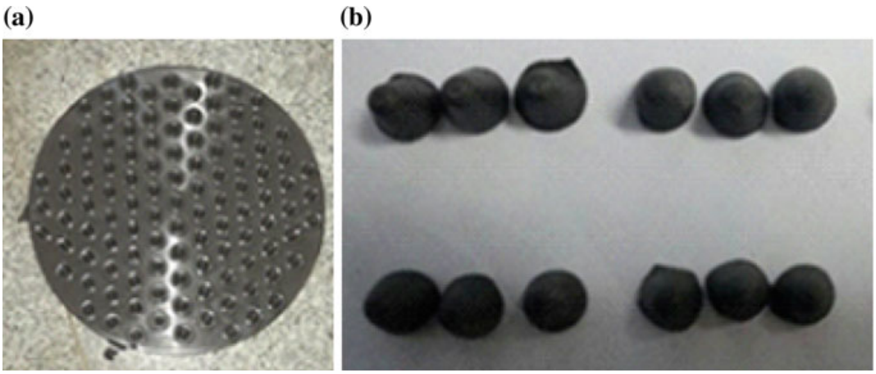


Fig. 2.101 Photographs of the mold and molded resin abrasive blocks. **a** Mold; **b** molded resin abrasive blocks

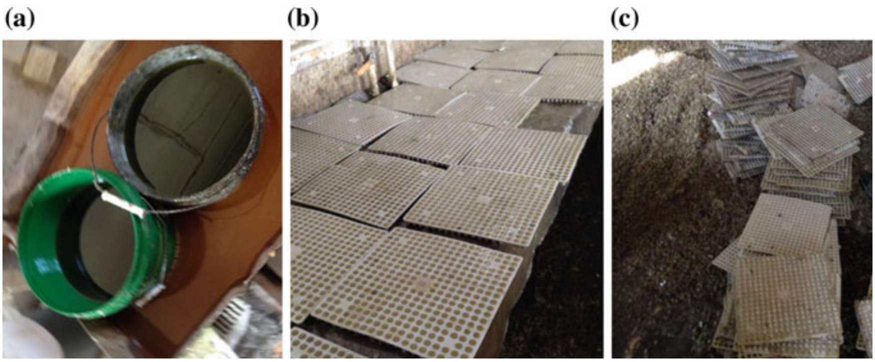


Fig. 2.102 Photograph of casting process for resin abrasive blocks. **a** Raw materials; **b** curing molding; **c** demolding

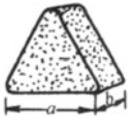
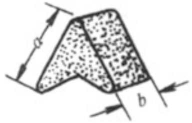
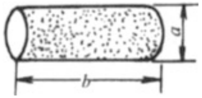
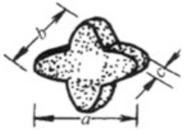
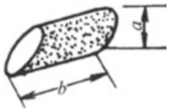
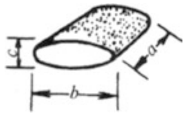
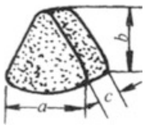
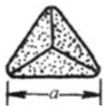
compressive strength is not less than 9×10^7 N/m^2, the toughness is more than 1 kN m/m^2, and the water absorption rate is less than 0.7%.

Quality evaluation of abrasive blocks with the same material, the hardness, the size, and the shape by different manufacturers or different batches of the same manufacturer is difficult through single performance index. A new index G can be adopted to a comprehensive comparison evaluation of finishing quality and using results of abrasive blocks.

$$G = \frac{C}{C'} \tag{2.81}$$

$$C = \frac{M - m}{M} \times 100 \tag{2.82}$$

Table 2.18 Shapes and sizes of sintered abrasive blocks with high temperature

Shape (code)	Shape sketch	Sizes/mm	Shape (code)	Shape sketch	Sizes/mm
Equilateral triangle prism (T)		3 × 3, 4 × 4, 6 × 4, 10 × 6, 15 × 8, 18 × 10, 25 × 12, 30 × 15, 35 × 20	Arrowhead prism (V)		13 × 13, 20 × 20, 25 × 25, 30 × 30
Oblique triangle prism (TP)		3 × 5, 4 × 6, 6 × 10, 10 × 15, 15 × 20, 18 × 25, 25 × 30, 30 × 20	Tri-stars prism (ST)		10 × 10 × 10, 20 × 20 × 20, 25 × 25 × 25, 30 × 30 × 30
Equilateral cylinder (R)		3 × 6, 4 × 8, 6 × 12, 8 × 16, 10 × 20, 15 × 30, 18 × 35, 25 × 40, 30 × 50	Four-pointed stars prism (FST)		45 × 22 × 15, 35 × 7×11, 18 × 10 × 9
Oblique cylinder(RP)		3 × 6, 4 × 8, 6 × 12, 8 × 16, 10 × 20, 15 × 30, 18 × 35, 25 × 40, 30 × 50	Elliptical cylinder (E)		15 × 4×15, 15 × 6×15, 20 × 8×20
Quadrants prism (F)		7 × 7×5, 10 × 10 × 7, 15 × 15 × 10, 20 × 20 × 12, 30 × 30 × 14	Equilateral tetrahedron (FT)		10,12, 15, 20

(continued)

Table 2.18 (continued)

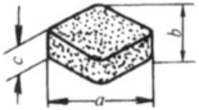
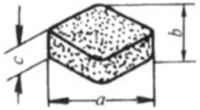
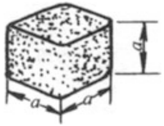
Shape (code)	Shape sketch	Sizes/mm	Shape (code)	Shape sketch	Sizes/mm
Diamond prism (D)		23 × 16 × 10, 36 × 25 × 18, 46 × 30 × 20, 55 × 35 × 24	Sphere (S)		1.5, 2, 3, 4, 5, 6, 8, 10, 12, 15
Cube (C)		10, 15, 20	Random shape (G)		1.0–1.5, 1.5–2.0, 2.0–2.5, 2.5–3.0, 3.0–4.0, 4.0–5.0

Table 2.19 Shapes and sizes of resin and metallic abrasive blocks

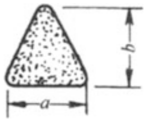
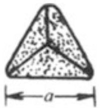
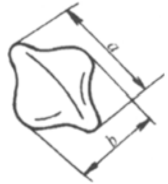
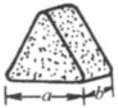
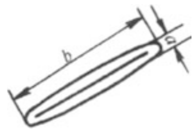
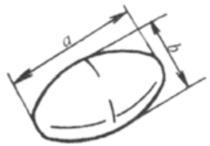
Shape (code)		Shape sketch	Sizes/mm	Shape (code)		Shape sketch	Sizes/mm
Resin abrasive blocks	Cone (PLCO)		10 × 10, 15 × 15, 20 × 20, 25 × 25, 30 × 30, 35 × 35, 40 × 40, 45 × 45, 50 × 50, 60 × 60	Metallic abrasive blocks	Sphere (SS)		1.588, 2.381, 3.175, 3.969, 4.762, 5.556, 6.350
	Equilateral tetrahedron (PLFT)		10, 12, 15, 20		Double pins (STS)		4.5 × 3.2, 5.1 × 3.7, 7.0 × 4.7, 8.9 × 6.3
	Equilateral triangle prism (PLT)		6 × 4, 10 × 6, 15 × 8, 18 × 10, 25 × 12, 30 × 15, 35 × 20		Pin (SP)		$\varphi 2 \times 8.5$, $\varphi 2 \times 10$
					Oval (SE)		7.0 × 4.7, 8.9 × 6.3

Fig. 2.103 Variety of abrasive blocks

Table 2.20 Performance indexes and test standards of abrasive blocks

Performance indexes	Test standards
Hardness	GB/T 2490
Compressive strength	GB/T 4740
Toughness	GB/T 4742, GB/T 3810
Water absorption rate	GB/T 10153
Wear rate of abrasive blocks	GB/T 10153
Material removal rate of the workpiece	GB/T 10153
Geometry precision	GB/T 10153

$$C' = \frac{M' - m'}{M'} \times 100 \tag{2.83}$$

where C and C' are material removal rate of the workpiece and wear rate of abrasive blocks; M and m are initial weight and final weight of the workpiece; M' and m' are initial weight and final weight of abrasive blocks.

Under the condition of ensuring processing quality, the larger the G is, the better the performance of abrasive blocks is.

(5) Failure mode of abrasive blocks

Abrasive blocks have three failure modes:

(1) The initial failure

If the naked eye can discern uneven hole in the surface of abrasive blocks newly purchased (through pre-finished), the surface of abrasive blocks forms piebald holes after normal use and has obvious influence on the workpiece quality. So, it should not be used. If this kind of abrasive blocks is broken, small holes are recognizable at the break position, known as porosity. The reason may be not enough vacuum refining time or vacuum in the manufacturing of abrasive blocks. Such abrasive blocks quickly wear in normal use. Performance indexes, having obvious difference mentioned above, should not be used.

(2) Crushing failure

Due to manufacturing defects or improper use, the edges of abrasive blocks are seriously off or abrasive blocks are broken. The broken fragments or edges have a great impact on workpiece surface quality. Therefore, abrasive blocks should be cleaned and sieved, or else it should not be used.

(3) Wear failure

Under conditions of normal use, edges of abrasive blocks will be blunted, and their sizes will be smaller. When the volume of a single abrasive block is reduced to about 0.5 of the original size, it has great influence on the finishing quality and productivity, and it should be considered to replace at this moment.

3. Impact on finishing results of abrasive blocks parameters

Characteristic parameters of abrasive blocks include composition, abrasive size, hardness, microstructure, the shape and size, the binder similar to the methods of grinding wheel. However, because of different working features between abrasive blocks and the wheel, the abrasive size, and the hardness, the shape and the size are main factors [56]. Under definite experimental condition (machine type is 2M3110, the workpiece is 45 steel $\phi 10 \times 10$, and finishing time is 30 min), the experimental data comparisons of finishing effects of abrasive blocks parameters are shown in Table 2.21.

(1) Abrasive size

The size refers to the abrasive size of abrasive blocks.

(1) Effects on the workpiece surface roughness value. In general grinding processes, the smaller the abrasive size is, the smaller the surface roughness value after processing is. In the barrel finishing processes, sharp corners on the abrasive are removed after pre-finished or a period of use, which can improve conditions of the coequal highness. When the mutual force between abrasive blocks and the workpiece is low, smaller surface roughness of the workpiece can obtained no matter the abrasive size is large or small. Therefore, the influence on surface roughness of abrasive size is not obvious, and variety of surface roughness is obvious only when the abrasive size is very large or small. Under definite experimental condition (machine type is 2M3110, the workpiece is 45 steel, finishing time is 30 min, and *Ra* is 1.8 μm before finishing), influence rules of abrasive size on the workpiece surface roughness value are shown in Fig. 2.104a, and the results show that surface roughness is basically same after finishing with sphere shape abrasive blocks.
(2) Effects on the material removal rate. Generally speaking, if the abrasive size of abrasive blocks is smaller, the metal removal rate and finishing efficiency increases owing to the decrease of abrasive number per unit area and increase of intensity of pressure. But the relationship between the material removal rate and

Table 2.21 Comparisons of finishing effects of abrasive blocks parameters

Abrasive blocks			Ra/μm		Material removal rate C/(g/kg)	Wear rate C'/(g/kg)
Materials	Abrasive size	Sizes/mm	Before finishing	After finishing		
Corundum	80#	Oblique triangle prism 15 × 15 × 15	1.8	1.6	13.88	88.29
	150#		1.8	1.3	11.22	66.72
	240#		1.8	1.3	12.35	65.83
	W20		1.8	1.2	10.39	53.34
	80#	Oblique cylinder Φ10 × 20	1.8	1.4	15.48	106.75
	240#		1.8	1.0	11.83	77.67
	W20		1.8	1.0	10.33	54.16
	80#	Sphere Φ5	1.8	0.6	3.67	37.61
	240#		1.8	0.5	2.96	24.08
	W40		1.8	0.5	2.05	14.14
Alumina	240#	Sphere Φ3	1.8	0.9	0.38	2.17
		Sphere Φ5	1.8	0.6	0.54	1.25
		Sphere Φ8	1.8	0.4	3.21	4.32

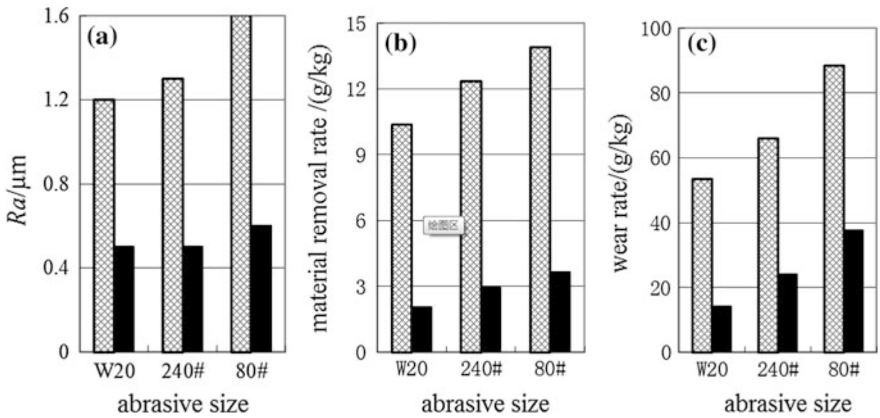


Fig. 2.104 Influence rules of abrasive size. In the figure, filling with black solid represents abrasive blocks with sphere, another with oblique triangle prism

the abrasive size is not a linear function. The relationship is that when the abrasive size is small, material removal rate increases rapidly with the increment of abrasive size; when reaching a limit size, material removal rate will increase lowly, and abrasive particle size is about 80 μm at the same time. Under the same experimental conditions in Fig. 2.104a, the influence rules of abrasive size on material removal rate are shown in Fig. 2.104b.

