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ORIGINAL ARTICLE

The milling–milling machining method and its realization

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Abstract We proposed a new processing method to reduce the cutting force of the machining process effectively, as well as to improve tool life and machining process efficiency. The proposed method, called the milling–milling machining method, is a new form of composite machining that is similar to the turn-milling method. It combines the advantages of face milling and helical end-milling cutters and uses the synthesis motion of these kinds of cutters to complete surface processing. This technique effectively reduces cutting force and, thus, improves tool life and machining efficiency. The milling–milling machining method has the advantages of a large diameter face mill with a large milling area, a low cutting force, a stable and highly efficient cutting process that is similar to that of a helical end-milling cutter, and trochoidal milling. The outstanding characteristics of face milling and helical end-milling cutters can be applied directly to the milling–milling machining method. In addition, the proposed method has unique features. The up–down milling–milling machining method can offset a portion of the cutting forces. Apart from proposing the theory for the milling–milling machining method, we also designed new equipment, namely the planetary cutter, milling–milling driving head, and a computer numerically controlled milling–milling machine. We compared the proposed method and the common face milling method from the perspective of cutting forces. Experimental results show that the milling–milling machining method considerably reduces cutting forces compared with conventional methods.

Keywords Milling–milling machining method · Turn-milling method · End-milling cutter · Up–down milling–milling machining method · Trochoidal milling

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1 Introduction

Previous studies have examined methods for decreasing cutting forces and cutting heat as well as for increasing tool life and machining efficiency. Composite machining, wear homogenized thinking, and multi-edge processing sequence have been integrated into machining theory and applied in all aspects of production. Literature [1–3] defines the turn-milling method as the application of composite machining and an advanced processing technology in which the synthetic sports of turning and milling are applied to mill all kinds of surface through rotary milling. For example, the effective use of a composite machining method enhances productivity, whereas the turn-milling method solves the problem of breaking chips. Literature [4–7] describes the self-rotary cutting tool as the application of the homogenization wear concept. Total wear amount is divided by the different blade sections of circular cutters, which clearly improve tool life. The wheel is a typical multi-blade knife, and grinding improves processing efficiency. However, a disordered multi-blade cutter wheel has many drawbacks. For example, the ratio of the normal force to the tangential force is excessively large and grinding temperature is considerably high. In literature [8], these drawbacks have been solved by processing multi-edge ideas in an orderly manner.

Difficult-to-cut materials have been widely used in many industrial areas. These materials always satisfy actual application requirements because of their excellent properties, such as high strength at high temperatures, hardness, high hard inclusion contents, and inhomogeneity. However, high temperature and high stress occur during cutting processes, which worsen machining conditions, reduce the life of cutting tools, and lower machining efficiency. Improving tool life during large-part machining to satisfy processing requirements, as well as reducing cutting forces to lessen deformation, particularly for large, thin-walled components, has been widely studied. Therefore, the machinability of difficult-to-cut materials and large parts should be examined to promote cutting performance and explore related technical solutions. The present study proposes an innovative method that can effectively address these problems.

The proposed method, i.e., the milling–milling machining method, is based on the concepts of composite machining, wear ideological homogenization, and orderly multi-edge machining. It adopts a composite machining process that is similar to the turn-milling method. The milling–milling machining method combines the advantages of face milling and helical end-milling cutters and uses the synthesis motion of these two cutters to complete surface processing.

2 Theory and typical forms of the milling–milling machining method

2.1 Theory of the milling–milling machining method

Based on the concepts of composite machining, wear ideological homogenization, and orderly multi-edge machining, we replaced all straight edge cutters of the face milling cutter with helical end-milling cutters (Fig. 1a, b). We designed each helical end-milling cutter to rotate simultaneously on the machine spindle axis and on its own axis with the velocities of v_c and v, respectively. We can process the surface of the workpiece by combining its movement with the synthetic movement of the face milling and helical end-milling cutters (Fig. 1c). The resulting composite machining method is called the “milling–milling machining method.”

2.2 Typical forms of the milling–milling machining method

The milling–milling machining method can be classified into constant and variable speed types based on whether the velocities of each helical end-milling cutter (v) are equal. In particular, the method is classified as the former when the velocities of all helical end-milling cutters are equal; otherwise, it is categorized as the latter.

The milling–milling machining method can also be categorized into same or different direction types based on whether each helical end-milling cutter rotates on its own axis in the same direction. In particular, the method is classified as the former when the rotation directions of all the helical end-milling cutters are the same; otherwise, it is categorized as the latter.

Variable speed and different direction milling–milling machining methods can be classified further. That is, the up–down milling–milling machining method, which is under the different direction category, exhibits the greatest advantage.

In different direction milling–milling machining method, the right- and left-handed helical end-milling cutters rotate clockwise and counterclockwise, respectively, when the helical end-milling cutter on the cutter body exhibits the staggered arrangement of the right- and left-handed helical end-milling cutters shown in Fig. 2a. This setup is called the up–down milling–milling machining method.

In this method, the counterclockwise milling of the left-handed end-milling cutter performs down milling if the clockwise milling of the right-handed end-milling cutter is performing up milling (Fig. 2b, c) and vice versa. We assume that the number of end-milling cutters involved in cutting is n_z and that the helical end-milling cutter on the cutter body exhibits the staggered arrangement of the right- and left-handed helical end-milling cutters. Meanwhile, the right- and left-handed helical end-milling cutters rotate clockwise and counterclockwise, respectively. If n_z is two or more, then up milling and down milling occur simultaneously.

The force analyses of the cutters during up milling and down milling are shown in Fig. 2b, c, respectively, where F_t and F_r are the tangential and radial forces of the tooth of the end-milling cutter, respectively. The stress analyses of up milling and down milling reveal that the directions of F_t on the corresponding cutter tooth are opposite, and thus, tangential force F_t is partially offset. Similarly, the directions of feed force F_{fn} are opposite during up milling and down milling.