(3) Effects on wear rate of abrasive blocks. The larger the abrasive size of abrasive blocks is, the larger the bonding force between the abrasives is, the lower

breaking possibility of abrasives from block body is. Therefore, abrasive blocks more easily maintain its original shape, and the wear rate is small. Under certain experimental conditions, influence rules of abrasive size on wear rate are shown in Fig. 2.104c. It can be seen that the wear rate is smaller with larger abrasive size. From the point of lower wear rate of abrasive blocks, abrasive blocks with larger abrasive size are more suitable to deburring and finishing.

(4) Selection principle of abrasive size. Above all, the selection should meet deburring and finishing requirements of the workpiece. Then, abrasive size with high material removal rate (high finishing efficiency) and low wear rate (good economy) should be considered. According to this principle, abrasive size is generally about 80 μm or more for the less obvious influence on surface roughness.

(2) Hardness

The hardness of abrasive blocks generally refers to difficulty degree of surface abrasives off from the block body with the external force. If abrasives wear off easily, the hardness of abrasive blocks is soft, and otherwise is hard. Although this concept is different with metal hardness, it has relationships with blocks hardness. Therefore, abrasive blocks with smaller abrasive size (80 μm or more is provided in GB 2491) can use Rockwell hardness to express its hardness.

In the barrel finishing processes, main functions of abrasive blocks on the workpiece surface are collision, extrusion, and micro-grinding, and therefore extremely sharp cutting edges of abrasives and automatic peeling-off capacity of the dull abrasives may not be required. Since the cutting force during processing is small, and water plays a role of cleaning and cooling effect on abrasive blocks, workpiece overheating, and chip clogging the surface of abrasive blocks, and other issues will not appear. Therefore, the use of hard abrasive blocks also did not lead to workpiece burning and larger thermal deformation due to overheating.

Using hard abrasive blocks has following advantages:

(1) Rockwell hardness value of abrasive blocks must be greater than the workpiece hardness, so hard abrasive blocks can be used in a variety of workpiece hardness, which may reduce the hardness type of abrasive blocks and be easy for production, storage, and usage of abrasive blocks.
(2) Harder the abrasive blocks are, the smaller wear rate of abrasive blocks is, and this can increase the life span of abrasive blocks (good economy).
(3) Hard abrasive blocks are easy to maintain the original shape and less prone to breaking in the finishing process. Especially for finishing requirements with low surface roughness of the workpiece, the surface roughness can be affected greatly by peeled chips and edges.

The hardness of abrasive blocks has relations with the material removal rate. In general, the hardness of abrasive blocks must be greater than the workpiece hardness in the barrel finishing processes (but harder abrasive blocks are not related to greater material removal rate). According to the relevant literature, when the ratio of abrasive blocks hardness and workpiece hardness exceeds K (K is 1.3–1.7 based on many experimental results), the material removal rate does not increase any more. So, the hardness of abrasive blocks selected should be greater 1.3–1.7 times than the workpiece hardness to obtain large material removal rate. If the hardness is not enough (K is less than 1.3), material removal rate declines sharply. Generally, the Rockwell hardness of hardened steel is about 60–70HRC, so the Rockwell hardness of abrasive blocks should be above 100HRC.

(3) Shape and size

Different with ordinary grinding processes, abrasive shape and size influence on finishing effects are very obvious, including surface roughness, surface damage and deformation of the workpiece, finishing efficiency, and economy. Therefore, they are key factors of realizing finishing request.

(1) Effects on the workpiece surface roughness value. With the same material and same abrasive size, different shape of abrasive blocks will lead to great difference of the surface roughness. The experimental results show that the more the angular and sharp edges and corners of abrasive blocks are, the greater the surface roughness values after finishing are. Under definite experimental condition (the workpiece is 45 steel, abrasive blocks are $80^{\#}$Corundum, finishing time is 30 min, and Ra is 1.8 μm before finishing), test results are shown in Table 2.22. Among them, sphere is the best, followed by oblique cylinder, and oblique triangle prism. Therefore, if low surface roughness or good surface brightness is required, sphere shape should be chosen.

Under other same conditions, the high pressure, large contact area between the abrasive block and the workpiece, and large scratching traces of the workpiece surface may produce with large abrasive blocks. Therefore, after finishing surface roughness and brightness are not well. Under definite experimental conditions (the workpiece is 45 steel, abrasive blocks are $80^{\#}$ Corundum, finishing time is 30 min, and Ra is 1.8 μm before finishing), test results are shown in Table 2.23.

The surface roughness value above mentioned should be the ultimate value of surface roughness. Due to the material removal rate with small size abrasive blocks is low, the surface roughness of the workpiece reached the limit value for a long time. When the ultimate value of surface roughness with large size abrasive blocks obtains, the ultimate value cannot obtain with small size abrasive blocks at the same time. Therefore, the surface roughness value is larger with sphere Φ3 in Table 2.24.

(2) Effects on the material removal rate. With the same material and the same abrasive size, different shapes of abrasive blocks will also lead to great

Table 2.22 Test results of *Ra* with different shapes

Shapes	Oblique triangle prism 15 × 15 × 15	Oblique cylinder Φ10 × 20	Sphere Φ5 mm
Ra value after finishing/μm	1.6	1.4	0.6

Table 2.23 Test results of *Ra* with different sizes

Sizes/mm	Sphere Φ3	Sphere Φ5	Sphere Φ8	Sphere Φ10
Ra value after finishing/μm	0.50	0.45	0.50	0.70

difference of the material removal rate. Experimental results shown in Table 2.25 indicate that the more the angular and sharp edges and corners of abrasive blocks are, the greater the material removal rate is. Among them, equilateral tetrahedron is the largest, followed by oblique triangle prism, oblique cylinder, and sphere. Therefore, if only for rough machining for deburring and descaling, it has maximum efficiency with equilateral tetrahedron or oblique triangle prism shape.
The material removal rate of the workpiece increases with abrasive blocks size increasing for greater pressure on the workpiece. The relationship between the diameter of abrasive blocks (spherical alumina) and material removal rate is shown in Table 2.26.

(3) The relationship between the shape and the size of abrasive blocks and the workpiece. The shape and the size of abrasive blocks should provide access to all workpiece surfaces requiring deburring or finishing, not lodge in holes or recesses, and permit easy separation from parts at the end of the cycle in mass production.

Table 2.24 Test results of the material removal rate with different shapes

Shapes and sizes	Sphere Φ10 mm	Oblique cylinder Φ10 mm × 20 mm	Oblique triangle prism 15 mm × 15 mm	Equilateral triangle prism 10 mm × 10 mm
Material removal rate/(g/kg)	6.89	10.33	10.49	28.83

Table 2.25 Test results of the material removal rate with different sizes

Sizes	Sphere Φ3	Sphere Φ5	Sphere Φ8	Sphere Φ10
Material removal rate/(g/kg)	0.38	0.54	3.21	6.89

Table 2.26 pH value of various compounds and main compositions

Workpiece materials	Black metal	Copper, aluminum	Zinc alloy	Stainless steel
pH value	>8	About 7	<7	>10
Main compositions	Triethanolamine, sodium dodecylbenzene sulfonate, oleic acid, sodium nitrate, sodium phosphate, and the like			

When using large size abrasive blocks, it is easy for low-rigidity workpiece to deform due to large impact force on the workpiece. Abrasive blocks also help to keep workpieces from impinging on each other, but this effect is not well if abrasive blocks are small size or low edges [57].

For the workpiece with holes or recesses, the size of the abrasive block should be 1/3 or less of the hole or recess size, to ensure holes or recesses finishing and not lodging in.

When finishing more sophisticated workpieces such as thread or gear, abrasive blocks with less angular and small size should be chosen to avoid bumping. The radius of spherical abrasive blocks for finishing machining should be less than fillet radius of the workpiece. Therefore, a mixture of abrasive blocks shapes is sometimes used.

2.8.2 Liquid Medium

Compounds, known as liquid medium shown in Fig. 2.105, are added to parts and abrasive blocks to increase deburring action, remove scale and heat-treat tints, scour surfaces, and clean parts, abrasive blocks, and the container. In addition, compounds modify luster or color of workpieces. They can add corrosion-inhibiting coatings for metal workpiece such as steels and aluminum. In some cases, abrasive blocks in the compounds may be used to keep flat parts from sticking together.

Most compounds are combinations of chemicals that dissolve in water and form solutions to maintain consistency or to modify the action of abrasive blocks on the workpiece. The use of too little, too much, or an improper compound can adversely affect the cycle time and/or ability of abrasive blocks to perform as intended.

Generally, good compounds include water, water conditioners, cleaners, wetting agents, lubricants, foam control agents, pH buffers (pH control chemicals), rinse agents, suspension agents, and emollients. Some also contain metal brighteners and corrosion inhibitors. The list of chemicals is extremely long, and the amount of

Fig. 2.105 Photographs of compounds produced by Langfang Beifang Tianyu Mechanical and Electrical Technology Co., Ltd

various chemicals used is almost as much as the variety of chemicals, depending upon finishing results desired and economics of the manufacturer, and the user.

There are some finishing applications where no compound solutions are used. For example, loads of workpieces are sometimes finished dry, perhaps with sawdust, ground corncobs, or other abrasive blocks.

1. Cleaning functions

All mass finishing operations require clean machine compartments, abrasive blocks, and workpieces for effective and efficient results. Compound solutions are often required to clean workpieces by removing tarnish or scale, emulsifying oils, and suspended solids. Compound solutions are also expected to maintain the cleanliness of workpieces and abrasive blocks during the finishing cycle. Buildup of dirt on the abrasive block causes glazing and reduces cutting capability. Strongly alkaline formulations are often used for cleaning iron and steel parts, while milder alkaline to mildly acidic compositions is generally best for nonferrous metals and alloys. Some workpieces require cleaning and/or descaling prior to mass finishing.

Therefore, the replacement of compounds in mass finishing processes should pay attention to realize timing cleaning of abrasive blocks. Generally, replacement time should be 3–4 h in rough machining, and it can be 6–8 h in finish machining.

2. pH control

pH control chemicals hold the pH at the required level of alkalinity, neutrality, or basicity. The pH is controlled to make the chemical system of pH sensitive work properly.

Selecting compounds for different workpiece materials, the pH value and main compositions are shown in Table 2.27.

3. Loads

Compounds loads directly affect the deburring and finishing effect. If the load is too less, lubrication and cushioning action are not well, causing roughness and scratch of workpiece surface, even damaging workpiece surface. If the load is too much, the processing efficiency will decrease. Practice shows that compounds loads in a sealed drum are appropriate for just submerging the workpiece and abrasive blocks.

Experimental conditions: The type centrifugal barrel finishing equipment is 2M3160 ($N = -n = 180$ r/min), workpieces are 45 steel of $\varphi 10$ mm $\times$ 15 mm by finishing turning, sphere abrasive blocks are alumina material of $\varphi 5$ mm, and the processing time is 20 min. Finishing effects comparison is shown in Table 2.28. Experimental results show that adding proper amount of compounds is beneficial for improving finishing quality and efficiency.