3 Realizing the milling–milling machining method

The actual cutting speed of milling–milling machining method is the synthesis speed of v (end-milling cutter) and v_c (cutter body) as shown in Fig. 1c. Therefore, when the end-milling cutter speed v has a large value, the cutter body speed v_c has a smaller value. This condition can realize high-speed cutting of the milling–milling machining method. Unlike the traditional

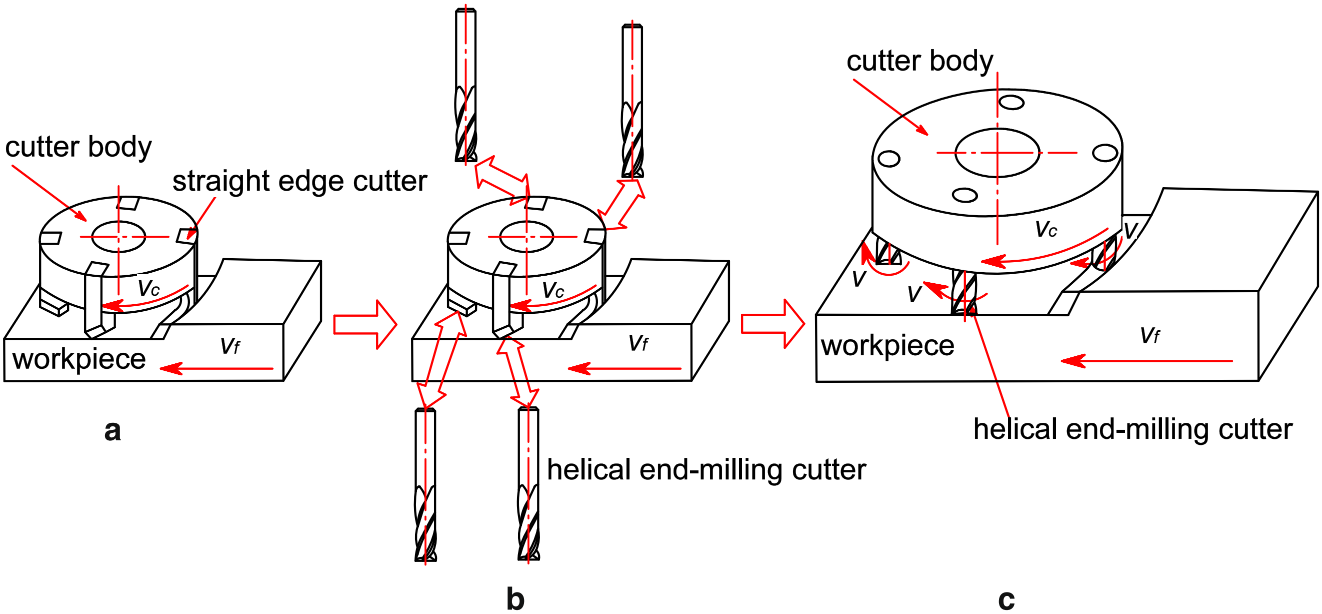
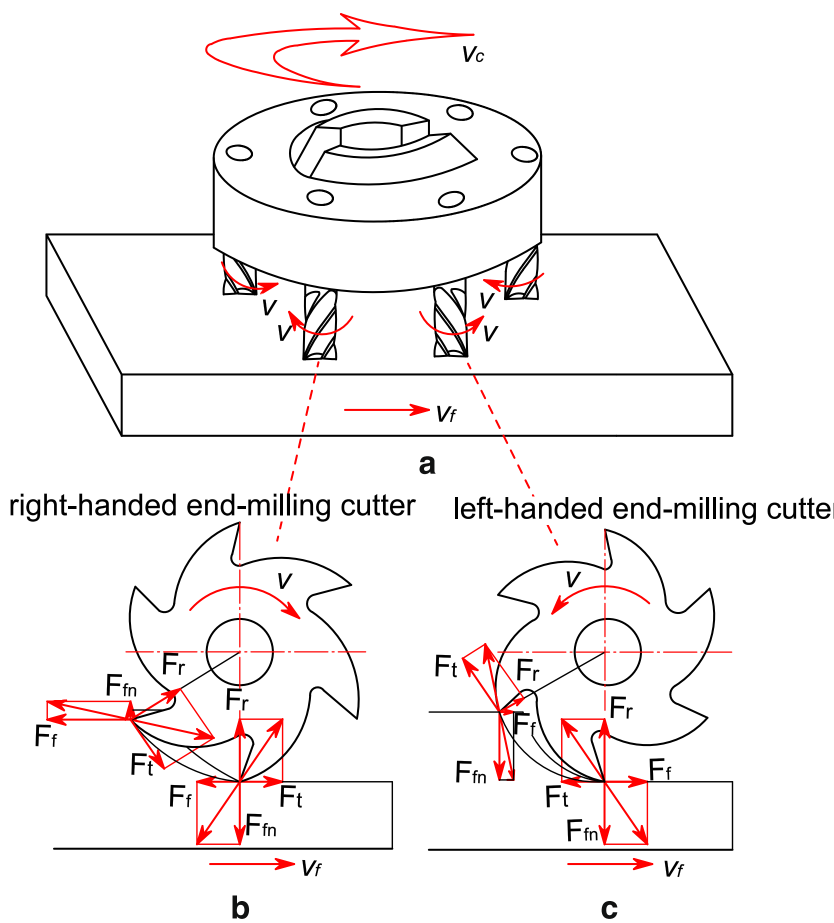


Fig. 1 Theory of the milling–milling machining method

face milling method, the milling–milling machining method can realize high-speed cutting when the cutter body has low speed. This situation is conducive to realizing the milling–milling machining method.