Table 2.27 Finishing effects comparison of compounds

Finishing status	The surface roughness *Ra* value/μm		Brightness after finishing	Material removal rate
	Before finishing	After finishing		
Compounds LC-10	1.6	1.25	Good	Larger
Without compounds	1.6	1.45	Bad	Smaller

Table 2.28 Equipment selection and notes

Shapes and sizes of the workpieces	Equipment type	Notes and explanations
Miscellaneous parts with small sizes	Centrifugal type	The flat parts are easy to stick, thin-walled or bar parts are easy to deform in batch production. Larger loads of the mixture or more less amounts of parts may appropriately reduce these phenomena
	Vibratory type	Solid parts mixed with the medium are difficult to vibrate, and finishing results are poor. Except for selecting abrasive blocks with large size, other barrel finishing processes may be used
	Whirling type	It is possible for flat parts to insert the connection position between stationary sidewalls and rotary disk. In general, the thickness of the workpiece should excess 2 mm.
	Rotary type	This process has low material removal capacity and poor finishing efficiency and also has little applications at present
Shaft disk parts with small or medium sizes	Vertical spindle type	Shaft parts should not be too long for the workpiece inserts into the barrel through cantilever action. If necessary, parts may turn 180° and be fixed to deburr or finish. For short shaft parts, several parts can be deburred or finished simultaneously on a spindle. In addition, finishing uniformity of end surface on disk parts is not well
Shaft parts with large sizes	Horizontal spindle type	Practical finishing problems of the crankshaft can be solved by this process. The surface quality can be improved synthetically, especially cleanliness degree of crankshaft parts
Disk parts with large or medium sizes	Intermeshing spindle type	All surfaces of disk parts can be achieved to finish, but the adjustment of equipment parameters is complicated
Casing parts with medium sizes	Vibratory type	Enough space of the equipment size must be to ensure enough space of parts vibration in the container

2.9 Mass Finishing Applications

2.9.1 Introduction

1. Three stages of mass finishing application

Practical applications of the mass finishing technology involve three stages: pre-treatment before mass finishing, mass finishing, and post-treatment after mass finishing.

(1) Pre-treatment

The pre-treatment of the workpieces mainly get rid of oil dirt residual by last procedure, in order to avoid reducing the cleaning function of the liquid medium, darkening the workpiece surface, weakening the cutting force of abrasive blocks, and decreasing the finishing effect.

For some systems to work properly, heavy oil must be removed before it covers barrel liners and fouls drain systems. Special cleaners of some design will be needed before finishing of parts. This is different from the cleaning process that is needed after finishing.

Different kinds of metal cleaning solutions are mainly used for the pre-treatment, and the most common is water-based cleaning solutions (mass proportion is often 5%) in which workpieces are soaked or washed. This kind of solutions can be continuously used in two weeks. It is necessary adding appropriate cleaning solution (5–10% of the load) every 3 days.

(2) Mass finishing

Equipment type, finishing parameters, finishing media, and so on are main considerations for selecting or determining mass finishing processes, and mainly based on the workpiece material, shape and size, finishing requirements, etc. The selection of equipment type is shown in Table 2.29. Finishing parameters and finishing media of different equipment are described as the above chapter.

(3) Post-treatment

The post-treatment of workpieces involves the sieving between abrasive blocks and workpieces, cleaning of abrasive blocks and workpieces, drying and preventing rust of workpieces.

The common sieving device for abrasive blocks and workpieces includes mechanical sieving and magnetic sieving. Mechanical sieving device may be either a part of the mass finishing equipment, or an auxiliary device, and its principle is shown in Fig. 2.106. Separation workpieces 5 sieving from abrasive blocks 4 is realized by vibrating screen 3 driven mechanically. In general, the efficiency of vibrating sieving method is high, and the way of swing or rotating the screen may also be used.

Magnetic sieving is to separate workpieces from abrasive blocks through sticking workpieces by magnetic forces, so this method is only suitable for the

Table 2.29 Methods and applicable conditions of drying and preventing rust methods

The methods of drying and preventing rust	The applicable conditions
Soaking in sodium nitrite solution, the mixture of sodium nitrite and sodium carbonate, sodium silicate solution	Better effects, but harmful to humans health, so applications should be minimized
Oven drying and anti-rust oil soaking	Large investment and cost; not suitable to the small flat workpiece; the fit face of the workpiece taking from the oven may be rusted because there is water between workpiece and dryer frame
Blow-drying with a hairdryer and drying with fresh cloth	Low efficiency, so only for experiments
Alcohol drying and anti-rust oil soaking	The processing effects are remarkable, but the cost is high and the service cycle of the alcohol is short
Dryers drying and anti-rust oil soaking	Economical and practical, but inapplicable to heavy thin parts(less than 0.1 mm)

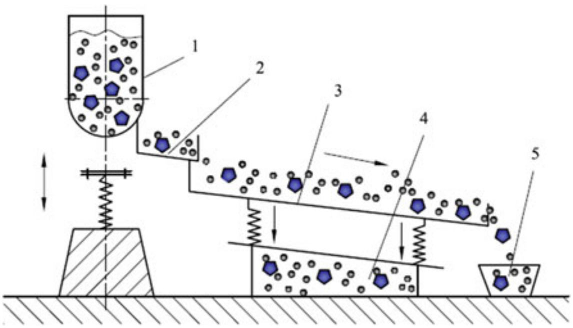


Fig. 2.106 Principle diagram of mechanical sieving device. 1—Mass finishing equipment; 2—discharging exit; 3—vibrating screen; 4—abrasive blocks; 5workpieces

separation of ferromagnetic material parts. In general, the common magnetic sieving devices have both conveyor belt and magnetic disk. The principle diagram of conveyor belt sieving with magnetic forces is shown in Fig. 2.107. Workpieces and abrasive blocks climb to the feeder export through slight vibrating of spiral feeder 1, then fall on magnetized driving wheel 2, and sent to magnetized-driven wheel 5 with conveyor belt 8. Abrasive blocks fall into abrasive blocks in Box 6 through conveyor belt end because the media is not magnetized. But workpieces continue to move with the conveyor belt in suction of magnetized-driven wheel until conveyor belt disjointed from magnetized-driven wheel, and magnetic forces become weaken. At that time, workpieces fall into workpieces inbox 7 under their weights and separate with abrasive blocks. The principle diagram of the magnetic disk sieving is shown in Fig. 2.108. Its fundamental principle is the same with conveyor belt sieving. Magnetic disk 4, constituted non-ferromagnetic material such as Al alloys dish and some magnet, is installed over barrel finishing equipment 7. After barrel finishing, disk Bracket 2 is rotated to put the magnetic disk into the barrel.

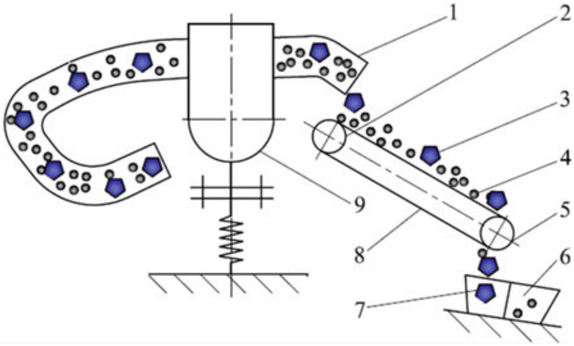


Fig. 2.107 Principle diagram of conveyor belt sieving with magnetic forces. 1—Spiral feeder; 2—driving wheel; 3—workpieces; 4—abrasive blocks; 5—driven wheel; 6—abrasive blocks inbox; 7—workpieces inbox; 8conveyor belt; 9—barrel finishing equipment

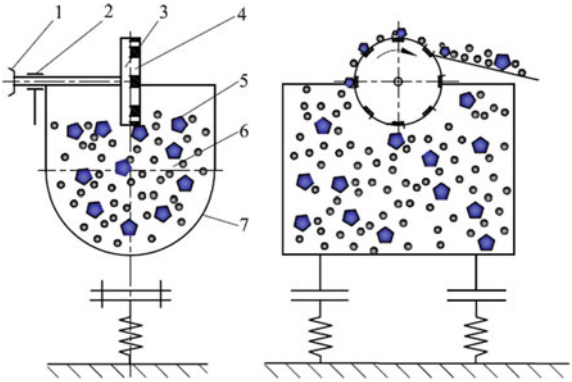


Fig. 2.108 Principle diagram of the magnetic disk sieving. 1—Hand wheel; 2—bracket; 3—scraper; 4—magnetic disk; 5—workpieces; 6—abrasive blocks; 7—barrel finishing equipment

Workpieces are magnetized and hold by magnets when the disk rotates in the mixture. Workpieces rotate with the disk together and fall into workpieces inbox when passing through Scraper 3.

Barrel finishing operations have the built-in ability to clean parts as part of the process. In some situations, however, it is necessary to add an ultrasonic cleaning step, which requires an ultrasonic cleaner in the work area. Spray cleaners may also be appropriate. Water softeners may be necessary for finishing and cleaning operations. If workpieces cleaning is not dry, drying and preventing rust should be taken into account.

Experiments show that workpiece surface is bright after barrel finishing, and the surface is oxidized and becomes black soon after the surface active metal molecular is exposed in the air. The surface will become rusty after cleaning and dipping into the corrosion resistant fluid in half an hour. The dirt, oxide layer, rust spots, and other defects of workpieces after barrel finishing are removed, and this leads to expose fresh metal material into air. In addition, the surface of the workpiece has a water layer after cleaning with water solutions, which is enough to form a electrolyte solution that is necessary for electrochemical corrosion. Water ionization degree is small, but can be still ionized H^+ and $[OH]^-$. This ionization process increases with the raising temperature, that is,

$$H_2O \rightarrow H^+ + [OH]^-$$

There are CO_2 and SO_2 dissolved in water and form the following reaction:

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + [HCO_3]^-$$

Corrosion cell is formed with Fe and the impurity soaked in the ionic solution with various kinds of H^+, $[OH]^-$, $[HCO_3]^-$, etc., and Fe is the anode and the impurity is the cathode. In general, the water layer contains oxygen, anodic Fe is oxidized to Fe^{2+} ions and forms $[OH]^-$ions in cathode by obtaining oxygen. Corrosion reaction is

$$2Fe + O_2 + 2H_2O = 2Fe(OH)_2$$

There are many methods to drying and preventing rust, and different methods have their advantages and disadvantages. Specific methods and using cases are shown in Table 2.29.

As stated above, practical process of barrel finishing technology is as follows: degreasing → cleaning → deburring and finishing → sieving → cleaning → drying → anti-rust, as shown in Fig. 2.109. The workpiece that switches to later processes soon or is not allowed to dig oils will adopt dehydration methods of head drying, which can get the ideal effect.

2. The method of experimental study

(1) Research methods of finishing procedure and mechanism

Common methods about finishing procedure and mechanism are shown in Fig. 2.110. These methods can model, deepen finishing theory, and optimize parameters through recording the mixture motion (by high-speed camera), testing the force situation, simulating (by finite element analysis and discrete element analysis), etc., finally to gain finishing results as needed.

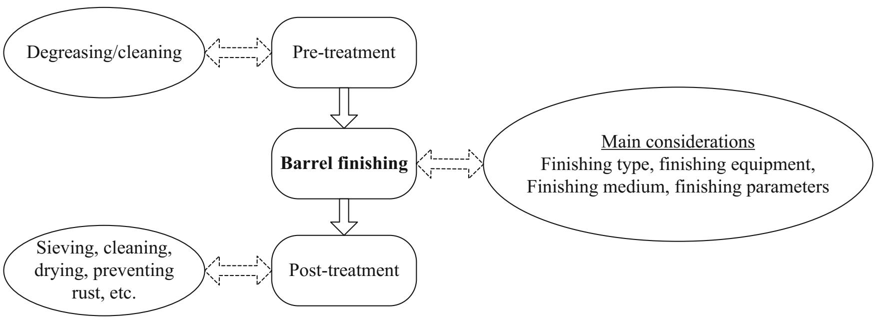


Fig. 2.109 Technical process of barrel finishing

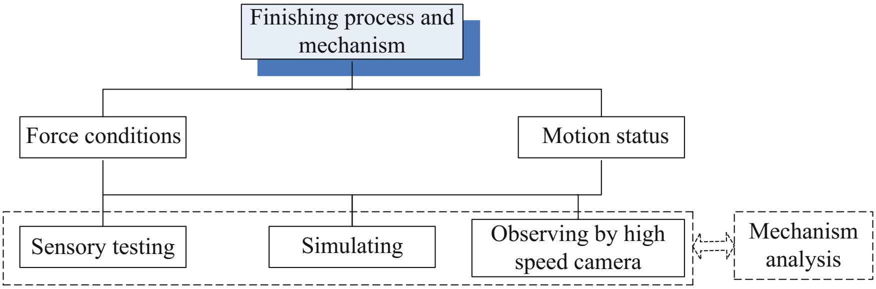


Fig. 2.110 Common study methods of finishing process and mechanism

(2) The method of finishing effects

Common study methods about finishing effects are shown in Fig. 2.111. These methods mainly study the material removal ability of the workpiece and the improvement of surface geometric features (surface roughness, surface texture, surface defect, etc.) and the physical and mechanical properties of surface layer (surface micro-hardness, surface metamorphic layer, surface stress state,etc.) under various actions of influence factors. Additionally, the processing capacity of certain barrel finishing technique, the influence rule of surface quality, and surface integrity can be studied, to provide reasonable parameters for industrial application.