Fig. 2 Up–down milling–milling machining method



3.1 Realization based on epicyclic gear trains

Based on its characteristic, the milling–milling machining method can be realized by using epicyclic gear trains. An epicyclic gear train can be divided into a planetary gear train with one plane degree of freedom (DOF) and a differential planetary gear train with two plane DOFs. Figure 3 illustrates the implementation of the planetary gear train of the milling–milling machining method. The schematic in Fig. 3a shows that the cutter body (planet carrier) is connected to the spindle of the machine tool and rotates with it. The center wheel is connected to the spindle box (both are relatively stationary), and the helical end-milling cutter is connected to the planetary gear and rotates with it. The rotations of the cutter body and the helical end-milling cutter, as well as the table movements, comprise composite milling and complete the machining of the workpiece. Figure 3b presents the 2D plane diagram of concrete implementation based on the schematic, whereas Fig. 3c shows its corresponding 3D diagram. The position of the end-milling cutter depends on the taper shank and the cone hole below the planetary gear. The end-milling cutter is connected to the planetary gear by two round nuts (Fig. 3b). When a large transmission ratio is required between the cutter body (the planet carrier) and the planet wheels, speed change gear groups can be installed between the planetary gear and the central wheel. Figure 3d presents this schematic.

The planetary gear train implementation form of the milling–milling machining method is called a planetary cutter, which is a newly designed cutter based on the aforementioned method. The greatest advantage of this cutter is realizing milling–milling machining without changing any of the existing machining equipment.

Figure 4 shows the schematic of the differential planetary gear train implementation form of the milling–milling machining method. We can change n_2 to control the speed of the end-milling cutter when the spindle speed (n_1) is constant. The main advantage of this implementation form is achieving a large transmission ratio between the planetary gears and the cutter body (the planet carrier). Meanwhile, its drawback is the requirement to change or redesign a new machine.

When the milling–milling ideas of the epicyclic gear train are used as bases, the hardware cannot achieve variable speed and different direction types of milling–milling machining.

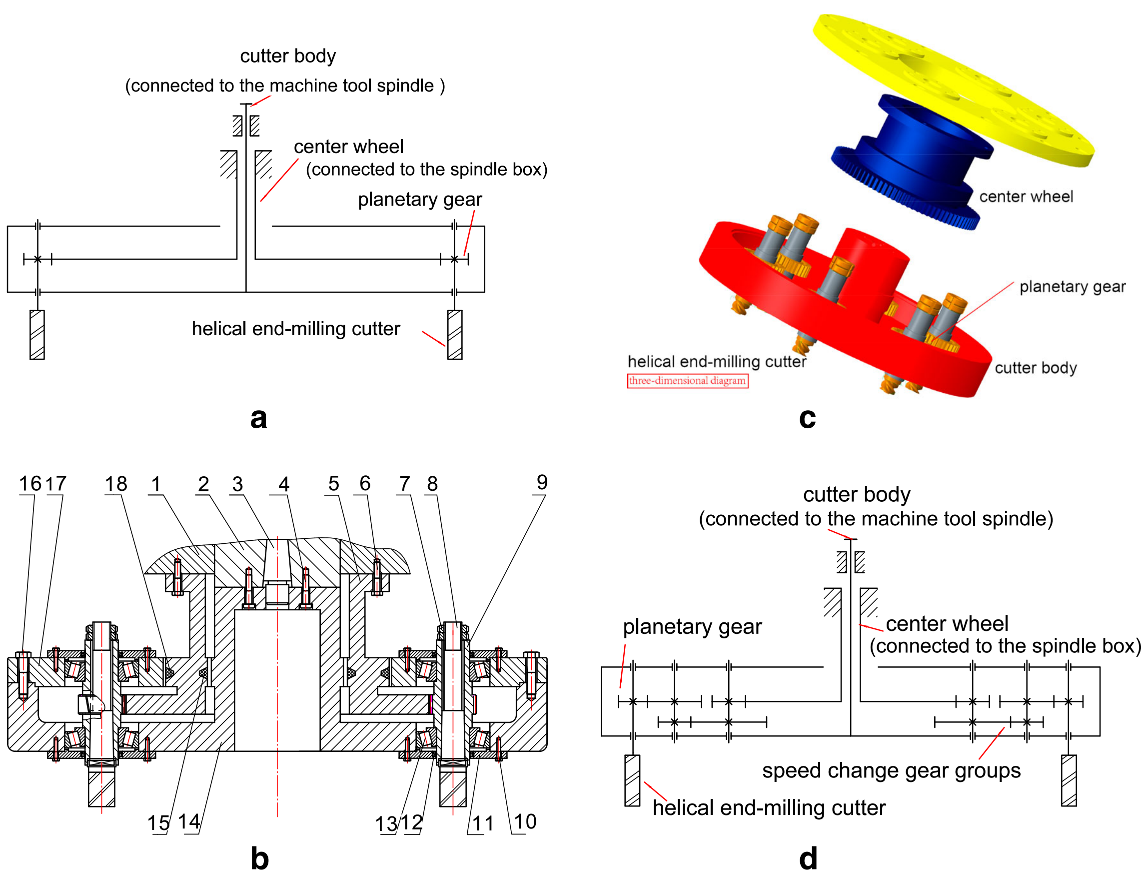


Fig. 3 Planetary gear train implementation form of the milling–milling machining method (planetary cutter). *1* machine tool spindle box, *2* spindle, *3* positioning mandrel, *4* fastening screws, *5* center wheel, *6* bracket bolts, *7* round nut, *8* helical end-milling cutter, *9* planetary gear, *10* gland screws, *11* bearing gland, *12* seal, *13* bearings, *14* cutter body (planet carrier), *15* seal stent, *16* bolt, *17* cover, *18* stand outside the seal

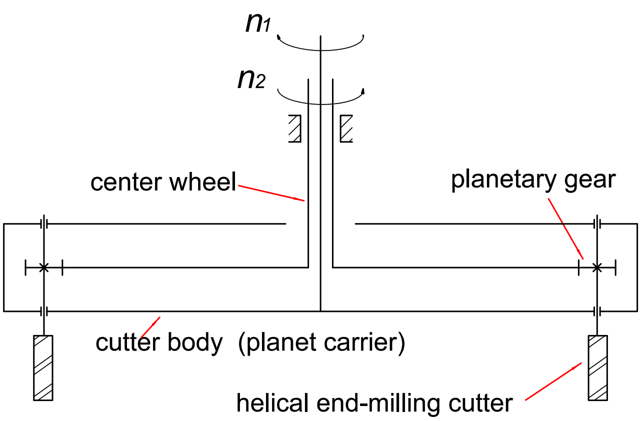


Fig. 4 Differential planetary gear train implementation form of the milling–milling machining method

However, these types can be realized if the milling–milling ideas of mechatronics are used.