2.9.2 Applications

1. Barrel finishing processes of miscellaneous parts with small sizes

Miscellaneous parts have a great variety and can divide into castings, punching parts, powder metallurgical parts, machining parts, spring parts, and special parts according to final forming method.

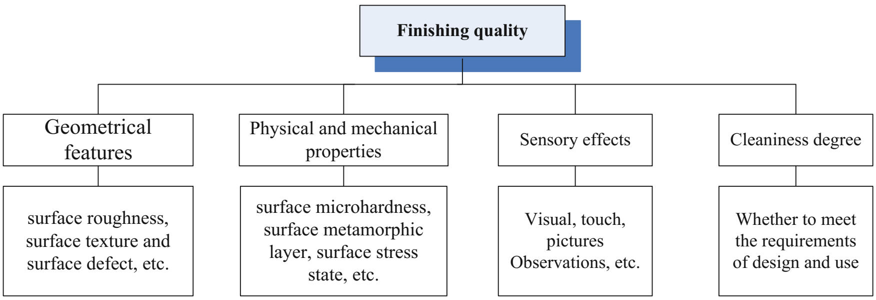


Fig. 2.111 Common study methods of finishing results

Case 1. Safes-handle

(1) Workpiece conditions and requirements of barrel finishing

Safes-handle is steel material, its blank is casting, and large flash is removed with grinding wheel after casting. Surface requirements of safes-handle need to be smooth and meet electroplating requirements.

(2) Finishing equipment

The horizontal inclined centrifugal mass finishing equipment is adopted. The drum total volume is 4 × 15 L. The revolution speed of the drum is 180 r/min, and the rotational speed of the drum is −180 r/min.

(3) Process arrangement and finishing medium

Rough processing:

Abrasive blocks are brown alumina, oblique triangle prism with 15 mm × 15 mm × 15 mm, the granularity is $180^{\#}$, and the total volume is approximately 40% of the drum volume. Compounds' solution is LC-10 (suitable to ferrous metal), and the load is about 50 g for each drum. The total volume of parts added is approximately 40% of the drum volume. Enough water is added to cover the mixture of abrasive blocks and parts, above 10 mm than the mixture. The processing time is 40 min.

Finishing processing:

Abrasive blocks are white alumina, sphere with Φ5 mm, and the granularity is $240^{\#}$; the total volume is approximately 55% of the drum volume. The total volume of parts added is approximately 20% of the drum volume. Compounds' solution is LC-10, and the load is about 80 g for each drum. Enough water above 15 mm of the mixture is added. The processing time is 20 min.

(4) Processing results

After rough processing, the surface of the workpiece is smooth and even. By finishing processing, workpiece surface is smooth and light, and meets electroplating requirements.

Using similar barrel finishing method, all kinds of miscellaneous casting or forging parts with small sizes can be deburred or finished, such as various wrench by forging forming, pipe joints of malleable steel casting, hose connections of cast steel, engine connection rod, valve pendulum pole, cipher lock case.

Case 2. Lock body plate

(1) Workpiece conditions and requirements of barrel finishing

The shape of lock body plate is shown in Fig. 2.112. The material of the lock body plate is Q235. All edges of lock body plate have burrs after stamping process. The size of the workpiece is small and thin. Finishing requirements are removing all burrs and rust spots.

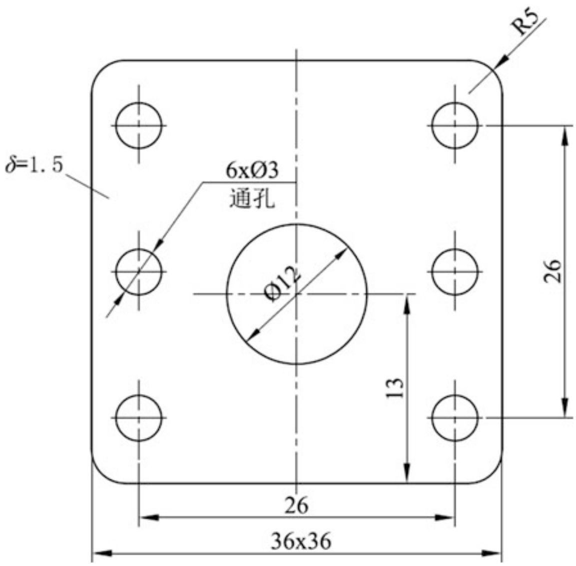


Fig. 2.112 Diagram of lock body plate

(2) Finishing equipment

Vertical vibratory barrel finishing equipment is adopted. The total volume of the barrel is 150 L, vibratory frequency is 1800 times/min, and amplitude is 3–4 mm.

(3) Finishing medium and finishing parameters

The abrasive blocks are brown alumina, oblique triangle prism with 12 mm × 12 mm × 12 mm, the granularity is $240^{\#}$, and the total volume is approximately 60% of the barrel volume. The total volume of parts added is approximately 1/4 volume of abrasive blocks used. Dry finishing is applied to avoid workpieces sticking together. The processing time is about 30 min.

(4) Processing results

After finishing, workpiece surface is gray and is not so bright, but all burrs are removed and the workpiece has no distortion.

Using similar barrel finishing method, deburring ability is good for all kinds of flat parts, such as motor stator plates, chain plates of stepless speed regulator.

Case 3. Universal wheel frame

(1) Workpiece conditions and requirements of barrel finishing

Universal wheel frame is formed with stamping and bending using Q235 steel plates. There are burrs at the stamping circumference and bending marks. Finishing requirements are used to remove all burrs, smooth and bright surfaces, and to meet the electroplating requirements.

(2) Finishing equipment

The horizontal centrifugal barrel finishing equipment is adopted. The drum total volume is 4 × 20 L. The revolution speed of the drum is 180 r/min, and the rotational speed of the drum is −180 r/min.

(3) Process arrangement and finishing medium

Rough processing:

The abrasive blocks are brown alumina, oblique triangle prism with 15 mm 15 mm × 15 mm, the granularity is 200#, and the total volume is approximately 45% of the drum volume. Compounds solution is LC-10, and the load is about 40 g for each drum. The total volume of parts added is approximately 15% of the drum volume. Enough water is added to cover the mixture of abrasive blocks and parts, and it is above 10 mm than the mixture. The processing time is 30 min.

Finishing processing:

Abrasive blocks are white alumina, sphere with Φ5 mm, the granularity is 240#, and the total volume is approximately 55% of the drum volume. The total volume of parts added is approximately 15% of the drum volume. Compounds solution is LC-10, and the load is about 80 g for each drum. Enough water above 15 mm of the mixture is added. The processing time is 15 min.

(4) Processing results

After rough processing, workpiece surfaces have no rust or scratch, and all burrs are removed. By finishing processing, workpiece surface is smooth and light, and meets electroplating requirements.

Using similar barrel finishing methods, all kinds of stamping parts can be finished, such as stamping parts on textile machine/camera/printer/bicycle.

Case 4. Metal glasses frame

(1) Workpiece conditions and requirements of barrel finishing

Metal glasses frame is mainly welded using thin rod blank with alloy material. Its surfaces are rough and have welding burrs. The surface requirements need to be smooth and bright, and meet the electroplating requirements.

(2) Finishing equipment

Vertical vibratory barrel finishing equipment is adopted. The total volume of the barrel is 150 L, vibratory frequency is 1800 times/min, and amplitude is 3–4 mm.

(3) Process arrangement and finishing medium

Rough processing:

Abrasive blocks are ceramic, and oblique triangle prism with 10 mm × 10 mm × 10 mm; the total volume is approximately 60% of the barrel volume. The total volume of parts added is approximately 1/6 ~ 1/5 the volume of abrasive blocks used. Compounds solution is LC-13 (suitable for nonferrous alloy materials). The water in the container, using water circulation device, is not less than 10 kg, and the mass portion of compounds in water is about 5‰.

Finishing processing:

The abrasive blocks are high alumina ceramics, it has sphere with Φ5 mm, and the total volume is approximately 70% of the barrel volume. The total volume of parts added is approximately 1/6 the volume of used abrasive blocks. The water in the container, using water circulation device, is not less than 15 kg, and mass portion of compounds in water is about 1%.

(4) Processing results

After rough processing, workpiece surfaces are smooth, and all burrs are removed. By finishing processing, workpiece surface is smooth and light, and it meets electroplating requirements.

Using similar barrel finishing methods, all kinds of thin rod parts and stamping flat parts can be finished, such as camera's optical eye, bearing cage.

Case 5. Magnetic sheet for neodymium iron boron (NdFeB) material

(1) Workpiece conditions and requirements of barrel finishing

The hardness of magnetic sheet is high, and the size is generally 10 mm × 10 mm × 2 mm or Φ15 mm × 1.5 mm. Edges of magnetic sheet after forming are sharp. Finishing requirements are the uniform edge rounding and edge radius of 0.1–0.2 mm.

(2) Finishing equipment

The horizontal inclined centrifugal mass finishing equipment is adopted. The drum total volume is 4 × 8 L, and each drum is detachable. The revolution speed of the drum is 200 r/min, and the rotational speed of the drum is −200 r/min.

(3) Finishing medium and finishing parameters

Abrasive blocks are high alumina ceramics, oblique triangle prism with 15 mm × 15 mm × 15 mm, and the total volume is approximately 45% of the barrel volume. The total volume of parts added is approximately 15% of the drum volume. Compounds solution is LC-10, and mass portion of compounds in water is about 5‰. Enough water above 15 mm of the mixture is added. The processing time is 30 min.

(4) Processing results

After the barrel finishing, edges of magnetic sheet are uniform and the edge radius is about 0.1–0.2 mm. Electroplating requirements can be improved, and electroplating quality is increased.

Case 6. Push rod

(1) Workpiece conditions and requirements of barrel finishing

A kind of push rods for safe device is shown in Fig. 2.113. Its material is 45 steel. Requirements are as follows: Cylindrical dimension precision is high, and the right cone mating with bearing seat hole is smooth and it cannot have burrs.

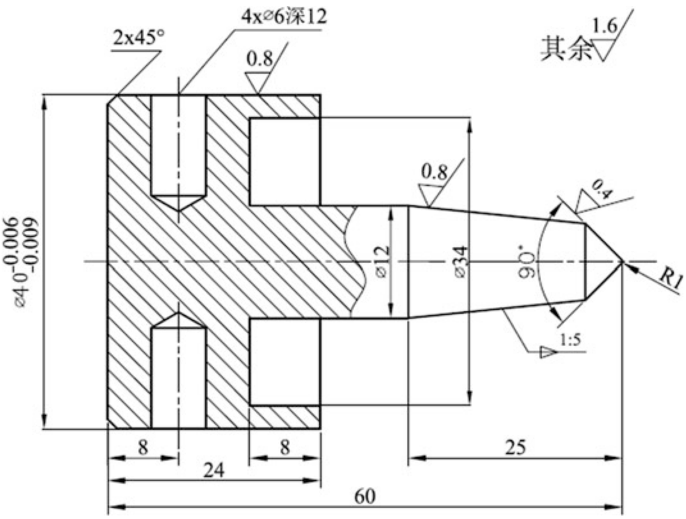


Fig. 2.113 Diagram of the push rod

(2) Finishing equipment

The horizontal centrifugal barrel finishing equipment is adopted. The drum total volume is 4 × 15 L. The revolution speed of the drum is 180 r/min, and the rotational speed of the drum is −180 r/min.

(3) Finishing medium and finishing parameters

Abrasive blocks are white alumina, sphere with Φ5 mm, and the granularity is 240#; the total volume is approximately 65% of the drum volume. The total volume of parts added is approximately 8–10% of the drum volume. Compounds solution is LC-10, and the load is about 30 g for each drum. Enough water above 10 mm of the mixture is added. The processing time is 15 min.

(4) Processing results

The surface roughness value *Ra* decreases from 0.8–1.2 μm to 0.6 μm. Edge radius can be assured. The hardness of surface layer increases in an average of 14 HV. All burrs are removed. The cone surface after assembly can be flexible to rotate and can ensure the service performance.

Using similar barrel finishing method, black metal machined parts with high dimensional accuracy can be finished, such as valve rod, valve lifter, fuel injection nozzle, bearing inner ring and outer ring, CO_2 welding nozzle, insulating bushing, conductive nozzle.

Case 7. The base of sight device

(1) Workpiece conditions and requirements of barrel finishing

The base of sight device for certain shotgun is shown in Fig. 2.114. Its material is aluminum alloy, and the shape is complex and is made of spherical surface, cylindrical surface, oblique plane, etc. Precisions of form and position by turning and milling processes are high. Finishing requirements are removing all burrs, and surface roughness value *Ra* is 0.8 μm.