3.2 Realization based on mechatronics

The milling–milling machining method can be achieved by integrating mechanical and electrical aspects. The greatest feature of this method is that each helical end-milling cutter is individually driven by the corresponding motor spindle. Energy and information are inputted into the motor spindle by movable contact contacts and dynamic contact slip rings. A machine based on the milling–milling ideas of mechatronics is called a computer numerically controlled (CNC) milling–milling machine (Fig. 5) in which the machine tool motor spindle and cutter motor spindles can rotate on their own axes. The control system directs the machine tool motor spindle, eight cutter motor spindles, as well as the longitudinal, transverse, and vertical feed tables. The machine tool motor spindle drives the cutter body, which is fixed to the spindle, to enable it to rotate. Eight cutter motor spindles drive each helical end-milling cutter to rotate on its own axis. The control system emits electrical signals to the spindles to control their rotation speed and direction. At this point, the rotation speed and direction of the eight helical end-milling cutters can be consistent or inconsistent. The rotations of the cutter body and the eight helical end-milling cutter, along with the longitudinal, transverse, and vertical feed table movements, comprise composite milling and complete the machining of the workpiece.

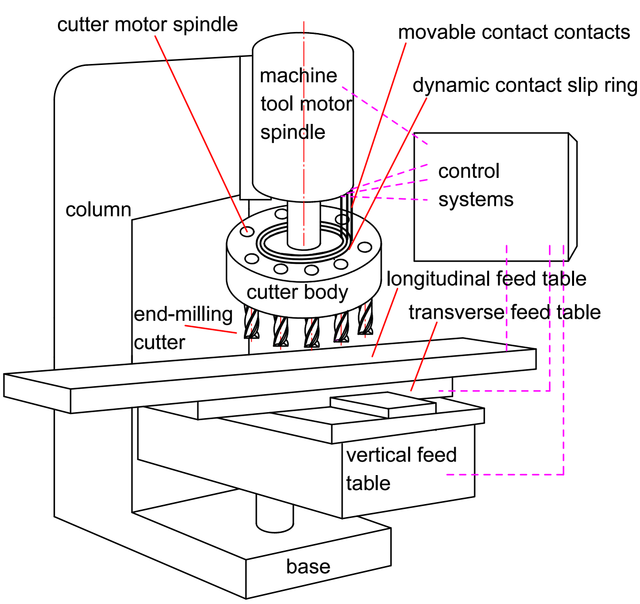


Fig. 5 Mechanical and electrical integration implementation form of the CNC milling–milling machine

Meanwhile, the milling–milling driving head consists of a cutter body, an end-mill motor spindle, a helical end-milling cutter, dynamic contact slip rings, and movable contact contacts, which can be separately installed on general machine tools. Milling–milling machining is completed by inputting energy from the movable contact contacts.

The achievement of the milling–milling machining method is flexible because each helical end-milling cutter on the cutter body can have the same or varying speeds and directions.

4 Analysis of the advantages of the milling–milling machining method

4.1 Advantages of the helical end-milling cutter in terms of cutting force

As shown in Fig. 6, an end-milling cutter with helix angle β, radius r, and N number of flutes is assumed. The axial depth of cut (ap) is constant. $\mathrm{d}F_{\mathrm{ti}}$, $\mathrm{d}F_{\mathrm{ri}}$, $\mathrm{d}F_{\mathrm{ai}}$ are the tangential force, radial force, and axial force, respectively, acting on a differential flute element. According to literature [9, 10], the resolution of the differential cutting forces ($\mathrm{d}F_{\mathrm{ti}}$, $\mathrm{d}F_{\mathrm{ri}}$, and $\mathrm{d}F_{\mathrm{ai}}$) in the X, Y, and Z directions is as follows:

$$\begin{cases} \mathrm{d}F_{tix} = -K_S t_i(\varnothing_i) r\cot\beta\cos\varnothing_i \mathrm{d}\varnothing \\ \mathrm{d}F_{tiy} = K_S t_i(\varnothing_i) r\cot\beta\sin\varnothing_i \mathrm{d}\varnothing \end{cases} \quad (1)$$

$$\begin{cases} \mathrm{d}F_{rix} = -c_1 K_S t_i(\varnothing_i) r\cot\beta\sin\varnothing_i d\varnothing \\ \mathrm{d}F_{riy} = -c_1 K_S t_i(\varnothing_i) r\cot\beta\cos\varnothing_i d\varnothing \end{cases} \quad (2)$$

$$\mathrm{d}F_{iz} = -c_2 K_S t_i(\varnothing_i) r\cot\beta d\varnothing \quad (3)$$

The sum of these equations provides the differential forces in the X, Y, and Z directions as follows:

$$\mathrm{d}F_{ix} = -K_S t_i(\varnothing_i) r\cot\beta(\cos\varnothing_i + c_1\sin\varnothing_i)\mathrm{d}\varnothing \quad (4)$$