(2) Finishing equipment

The horizontal centrifugal barrel finishing equipment is adopted. The drum total volume is 4 × 15 L. The revolution speed of the drum is 180 r/min, and the rotational speed of the drum is −180 r/min.

(3) Finishing medium and finishing parameters

Abrasive blocks are high alumina ceramics, oblique cylinder with Φ3 mm 5 mm, the granularity is 240#, and the total volume is approximately 70% of the drum volume. The total volume of parts added is approximately 8–10% of the drum volume. Compounds solution is LC-12 (suitable for zinc aluminum alloy), and the load is about 40 g for each drum. Enough water above 10 mm of the mixture is added. The processing time is 12 min.

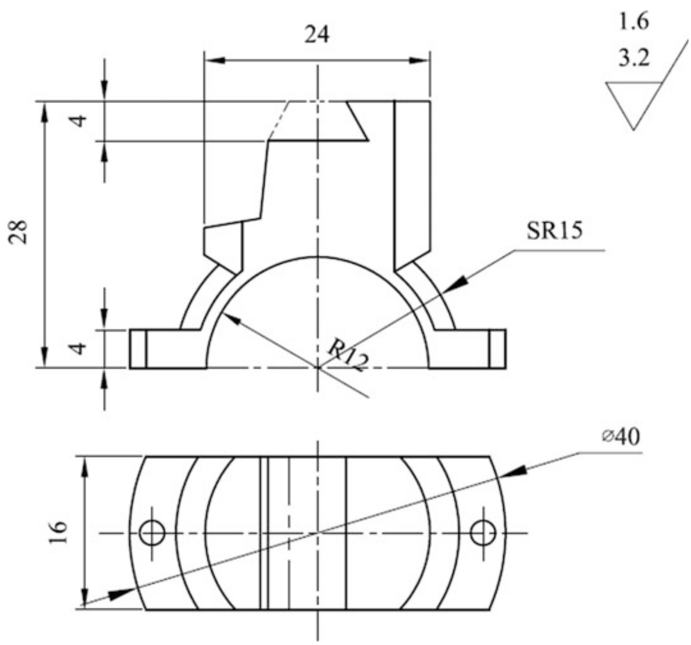


Fig. 2.114 Diagram of the base of sight device

(4) Processing results

After finishing, all burrs are removed and the edges are filleted. The surface roughness value *Ra* decreases from 1.6 to 0.8 μm, and the surface is smooth and the surface color is uniformly bright.

Using similar barrel finishing method, nonferrous metal complex parts with high dimensional precision can be finished, such as copper torch with argon arc welding, electrode, shunt, fittings, chuck, chuck base.

The process methods and equipment used for above cases are not unique. Other equipment with corresponding finishing parameters also can be chosen. For example, whirling barrel finishing equipment can also be selected to finish case 3, 6, and 7.

Except for parts mentioned above, some parts with special requirements can be finished with barrel finishing processes and obtain ideal effects. Here are some examples.

(1) Gears of the gear pump in one factory (gear material is 40Cr) were finished in 20 min by centrifugal barrel finishing process. After finishing, the gear machining precision degree did not change, the surface hardness increased to 15 HV, the surface roughness degree of teeth surface and end surface increased by one degree, the surface tensile stress (33.82 MPa) is converted to compressive stress (−589.4 MPa), and edges radius is 0.1–0.2 mm. After assembly with finished gears, the noise of the pump decreased by 2 dB, the scratches of end surface and pump body decreased, and using performance of the gear pump is improved.
(2) Springs in one factory, finished by barrel finishing, have good finishing quality: The burrs were removed, the physical and mechanical properties were improved, and service life was extended. Through fatigue tests, cycles of the spring are varied from 36,000 times to 52,000 times by barrel finishing.
(3) For riveting parts (such as new handcuffs) and hinging casting parts (such as universal ball hinge), comprehensive effects of deburring and surface finishing are well after barrel finishing.

Figure 2.115 shows comparison photographs before and after finishing of miscellaneous parts with small sizes.

2. Barrel finishing processes of shaft parts

Case 1. 195 crankshaft

(1) Workpiece conditions and requirements of barrel finishing

The material of 195 crankshaft is ductile cast iron. The break rate of the machined product is about 3‰ during normal use. Finishing requirements are surface comprehensive effects are good, and physical and mechanical properties are obviously improved after barrel finishing [58].

Fig. 2.115 Comparison photographs of miscellaneous parts with small sizes. **a** Before finishing; **b** after finishing

(2) Finishing equipment

The vertical spindle barrel finishing equipment is adopted. The diameter of the barrel is 900 mm, and the height is 650 mm. The rotational speed of the barrel is 35 r/min or 150 r/min for the spindle. There are four spindles, and four workpieces are loaded at one time.

(3) Finishing medium and finishing parameters

The abrasive blocks are white alumina, sphere with Φ5 mm, and the granularity is 240#. The height of abrasive blocks added is approximately 500 mm. Compounds solution is LC-10, and the load is about 500 g. Enough water above 10–20 mm of abrasive blocks is added. The processing time is 15 min, and the time for half period t is 1.5 min. The cycling process is done as $(N, -n, t) \Leftrightarrow (0, 0, \Delta t) \Leftrightarrow (-N, n, t)$.

(4) Processing results

Experimental results indicate that machining precision of the journals is unchangeable, surface quality obviously increases, and physical mechanical properties have heavy improvement. The testing data of 195 crankshaft before and after barrel finishing is shown in Table 2.30.

Case 2. 488 camshaft

The finishing equipment and finishing process are similar with 195 crankshaft finishing noted in Case 1. The camshaft is loaded into the spindle twice by turning the camshaft over 180°. After finishing, all burrs can be removed and the surface texture is finer. The stresses on different positions tend to be consistent, which are beneficial to improve fatigue resistance and decrease scratches between valve stem and cam surface. The testing data of the stress is shown in Table 2.31.

Using similar barrel finishing method, shaft disk parts with small or medium sizes can be finished, such as camshaft, crankshaft, spiral grooved shaft and drum on textile equipment, gear shaft, ball screw, worm, damping pipe, turbocharger turbine. Figure 2.116 shows comparison photographs of certain blade by vertical spindle barrel finishing process, and surface texture shown in Fig. 2.117. By fatigue testing, fatigue life is greatly improved, and it is shown in Fig. 2.118. Figure 2.119

Table 2.30 Comparison data of 195 crankshaft before and after barrel finishing

Finishing state	Ra/μm		Micro-hardness/HRC		Connecting rod journals stress/MPa		Metallographic observed under the electron microscopy
	Main journal	Connecting rod journal	Main journal	Connecting rod journal	tangential	normal	
Before finishing	0.63	0.67	40	39	−149	−423	Loose
After finishing	0.35	0.38	45.6	46	−703	−655	Dense layer with about 24 μm

Table 2.31 Comparison data of camshaft stress before and after finishing

Finishing state	Tangential stress/MPa			Axial stress/MPa		
	Top	Side	Bottom	Top	Side	Bottom
Before finishing	−357	−102	−281	−324	+167	−350
After finishing	−572	−543	−487	−494	−563	−519

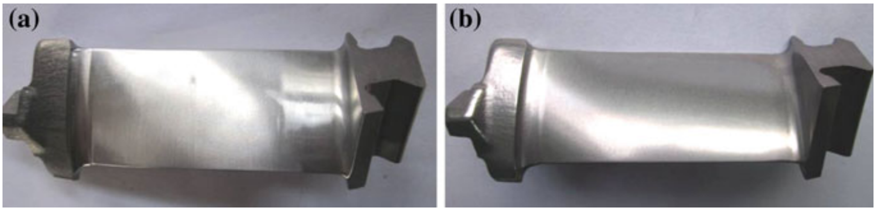


Fig. 2.116 Comparison photographs of certain blade by vertical spindle barrel finishing process. **a** Before finishing; **b** after finishing

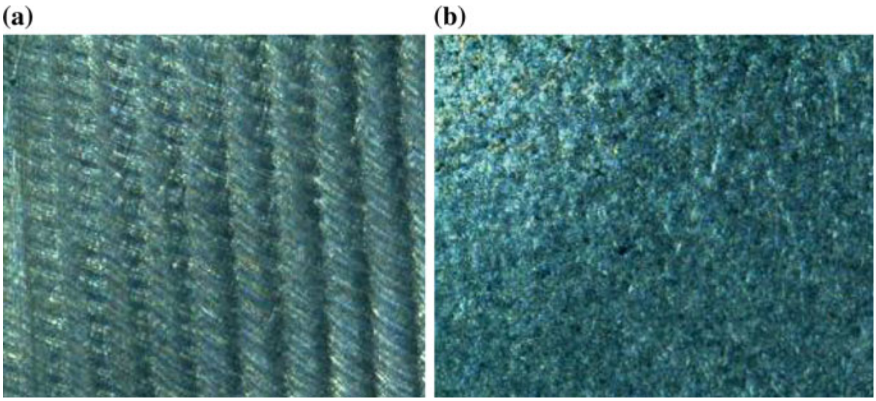


Fig. 2.117 Comparison of surface texture of certain blade by vertical spindle barrel finishing process. **a** Before finishing; **b** after finishing

shows comparison photographs of certain labyrinth disk by vertical spindle barrel finishing process.

For shaft parts with large or medium sizes (especially for camshaft, crankshaft), better finishing effects can be received by horizontal spindle barrel finishing process [59]. Comparisons of surface roughness value *Ra* for certain camshaft and crankshaft are shown in Tables 2.32 and 2.33.

Comparison curves of the material ratio of the profile for certain four cylinder diesel engine camshafts are shown in Fig. 2.120.

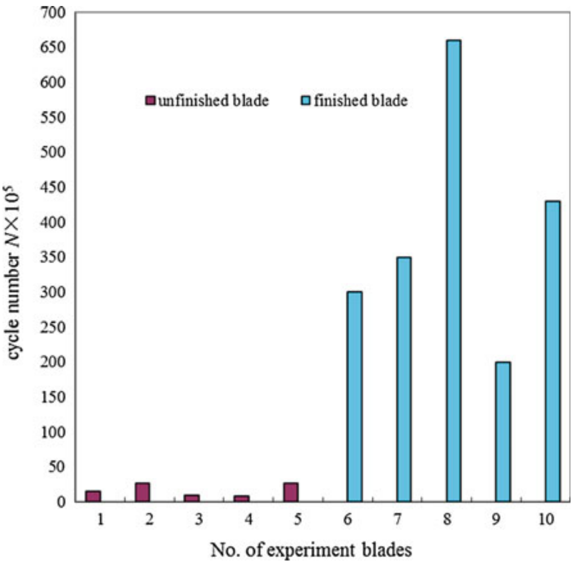


Fig. 2.118 Comparison of fatigue life of certain blade by vertical spindle barrel finishing process

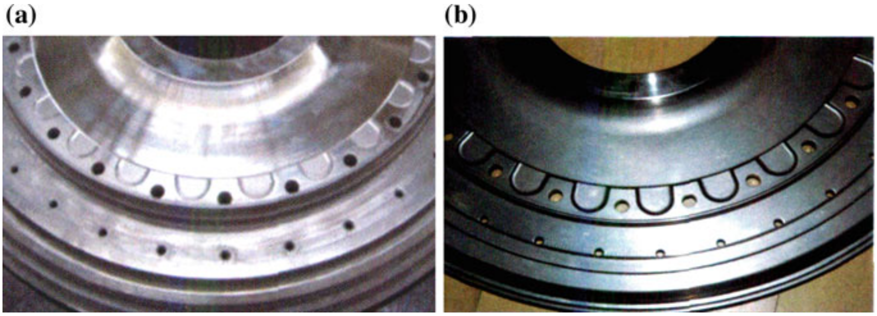


Fig. 2.119 Comparison photographs of certain labyrinth disk by vertical spindle barrel finishing process. **a** Before finishing; **b** after finishing

Table 2.32 Comparison of surface roughness value *Ra* for certain crankshaft

Finishing state	Connecting rod journals		Main journals
	The outside position	The inside position	
Before finishing	0.605	0.475	0.149
After finishing	0.170	0.276	0.06

Figure 2.121 shows comparison photographs of surface textures (500 times magnification) for M11 camshaft. Figure 2.122 shows comparison photographs of certain camshaft and crankshaft.

Table 2.33 Comparison of surface roughness value *Ra* for certain camshaft

Finishing state	The surface of bearing journal	The surface of small camshaft	The surface of large camshaft
Before finishing	0.361	0.442	0.486
After finishing	0.181	0.131	0.148

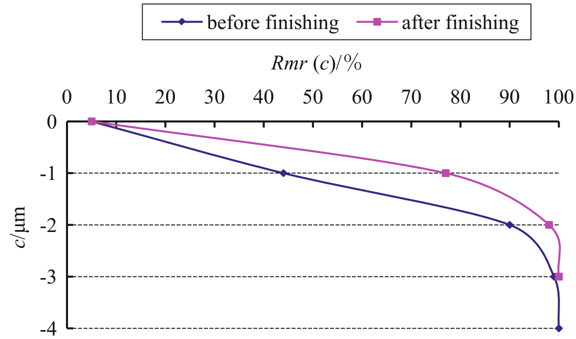


Fig. 2.120 Comparison curves of the material ratio of the profile for certain four cylinder diesel engine camshafts

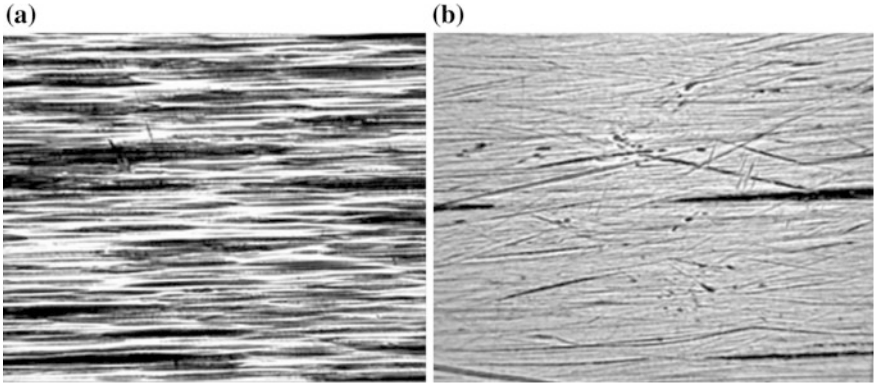


Fig. 2.121 Comparison photographs of surface textures (500 times magnification) for M11 camshaft. **a** Before finishing; **b** after finishing

Comparisons of some military camshaft after using 350 h are shown in Fig. 2.123. It can be shown that there are obvious scratches on the unfinished camshaft surface and not on finished surface. This phenomenon also illustrates that the changes of the surface roughness, surface textures, and physical–mechanical properties of the surface layer (surface micro-hardness, surface metamorphic layer, the surface stress state, etc.), can also lead to the wear resistance increase and scratches decrease after barrel finishing.

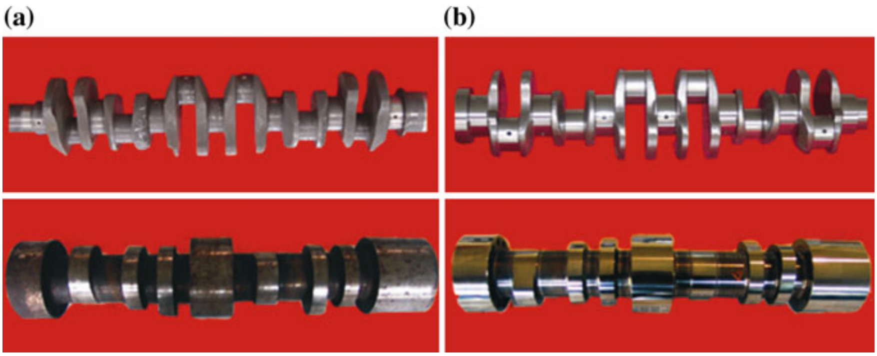


Fig. 2.122 Comparison photographs of certain camshaft and crankshaft. **a** Before finishing; **b** after finishing

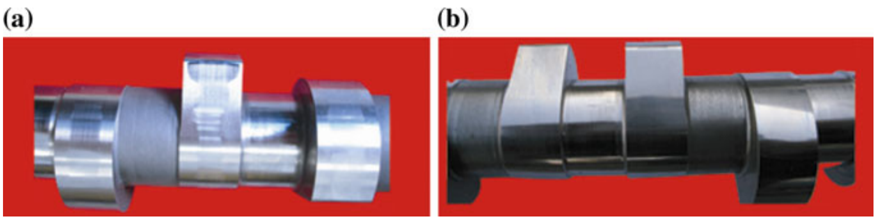


Fig. 2.123 Comparison photographs of some military camshaft after finishing 350 h. **a** Before finishing; **b** after finishing

Fig. 2.124 Finishing status of gear shaft with large gear module

By horizontal spindle barrel finishing process, gear shaft with large gear module can also be finished, and the finishing status is shown in Fig. 2.124.

3. Barrel finishing processes of disk parts

Case 1. Steel wheel hub for 130 automobile

(1) Workpiece conditions and requirements of barrel finishing

The blank of wheel hub for 130 automobile is welded after being rolled using steel plate and steel strip. The diameter of wheel hub is 440 mm, and the thickness is 200 mm. The rim of hub surface has burrs. The surface of steel plate and steel strip is untreated and has rust. One of the welding joints of cylinder surface has been razed. There are welding joints at the same circle of the axial end surface. Finishing requirements are as follows: All burrs are removed, all rust spots of outer and inner surface are cleaned, surfaces of welding joints are smooth, and electroplating requirements are met.

(2) Finishing equipment

Intermeshing spindle barrel finishing equipment is adopted. The diameter of the barrel is 1200 mm. The rotational speed of the barrel is 50 r/min or 88 r/min for the spindle. Spindle deviation angle α is 15° and β is 30°.

(3) Finishing medium and finishing parameters

Abrasive blocks are high alumina ceramics, sphere with Φ3 mm, and the granularity is $200^{\#}$. The height of abrasive blocks added is approximately 2/3 of the barrel height (about 250 kg). Compounds solution is LC-10, and the load is about 500 g. Enough water just covering abrasive blocks is added. The processing time is 20 min, and the time for half period t is 1.5 min. The cycling process is done as $(-N, -n, t) \Leftrightarrow (0, 0, \Delta t) \Leftrightarrow (N, n, t)$.

(4) Processing results

The wheel hub surfaces after finishing are smooth, light, and shining. The edges burrs are removed. Both surfaces of welding joints are smooth and meet electroplating requirements. Comparison photographs before and after finishing are shown in Fig. 2.125.

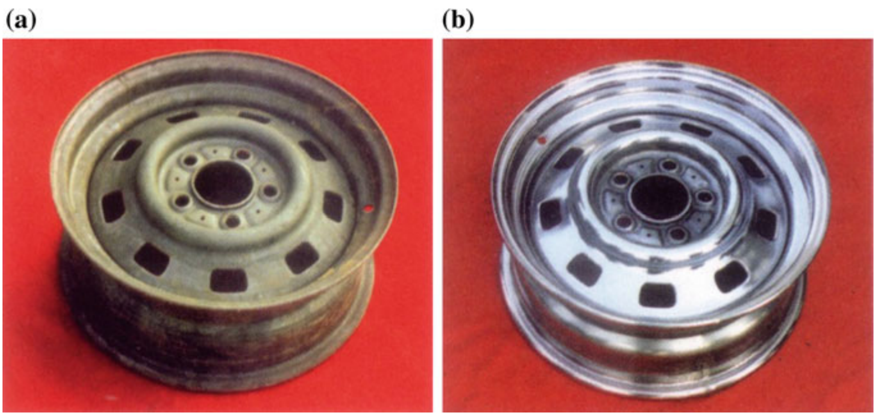


Fig. 2.125 Comparison photographs of wheel hub for 130 automobile. **a** Before finishing; **b** after finishing

Case 2. High-end aluminum alloy wheel hub

(1) Workpiece conditions and requirements of barrel finishing

Finishing requirements are as follows: All burrs and flash around the decorating holes are removed, all edges filleted are uniform and smooth, and each adjacent surface cannot be scratched.

For now, the used technological process on these issues at workshops is manually polishing using rotary scraper blade, but polishing quality is bad (main problems are remaining burrs, non-uniform edge radius, matte surface, easy to scratch adjacent surface, and low production efficiency).

(2) Finishing equipment

Intermeshing spindle barrel finishing equipment is adopted. The diameter of the barrel is 1200 mm. The rotational speed of the barrel is 50 r/min and 88 r/min for the spindle. Spindle deviation angle α is 15° and β is 30°.

(3) Finishing medium and finishing parameters

Rough processing:

The abrasive blocks mixed with different shapes and sizes are used to finish. The processing time is 10 min. Other conditions are the same with Case 1.

Semi-finishing processing:

Conditions are the same with Case 1.

Finishing processing:

The abrasive blocks are stainless steel, sphere with Φ5 mm, and some kerosene is added. The processing time is 5 min.

(4) Processing results

By rough processing, burrs are removed, edge filleting is uniform, and there are no scratches on the surface. After semi-finishing processing, the surface is smoother, and the surface texture is more isotropic. After finishing processing, all finished surfaces are smooth and bright. The comparison photographs of aluminum alloy wheel hub are shown in Fig. 2.126.

Based on the process principle of intermeshing spindle barrel finishing, two kinds of automatic production line for finishing high-end aluminum alloy wheel hub are developed independently, as shown in Fig. 2.127. Compared with other finishing processes for wheel hub, this process has good quality, high efficiency, and low cost. Finishing effects are shown in Fig. 2.128.

Case 3. Gear (gear module m = 3, teeth number z = 78)

In the standard of cylindrical gears accuracy (GB 10095), edge filleting has specific requirements [60]. Three edges along different directions from the teeth tip should be filleted (shown in Fig. 2.129), in order to improve bearing capacity, running stability, and reliability.

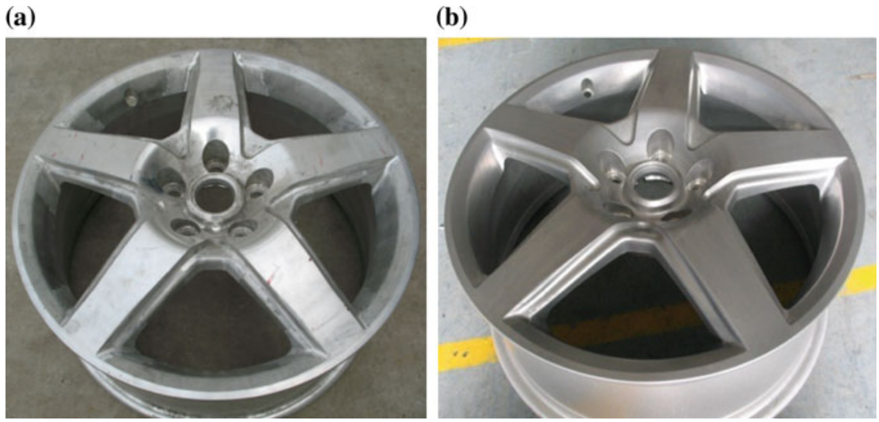


Fig. 2.126 Comparison photographs of aluminum alloy wheel hub. **a** Before finishing; **b** after finishing

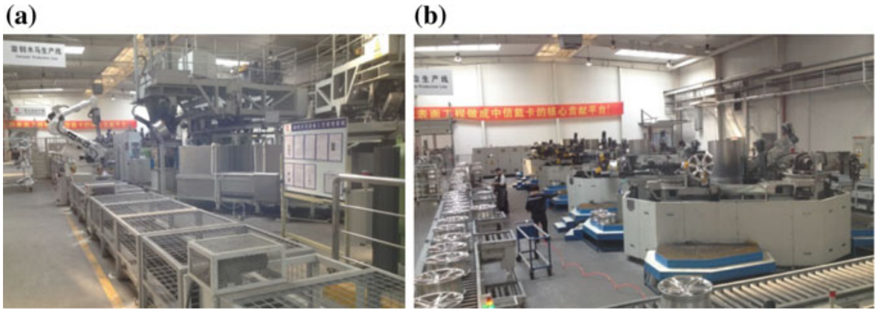


Fig. 2.127 Automatic production line for finishing high-end aluminum alloy wheel hub. **a** C410; **b** DQ500

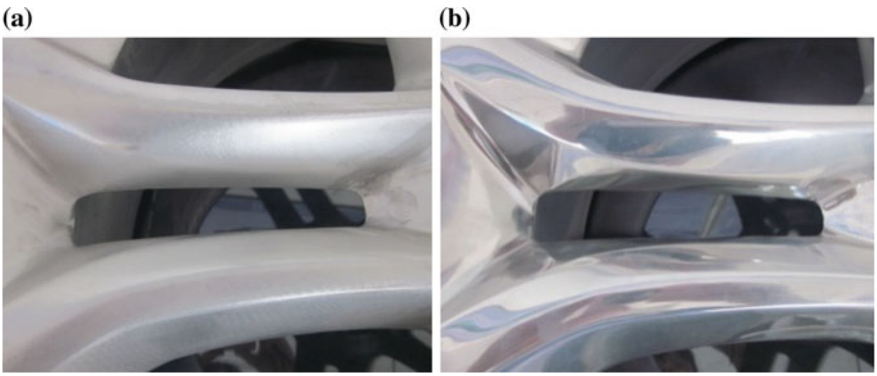


Fig. 2.128 Comparison photographs of high-end aluminum alloy wheel hub. **a** Before finishing; **b** after finishing

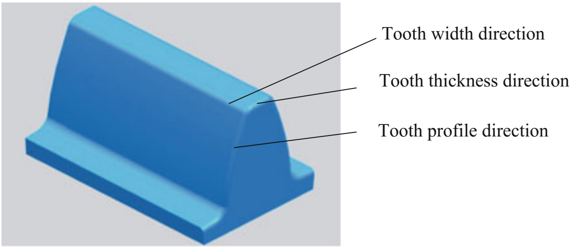


Fig. 2.129 Diagram of edge filleting for gears

For certain gear of textile equipment accessories (its material is 40Cr, and edge filleting along different directions need to be done in around 0.3 mm according to the drawing designs) produced by international joint ventures in China, the intermeshing spindle barrel finishing process is used to finish in about 15 min. Experimental results show that edges along different directions have small radius, all burrs are removed, and teeth surface roughness, surface hardness, and surface stress are improved. The comparison photographs before and after mass finishing are shown in Fig. 2.130.