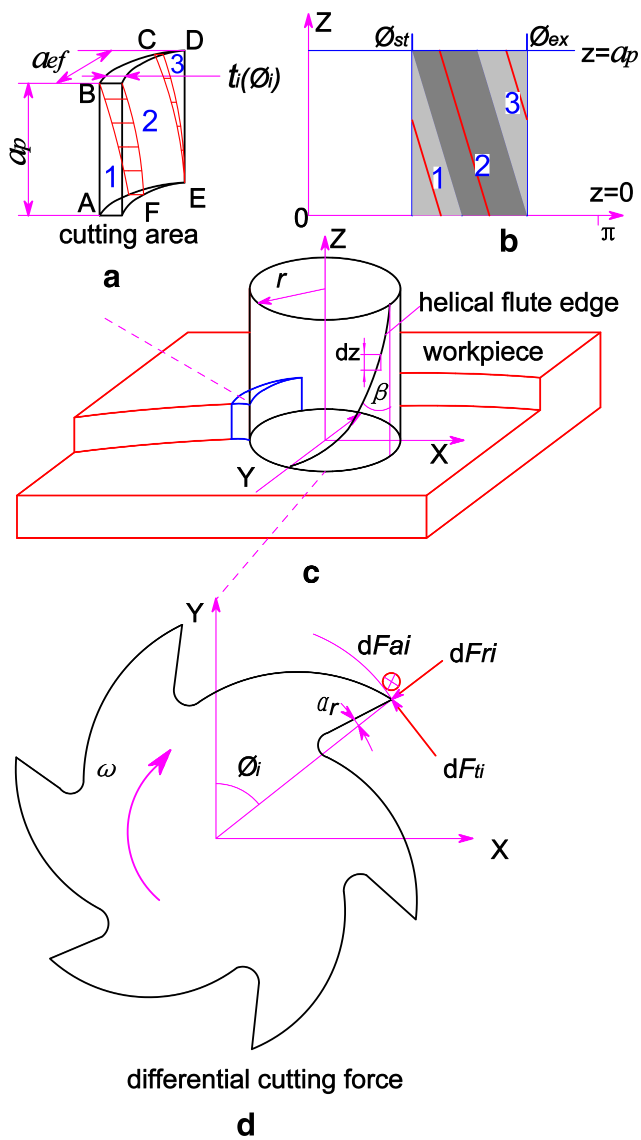


Fig. 6 Force analysis of the helical end-milling cutter in the cutting zone

$$\mathrm{d}F_{iy} = K_S t_i(\varnothing_i) r\cot\beta(\sin\varnothing_i - c_1\cos\varnothing_i)d\varnothing\infty \quad (5)$$

$$\mathrm{d}F_{iz} = -c_2 K_S t_i(\varnothing_i) r\cot\beta d\varnothing \quad (6)$$

where K_S is the tangential cutting force coefficient, $\varnothing_i$ is the position angle of a point on the cutting edge of the ith helical flute, $t_i(\varnothing_i)$ is the thickness of the undeformed chip of the ith tooth in angle position $\varnothing_i$, c_1 is the radial cutting force ratio, and c_2 is the axial cutting force ratio.

In Eqs. (4) to (6), the cutting force is directly proportional to $\cot\beta$ because $\cot\beta$ is the decreasing function in $\left[0, \frac{\pi}{2}\right]$ interval. A straight edge tool generally has no helix angle or only a small cutting edge inclination angle. Therefore, under the same cutting parameters, the cutting forces of the straight edge cutter are bigger than those of the helical end-milling cutter.

The relationship among the effective rake angle α_e, tool rake angle α_n, and helix angle β in the milling process is shown in Eq. (7). When helix angle β is in $\left[0, \frac{\pi}{2}\right]$ interval, real effective rake angle α_e increases along with helix angle β. This effect confirms the improvement of the helix angle on the cutting force in another manner.

$$\sin\alpha_e = \sin^2\beta + \sin\alpha_n\cos^2\beta = \sin\alpha_n + (1 - \sin\alpha_n)sin^2\beta \quad (7)$$

The integral calculation of Eqs. (4) to (6) can obtain the total cutting forces in the X, Y, and Z directions, i.e., F_{ix}, F_{iy}-F_{iz}, as shown in Eq. (8).

$$\begin{cases} F_{ix} = \int_{\varnothing_s}^{\varnothing_e} dF_{ix} d\varnothing_i \\ F_{iy} = \int_{\varnothing_s}^{\varnothing_e} dF_{iy} d\varnothing_i \\ F_{iz} = \int_{\varnothing_s}^{\varnothing_e} dF_{iz} d\varnothing_i \end{cases} \quad (8)$$

where $\varnothing_s$ and $\varnothing_e$ are the lag angular locations of the start and end points of cutting edge contact, respectively. According to literature [11], we can transform Eq. (8) into the dz integral as follows:

$$\begin{cases} F_{ix}(\varnothing_i(z)) = \int_{z_{i,1}(\varnothing_i(z))}^{z_{i,2}(\varnothing_i(z))} -k_\beta dF_{ix}(\varnothing_i(z))dz \\ F_{iy}(\varnothing_i(z)) = \int_{z_{i,1}(\varnothing_i(z))}^{z_{i,2}(\varnothing_i(z))} -k_\beta dF_{iy}(\varnothing_i(z))dz \\ F_{iz}(\varnothing_i(z)) = \int_{z_{i,1}(\varnothing_i(z))}^{z_{i,2}(\varnothing_i(z))} -k_\beta dF_{iz}(\varnothing_i(z))dz \end{cases} \quad (9)$$

where $k_\beta = \tan\beta / r$.

As shown in Fig. 6a, b, when the single helical blade is cutting the workpiece in and out, integral $[z_{i,1}, z_{i,2}]$ increases gradually in one (ABF) region, whereas integral $[z_{i,1}, z_{i,2}]$ decreases gradually in three (CDE) regions. In Fig. 6b, $\varnothing_{st}$ is the start angle, whereas $\varnothing_{ex}$ is the exit angle. When the cutter tooth gradually cuts into the workpiece in the one (ABF) region, the cutting force also increases gradually. When the cutter tooth gradually cuts out the workpiece in the three (CDE) regions, the cutting force decreases gradually. Thus, the helical cutter exhibits a more stable cutting progress than the straight edge cutter.

Through the aforementioned analysis, we can see that the helical end-milling cutter has a smaller cutting force and a more stable cutting process than the straight edge cutter. The milling–milling machining method changes the straight edge of face milling into a helical edge. From this perspective, the cutting force of the milling–milling machining method is lower than that of the face milling method under the same cutting conditions.

4.2 Actual cutting chip thickness of the milling–milling machining method is smaller than that of the face milling method under the same cutting parameters

The end-milling cutter in the milling–milling machining method rotates along with the cutter body with rotational speed n_c as shown in Figs. 7a and 1c. As the feed rate of the cutter body, the trajectory of a point in the cutter body is a trochoidal curve. The end-milling cutter is rotated with the cutter body, and thus, its trajectory in the milling–milling machining method is a trochoidal curve, as shown in Fig. 7b. Therefore, an individual end-milling cutter in the milling–milling machining method is actually performing trochoidal milling, which indicates that the milling–milling machining method exhibits the advantage of trochoidal milling.

However, the milling–milling machining method has other advantages that trochoidal milling does not have. First, the milling–milling machining method is a composite of end-milling and face milling cutters. Consequently, it has the advantages of a large diameter face mill with a large milling area as well as the capability to complete processing large and even large flat planes with high efficiency and material removal rate by increasing the number of end-milling cutters that simultaneously participate in the cutting. Theoretically, trochoidal milling can be performed in a large plane, but this process actually has low efficiency. Hence, trochoidal milling is only used to machine a narrow area of a workpiece. Second, the end-milling cutter that conducts trochoidal milling has a long tool life [12, 13]. In the milling–milling machining method, many end-milling cutters complete the machining of a workpiece in an orderly manner; thus, tool life in the milling–milling machining method is longer than that in trochoidal milling when the total amount of wear in all end-milling cutters is averaged.

As shown in Figs. 7a and 1c, the end-milling cutters rotate with the cutter body while rotating around their own axes to machine the workpiece in the milling–milling machining method. For the end-milling cutter, given the movement with the cutter body and the rotation on its axis, the trajectory of the ith tooth is also a trochoidal curve, as shown in Fig. 7b. Therefore, the synthetic trajectory of the ith tooth in the milling–milling machining method is the synthesis of the small trochoidal curve that the end-milling cutter rotates around on its own axis and the large trochoidal curve that it rotates on with the cutter body. That is, the synthetic trajectory of the ith tooth of the end-milling cutter in the milling–milling machining method is the small trochoidal curve of a large trochoidal curve, as shown in Fig. 7c.

According to the trajectory characteristic of a point in the cutter in the milling–milling machining method, we can obtain the actual cutting chip thickness between the ith and the $(i+1)$-

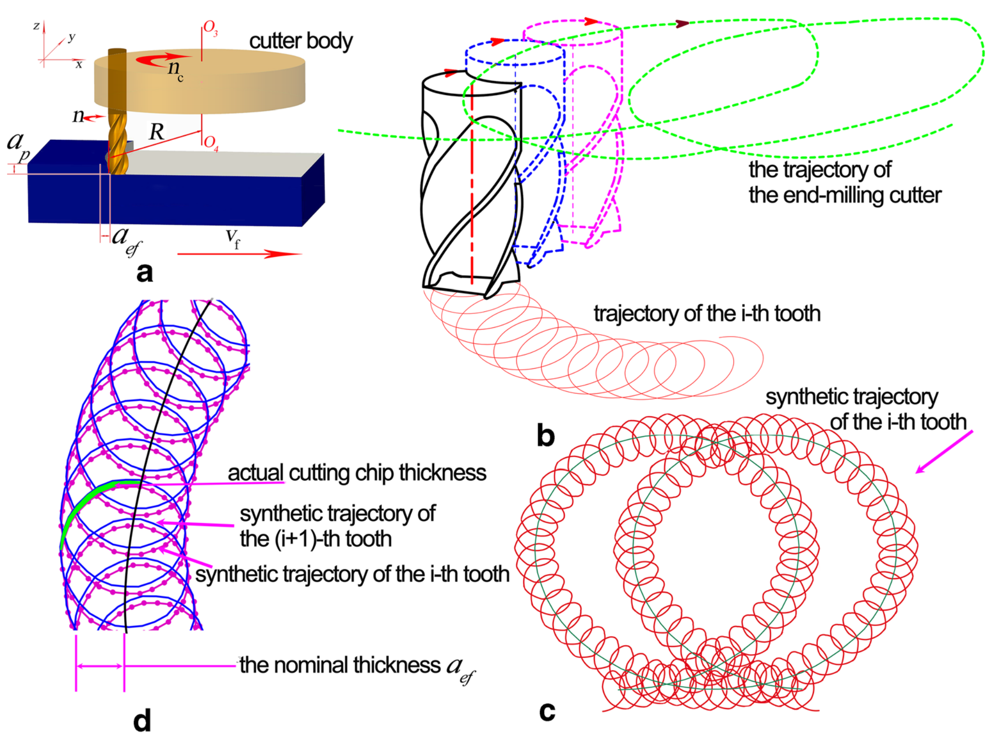


Fig 7 Tool path and actual cutting chip thickness of the milling–milling machining method

th of a tooth, as shown in Fig. 7d, in which the nominal thickness (a_{ef}) of the milling–milling machining method is broken down into small crescent-shaped actual cutting layers by two adjacent cutting edges. When the milling–milling machining method and the common face milling method have the same a_{ef}, the actual cutting chip thickness of the milling–milling machining method is smaller than that of the common face milling method (Fig. 7d).