Using similar barrel finishing methods, all kinds of gears, sprockets, cycloid gears, synchronous belt wheels, cams, automobile wheel hubs, motorcycle wheel hubs and rims, turbocharger turbines and cases, high-end nutrition pots with large or medium sizes can be finished. Figure 2.131 shows the comparison photograph of certain gear.

4. Parts cleanliness improvement

Crankshaft is one of the most critical components of the engine, and its cleanliness degree has important influence on engine reliability. Therefore, engine manufacturing enterprises not only control its material, machined sizes, and tolerances, but also control its cleanliness degree, which is one of the most important factors.

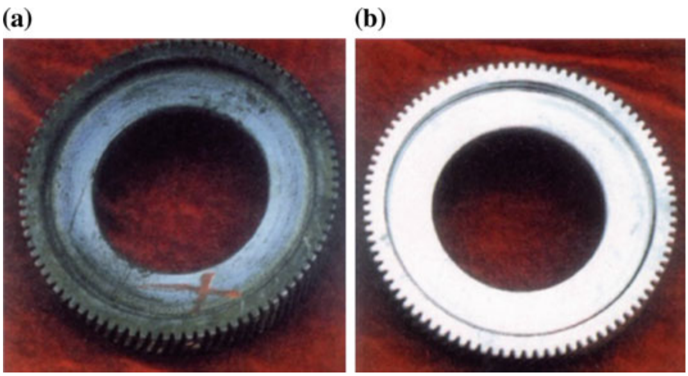


Fig. 2.130 Comparison photographs of certain gear of textile equipment accessories. **a** Before finishing; **b** after finishing

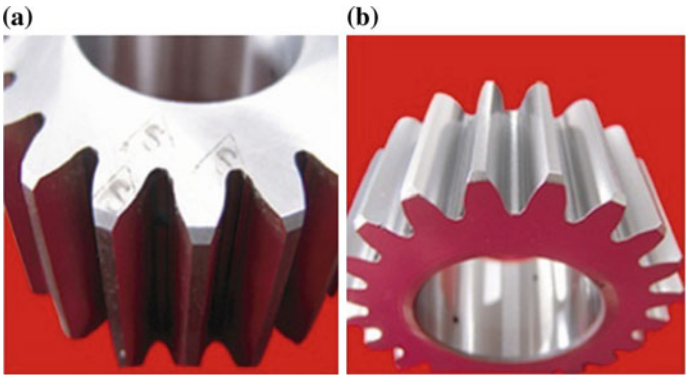


Fig. 2.131 Comparison photographs of certain gear. **a** Before finishing; **b** after finishing

The cleanliness is machinery residual impurity degree of products system and the channels. Effective factors on the cleanliness are residual impurities during processing, so improving the engine cleanliness is to reduce the abrasive wear caused by these impurities. Main source of these impurities is residual impurities which are not removed, such as the burrs, metal debris. These impurities could produce scratching or scoring to the cylinder, damage crankshaft, crankshaft bearing, hinder cooling water flow,etc., which affects the product life and performance. Therefore, it is important to improve the cleanliness degree of crankshafts.

Table 2.34 shows contrast data of cleanliness degree by crankshaft finishing. Before finishing, its cleanness degree cannot meet the design and use request. By barrel finishing, its cleanness degree improves (the reason includes the following: Burrs and residue on the casting are removed, and non-machined surfaces are finished). Therefore, it can further improve its usage performance and meet requirements.

Table 2.34 Contrast data of crankshaft cleanliness before and after barrel finishing

Company name	Crankshaft type	Cleanliness degree [mg]		
		Requirement	Before finishing	After finishing
Tianrun Crankshaft Ltd.	YC4108	≤ 66	>100	40.8 ± 10
Jiangsu Songling Crankshaft Ltd.	6 cylinder	≤ 200	>400	180 ± 20
Xiangtan Xinghuang Crankshaft Ltd.	G6135	≤ 200	>400	160 ± 30
Hangzhou Xianglong Crankshaft Ltd.	MR479Q	≤ 15	>20	10 ± 2

5. Improvement of the engine performance

The engine is a main power of automobile, engineering machinery, agricultural machinery, etc. It is an eternal subject developing the engine performance. Among factors influencing engine performance, surface quality of parts with frication pairs is one main factor. For a long time, the traditional manufacture level is relatively steady, and some technical requests of mechanical parts with frication pairs for mass products, such as deburring, edge filleting, are often be ignored. There are absences of understanding and realizing method about the surface texture, surface layer properties (physics, mechanics, chemistry, and optics), and the surface layer structure. Researches on improving the engine performance are often focused on modifying the engine's local structure, changing working process,etc. Owing to the difference of surface quality, the domestic running-in process is long in time and low in quality. There is more consumption in human and material resource.

With the development of special manufacturing process, surface finishing technique has been approbated through a long period application. It has functions on deburring, decreasing surface roughness, improving surface quality and physical–mechanical properties,etc. Aimed at the specific structure and the surface characteristic of engine's parts with frication pairs, it is imperative to develop the engine performance, decrease the fuel consumption, and improve the cleanness of the machine oil through using various finishing process.

Taking LL480QB diesel engines as the general testing subject, 17 kinds of parts are selected considering the overall structure of the engine (the friction parts mainly concentrated in the crank mechanism and the distribution mechanism) and the impact degree of the engine performance for surface quality and surface integrity of specific parts. Specific finishing technology is chosen according to the parts structure, the parts material, surface conditions, and finishing requirements (as shown in Table 2.35).

(1) Contrast analysis of finishing results

From the optical observation and the photograph contrast, parts have obvious burrs and sharp edges before finishing, and some parts look black (oxidized), dim, and rusty. After finishing, burrs and rusts are removed, sharp edges are filleted, and surfaces are smooth and glitter.

Testing comparisons of some typical parts is shown in Tables 2.36, 2.37, 2.38, 2.39, and Fig. 2.132. After finishing, the dimension precision can be insured because the dimension changes are within 0.001–0.005 μm. The surface roughness value *Ra* of all kinds of parts is basically reduced by around 0.5, and the material ratio of the profile Rmr(*c*) increases apparently, which can effectively improve wearing performances of frication pairs. The piston grooves and sharp edges of piston rings are filleted to around *R* 0.1 mm which has great significance on running-in quality of the cylinder liner and the decrement of fuel consumption.

Micro-hardness of the surface layer clearly increases, and the stress may vary from tensile stress to compressive stress (or the original compressive stress obviously increases), so the fatigue strength is developed and the service life is

Table 2.35 Specific finishing processes of main friction pairs

No.	Parts name	Parts material	Finishing processes	Finishing time/min
1	Crankshaft	QT800-2	Horizontal spindle barrel finishing	15
2	Connecting rod assembly (outside surface)		Vertical spindle barrel finishing	10
	Connecting rod assembly (two holes)		Magnetic abrasive finishing	8
3	Piston pin	20Cr10Si2Mo	Centrifugal barrel finishing	8
4	Piston	66-1eutectic silicon alloy	Vertical spindle barrel finishing	2
5	Piston ring components	Alloy casting	Centrifugal barrel finishing	8
6	Cylinder liner	Boron Cast Iron	Gas-particle two-phase flows finishing	10
7	Camshaft	45 steel	Horizontal spindle barrel finishing	15
8	Rocker shaft	20 steel	Vertical spindle barrel finishing	10
9	Intake valve	4Cr9Si2	Vertical spindle barrel finishing	10
10	Exhaust valve	4Cr10Si2Mo	Vertical spindle barrel finishing	10
11	Inner spring of valve	steel wire 4-10/50CrVA-2Y	Centrifugal barrel finishing	10
12	Outer spring of valve	steel wire 4-10/50CrVA-2Y	Centrifugal barrel finishing	10
13	Bump spur gear	45 steel	Intermeshing spindle barrel finishing	12
14	Crankshaft timing gear	45 steel	Intermeshing spindle barrel finishing	12
15	Camshaft gear	45 steel	Intermeshing spindle barrel finishing	12
16	Timing idler gear	45 steel	Intermeshing spindle barrel finishing	12
17	Idler gear	40Cr	Intermeshing spindle barrel finishing	12

prolonged. The surface texture of cylinder sleeve, crankshaft, and camshaft is P-shaped, and it is more suitable for oil storing than ring texture. The service life of valve springs increases by an average of 40% [58].

Deburring and improving edge quality can improve the suitability of frication pairs' parts and the engine cleanliness degree. Improving surface quality can enhance matching, sealing, and force transferring between parts with frication pairs;

Table 2.36 Comparison surface integrity indexes of crankshaft before and after finishing

Finishing state	*Ra*/μm		Micro-hardness/HRC		Tangential stress/MPa		Axial stress/MPa		Measured diameter basic size/mm	
	Main journal	Connecting rod journal	Main journal	Connecting rod journal	Main journal	Connecting rod journal	Main journal	Connecting rod journal	Main journal	Connecting rod journal
Before finishing	0.63	0.67	377	367	−293	−149	−171	−423	−0.015	−0.008
After finishing 15 min	0.35	0.38	449	444	−622	−703	−507	−655	−0.017	−0.012

Table 2.37 Comparison surface integrity indexes of camshaft before and after finishing

Finishing state	*Ra*/ µm	Micro-hardness/HV	Tangential stress/MPa			Axial stress/MPa		
			Top	Side	Bottom	Top	Side	Bottom
Before finishing	1.82	357	−289	+51	−20	−454	−365	−238
After finishing 15 min	0.95	393	−611	−524	−714	−899	−898	−775

Table 2.38 Varieties of main dimensions and *Ra* of piston before and after finishing

Finishing state	Ra/µm	Actual average size of tapered portion/mm	Actual average size of cylinder portion/mm
Before finishing	1.6	79.890	79.325
After finishing 2 min	0.4	79.886	79.320

Table 2.39 Surface integrity comparisons of idler gear before and after finishing

Finishing state	Ra/µm		Micro-hardness of the end face/HV	Stress of the teeth surface/MPa
	Tooth surface	End face		
Before finishing	0.71	0.42	525	33.82
After finishing 12 min	0.38	0.25	561	−589.40

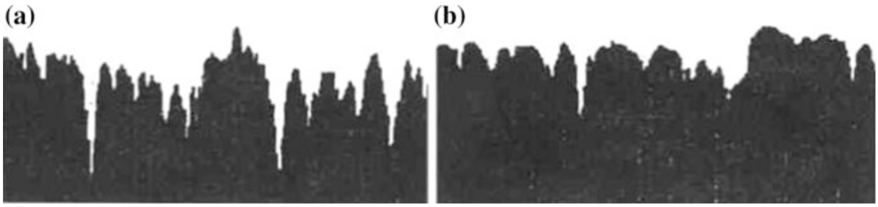


Fig. 2.132 Comparison photographs of surface texture of cylinder liner. **a** Before finishing; **b** after finishing

therefore, its initial abrasion can be decreased. Service life of parts and engines can be prolonged by improving physical–mechanical properties.