In numerous milling force theoretical prediction models [9–11, 14, 15] and practices, regardless of whether the tangential force (dF_{ti}), radial force (dF_{ri}), and axial force (dF_{ai}) are all proportional to the actual cutting thickness $t_i(\varnothing_i)$, the size of the milling force in Eqs. (1) to (6) exhibits the same relationship. Moreover, the actual cutting thickness of the milling–milling machining method is smaller than that of common face milling method. Therefore, from a practical perspective of cutting thickness, the cutting force of the milling–milling machining method is smaller than that of the face milling method when these methods have the same a_{ef}.

Through the aforementioned analysis, we can see that the milling–milling machining method can increase the number of end-milling cutters or improve the speed of end-milling cutters. In addition, it can increase the nominal value of the cutting thickness (a_{ef}) to improve the material removal rate. A high material removal rate can be achieved even when the speed of the cutter body is low. In such case, the milling–milling machining method can realize high-speed cutting and high material removal rate.

4.3 Comparison of the start and exit angles in the milling–milling machining and face milling methods

In the milling–milling machining method, the end-milling cutters rotate with the cutter body while rotating around their own axes to machine the workpiece. Therefore, the start and exit angles of the milling–milling machining method have their own characteristics. According to [12], the start and exit angles of the milling–milling machining method can be determined as shown in Fig. 8. The geometrical relationship in Fig. 8 shows three different start and exit angles, which stand for cutting into continuous cutting and cutting out of the workpiece. Under the continuous cutting process, the start angle $\varnothing_{st}=0$, whereas the exit angle $\varnothing_{ex}$ is

$$\varnothing_{ex} = \arccos\left(\frac{L_{1c}^2 + L_{2c}^2 - L_{12}^2}{2L_{1c}L_{2c}}\right) \tag{10}$$

in which

$$\begin{cases} L_{1c} = L_{2c} = r \\ L_{12} = \sqrt{(x_1-x_2)^2 + (y_1-y_2)^2} \end{cases} \tag{11}$$

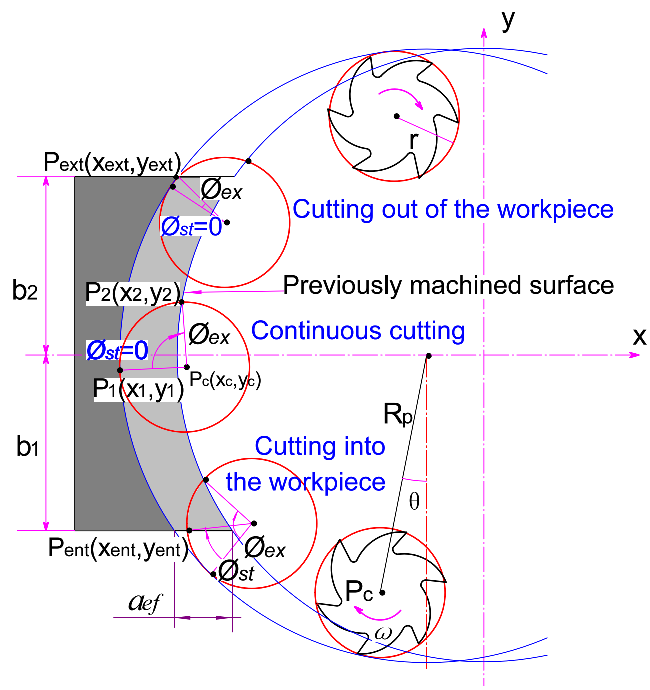


Fig. 8 Start and exit angles of a helical end-milling cutter

The accurate calculation of the start and exit angles in the three states (cutting into, continuous cutting, and cutting out of the workpiece) is described in literature [12]. When R_p value is large and under the continuous cutting process, exit angle $\varnothing_{ex}$ can be approximately expressed as follows:

$$\varnothing_{ex} \approx \arccos\left(1-\frac{a_{ef}}{r}\right) \tag{12}$$

From Fig. 8 and Eq. (12), the relationship between exit angle $\varnothing_{ex}$ and a_{ef} can be analyzed under continuous cutting of a workpiece, which is unrelated to the width of the workpiece (b_1+b_2). This relationship is different from that of the start and exit angles in ordinary face milling. Therefore, these characteristics of the milling–milling machining method can be used fully to optimize favorable cutting process parameters.

4.4 Advantages of the milling–milling machining method

The milling–milling machining method incorporates the concepts of orderly multi-edge machining and wear ideological homogenization; thus, orderly multi-edge tools are designed in this method to improve processing efficiency and tool life by averaging the total amount of wear in all end-milling cutting edges.

Moreover, the milling–milling machining method includes the idea of composite processing, which provides

Fig. 9 Measurement system for the milling experiments

the advantages of a large milling area for a large diameter face milling cutter as well as a light, stable, and highly efficient cutting of a helical end-milling cutter. The outstanding achievements of face milling and helical end-milling cutters can be applied directly to the milling–milling machining method. The wavy edge or variable pitch end-milling cutter can be applied directly to the milling–milling machining method. Meanwhile, the milling–milling machining method also has its unique characteristics. In particular, the up–down milling–milling machining method can offset a portion of the cutting forces.

The actual cutting speed of the milling–milling machining method is the synthesis speed of v (end-milling cutter) and v_c (cutter body) as shown in Fig. 1c. Therefore, when the end-milling cutter speed (v) has a large value, the cutter body speed (v_c) has a smaller value, which can realize high-speed cutting of the milling–milling machining method. This method exhibits the advantage of trochoidal milling. The milling–milling machining method can increase the number of end-milling cutters or improve the speed of end-milling cutters. Moreover, it can increase the nominal value of the cutting thickness (a_{ef}) to improve the material removal rate. A high material removal rate can be achieved even under low cutter body speed. In such case, the milling–milling machining method can achieve high-speed cutting and high material removal rate.