(2) Contrast testing of the engine performance

The mainly contrast of the engine performance is the contrast of running-in indexes in the factory. The normal standard is obtained by experience and analogy method based on the machining process, the condition of part quality, etc., which is shown in Table 2.40. According to the normal standard, oil samples of the engine

Table 2.40 Normal running-in standards

No.	Rotational speed/(r/min)	Power/kW	Dynamometer reading/N	Running time/min	Accumulated running time/min
I	700–2000	-	-	20	20
II	2200	-	32.5	35	55
III	2400	15	57.5	40	95
IV	2600	21	80.8	30	125
V	3000	26	92.3	15	140
VI	850	-	-	10	150

(No. 1 is the engine with unfinished parts, and No. 2 is the engine with finished parts) are extracted to take spectral analysis, and the fuel consumption rate is tested at regular intervals under various conditions. The principle of oil sample spectral analysis is that the wearing of frication pairs' parts becomes stable and normal when they are well-grounded, so the content of metal elements suspended in the engine oil becomes stable. The FAS-2C spectral analysis instrument is used in the experiment, and 20 ml oil samples are extracted to take spectral analysis at regular intervals when the engine runs in every operating mode, and the running-in quality is analyzed based on rules of elements' percentage in oil samples. The contents of 12 elements are separately tested, and contents of Fe, Al, and Cu are main factors that reflect the engine running-in performance (The content of Fe element is the most obvious, and other elements are essential elements of the fuel and its additive.). Table 2.41 is main experimental data on the normal standard [61, 62].

The contrast curves of Fe element content by spectral analysis are shown in Fig. 2.133.

Besides, the surface roughness *Ra* of friction pairs' unfinished/finished parts is tested before and after running-in, and contrast data are shown in Table 2.42.

Experimental results mentioned above show that ① in no-load and low-load running-in periods, Fe element content of oil sample in No. 2 is fewer by 18–35% than that in No. 1. The reason is that burrs are entirely removed, the surface roughness decreases, and the micro-peak wearing is light. These can indicate that the finishing process improves the engine cleanliness. ② In high-load period, Fe element content in No. 2 is basically stable, and this shows that the running-in time can be properly shorten. ③ The factory running-in fuel consumption in No. 2 reduces by around 30% more than that in No. 1, and the fuel consumption rate decreases by 3–4 g/kW h under the condition of 26 kW and 3000 r/min. ④ Fe element content in No. 2 decreases during continuous sampling under VI conditions, and its main reason is the obvious vibration behavior of the engine [63].

Through above analysis of testing results, there is an "extra running-in time" in the original running-in standards. New running-in standards after optimization are shown in Table 2.43. The main experimental data of the engine with unfinished parts under new running-in standards are shown in Table 2.44. The main experimental data of the engine with finished parts under new running-in standards are

Table 2.41 Main experimental data on the normal standard

Running-in conditions				Accumulated running time/min	Fe element content/ppm		Fuel consumption rate/(g/kW h)	
No.	*N*/(r/min)	*P*/kW	*Me*/N·m		№1	№2	№1	№2
I	0	-	0	0	2	4	-	-
	700	-	0	5	16	12	-	-
	1000	-	0	10	20	15	-	-
	1500	-	0	15	25	19	-	-
	2000	8	0	20	25	24	-	-
II	2200	-	32.5	25	31	31	-	-
				30	33	34	-	-
				35	36	34	-	-
				40	36	35	-	-
III	2400	15	57.7	48	39	36	-	-
				56	39	37	-	-
				64	42	37	-	-
				72	41	37	-	-
				80	40	36	-	-
IV	2600	21	80.8	88	40	35	276.23	255.07
				96	39	38	276.35	254.88
				104	42	40	274.88	253.89
				112	42	40	274.88	252.17
				120	40	40	274.14	251.28
V	3000	26	92.3	125	45	43	272.42	273.69
				130	49	44	320.86	273.48
				135	47	43	317.19	270.45
VI	600(667)	-	0	140	47	43	-	-
				145	47	38	-	-
				150	46	38	-	-

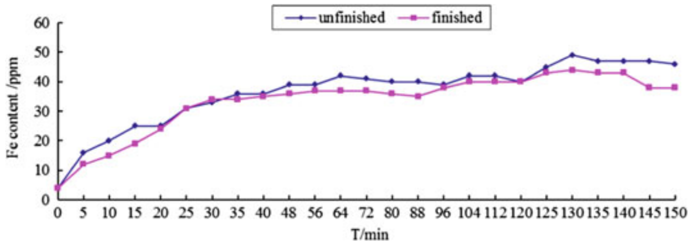


Fig. 2.133 Contrast curves of Fe element content

Table 2.42 Surface roughness comparisons of typical parts before and after running-in

Parts		Cylinder liner	Rocker shaft	Piston pin	Camshaft	Crankshaft		Intake valve	
						Main journal	Connecting rod journal	Journal	End surface
Before running-in	Unfinished	0.34	0.6	0.2	0.261	0.826	1.235	0.595	8.125
	finished	0.345	0.3	0.1025	0.126	0.66	0.875	0.25	7.5
After running-in	Unfinished	0.33	0.4	0.145	0.235	0.72	1.05	0.57	8.125
	finished	0.305	0.225	0.094	0.115	0.63	0.6525	0.245	7.45

Table 2.43 New running-in standards

No.	Rotational speed/(r/min)	Power/kW	Dynamometer reading/N	Running time/min	Accumulated running time/min
I	700–2000	-	-	20	20
II	2200	-	-	35	55
III	2400	15	62.5	40	95
IV	2600	21	80.7	30	125
V	3000	26	86.7	15	140

Table 2.44 Main experimental data of the engine with unfinished parts under new running-in standards

Running-in conditions				Accumulated running time/min	Fe element content /ppm	Fuel consumption rate/(g/kW h)	Air leakage/ (L/h)
No.	*N*/ (r/min)	*P*/ kW	*Me*/ N·m				
I	0	-	0	0	3	0	-
	700	-	0	3	15	-	11.1–11.8
	1500	-	0	6	20	-	13.5–13.6
	2000	8	40	10	25	-	18.1–19.2
II	2400	15	62.5	15	33	382.03	14.6–15.0
				20	36	377.50	11.8–12.4
				25	37	369.99	13.5–14.0

(continued)

Table 2.44 (continued)

Running-in conditions				Accumulated running time/min	Fe element content /ppm	Fuel consumption rate/(g/kW h)	Air leakage/ (L/h)
No.	*N*/ (r/min)	*P*/ kW	*Me*/ N·m				
III	2600	21	80.7	30	40	254.05	18.3–18.7
				35	40	253.22	16.1–16.5
				40	42	252.04	16.2–19.7
IV	3000	26	86.7	45	45	255.62	19.7–20.2
				50	47	252.84	19.4–20.1
				55	49	251.84	19.0–19.7
V	600	-	-	58	48	-	11.2–12
				60	44	-	11.8–12.5

shown in Tables 2.45 and 2.46. The contrast curves of Fe element content by spectral analysis under new running-in standards are shown in Fig. 2.134.

The data of air leakage in Tables 2.44 and 2.46 is measured by leakage monitor produced by Changsha test instrument factory. The basic principle of leakage

Table 2.45 New running-in standards

No.	Rotational speed/(r/min)	Power/kW	Dynamometer reading/N	Running time/min	Accumulated running time/min
I	1000–2000	0	0	10	10
II	2400	15	62.5	15	25
III	3000	26	86.7	15	40
IV	850	0	0	5	45

Table 2.46 Main experimental data of the engine with finished parts under new running-in standards

Running-in conditions				Accumulated running time/min	Fe element content /ppm	Fuel consumption rate /(g/kW·h)	Air leakage/ (L/h)
No.	*N*/ (r/min)	*P*/ kW	*Me*/ N m				
I	0	–	0	0	3	0	–
	700	–	0	3	18	–	21.6–22.3
	1500	–	0	6	19	–	18.4–19.0
	2000	8	40	10	20	–	14.8–15.3
II	2400	15	62.5	15	29	279.12	12.6–13.3
				20	31	278.08	12.0–12.5
				25	34	275.27	12.4–12.6
III	3000	26	86.7	30	38	249.58	–
				35	38	247.18	–
				40	38	246.43	–
IV	600	–	–	45	38	–	–

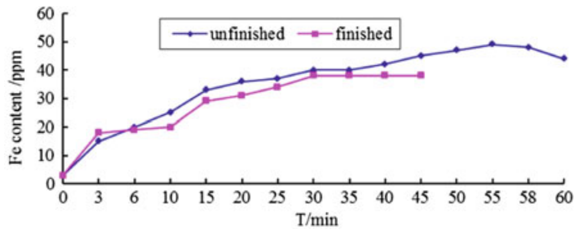


Fig. 2.134 Contrast curves of Fe element content under new running-in standards

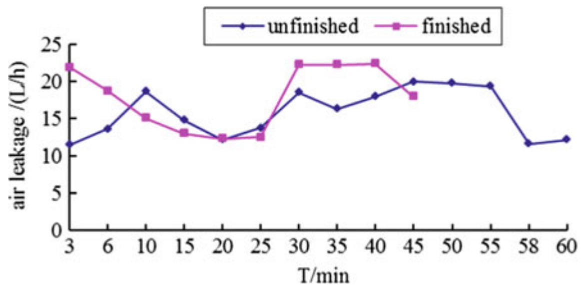


Fig. 2.135 Contrast curves of air leakage under the new running-in standards

analysis is as follows: The crankshaft case leakage and the cylinder compression pressure tend to be stable after well running-in of friction pairs parts and good seal of cylinder sleeves, piston, and piston rings. The contrast curves of air leakage under new running-in standards are shown in Fig. 2.135. Compared with the engine with unfinished parts, the leakage of the engine with finished parts can achieve a relatively stable value within a very short time and the value is relatively small. When the engine starts, the leakage with finished parts is high because of edge filleting (lead to the weak seal between the piston edge and cylinder liner).

The synthetic analysis indicates that ① statistics data shows that the fuel consumption rate of the engine with finished parts decreases 3–4 g/kW h more than those with unfinished parts under the conditions of 26 kW and 3000 r/min. ② There is 15 min "extra running-in time." This means that running-in time of the engine with unfinished parts can decrease from 60 to 45 min, and running-in time of the engine with finished parts can decrease from 45 to 30 min. ③ Running-in curve is getting closer to that ideal. Besides, it is possible to decrease running-in time, and it provides experimental basis to achieve international running-in standards.

The comparisons of external characteristics for two 4D30YB engines are shown in Fig. 2.136. Solid lines $1^{\#}$ in the figure represents the performance testing results of the engine with unfinished parts running 20 h under the usual experience over 2.5–7 h running-in standards. Dotted lines $2^{\#}$ in the figure represents the performance testing results of the engine with finished parts over 1–4 h running-in

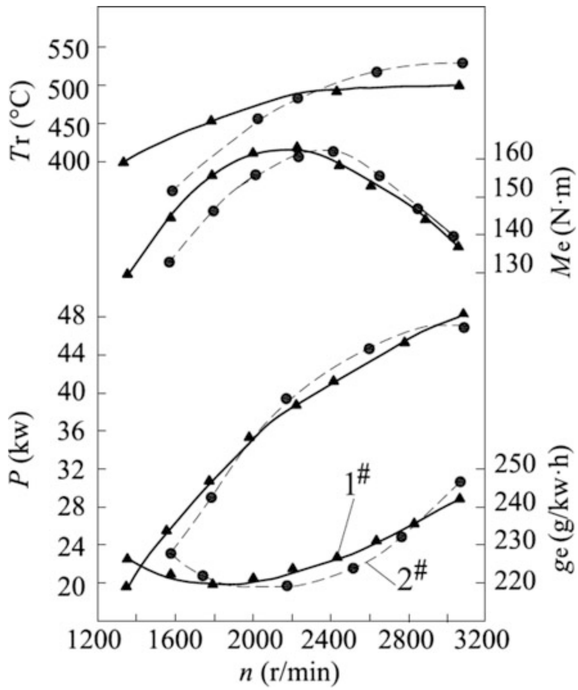


Fig. 2.136 Comparisons of external characteristics for 4D30YB engines

standards. It can be shown that the power and the torque of the engine with finished parts increase, the heavy oil consumption rate decreases, and the exhaust temperature rises when rotational speed is greater than 2000 r/min, which indicates that the power and economy performance of the engine with finished parts have all raised.

Experimental analysis comprehensively shows that running-in time of the engine with finished parts can be reduced by around 50%, and this can save a large number of diesel oil, man-hour, water and electricity fee, etc., and produce huge economy and society benefits; the abnormal cases, such as scuffing of cylinder bore, do not occur after disassemble testing; the noise of the engine with finished parts decreases more than 1 dB.

Finishing processes lead to improving surface quality and surface integrity for frication pairs' parts with the action of colliding, extruding, and the minim grinding (scraping and scoring). Therefore, the fatigue strength, the wear resistance, and the corrosion resistance are improved. Finally, the engine cleanness is increased, the valid power is developed, the fuel consumption is decreased, the running-in time is shortened, and the service life is prolonged. Barrel finishing for friction pairs' parts is one of the effective ways to improve the engine performance.

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