5 Experiments

5.1 Experimental equipment and design

The machine used in the experiments is a DMU80 monoBLOCK five-axis machining center, with a spindle power of 26 kW and a maximum spindle speed of 24,000 r/min. Its fastest feed rate, positioning accuracy, and repeat positioning accuracy are 30 m/min, 0.008 mm, and 0.005 mm, respectively. The cutting force measuring system consists of three dynamic Swiss Kistler piezoelectric dynamometers 9257B, a charge amplifier 5017A, a data cable, and a collection card. Figure 9 presents the test system.

The experimental material is Al6063. The experimental cutters are the face milling cutter (single tooth) and the helical end-milling cutter. All tool materials are cemented carbides, with rake and clearance angles of 10° and 12°, respectively. The helical end-milling cutter has four teeth and its helix angle is 30°. When the face milling cutter (single tooth) is used on a workpiece, the helical end-milling cutter rotates on its own axis as it cuts the workpiece in the same cutting parameters along the trajectory of the single tooth of the face milling cutter. That is, the entire helical end-milling cutter, which functions as a tooth in the milling–milling machining method, uses the same cutting parameters as that of the tooth of the face milling cutter. The cutting forces in both cases are measured. Figure 10 shows the experimental design, where o_1o_2 is the rotational axis of the face mill, and o_3o_4 is the equivalent and virtual rotational axes of o_1o_2, which are completed by an arc-shaped feed movement. In this movement, R is the radius, n_c is the rotational speed, a_p is the depth of cut, a_{ef} is the cutting width, and v_c=

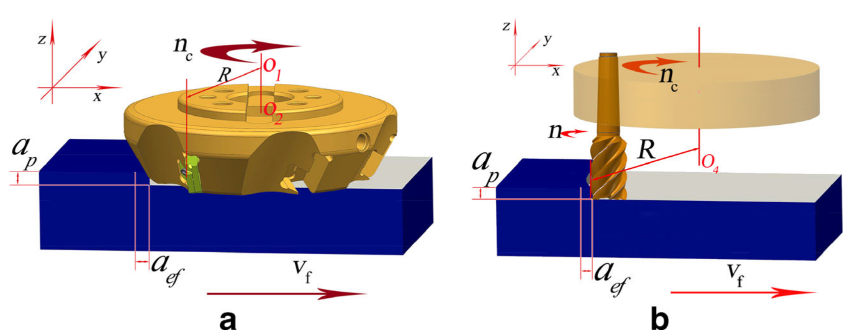


Fig. 10 Experimental program

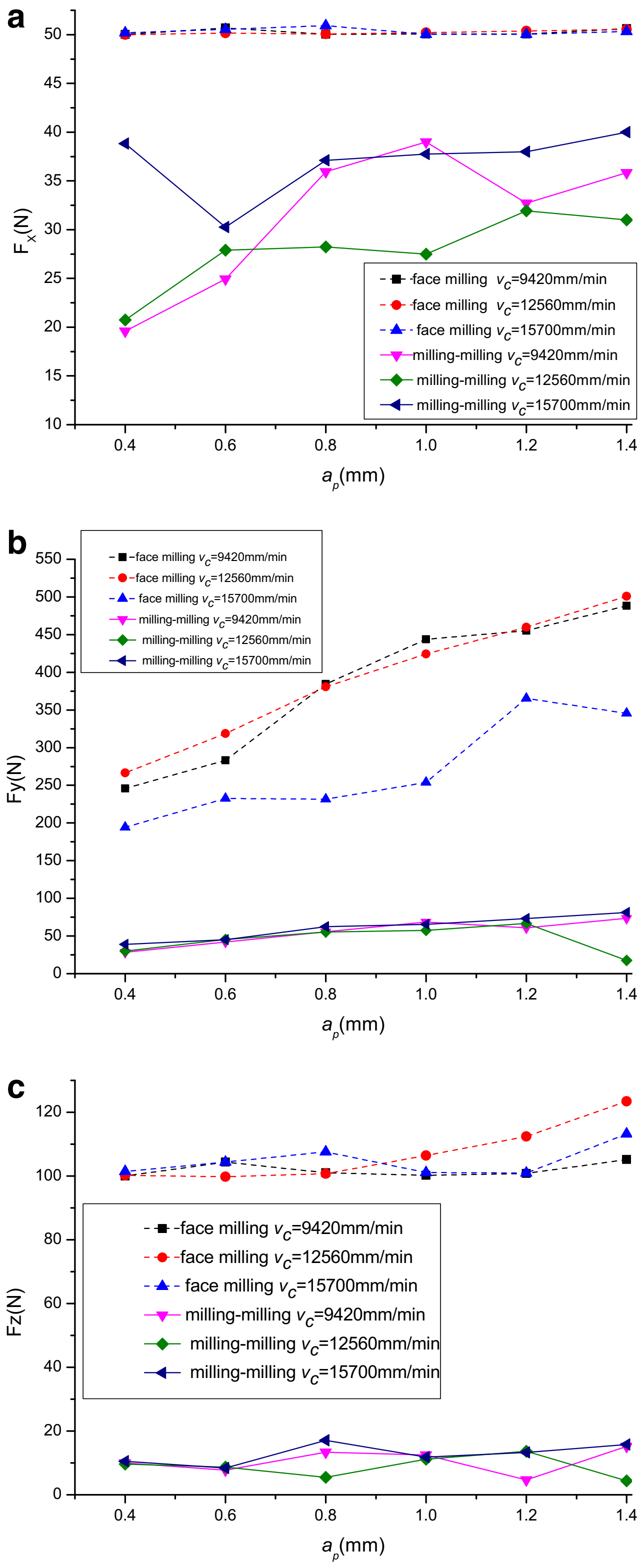


Fig. 11 Comparison of the cutting forces of the face milling and milling–milling machining methods

$n_c \times R$. In the two experiments, R, n_c, a_p, and a_{ef} are the same. To ensure that the cross-sectional areas of the cutting layer of the two methods are the same, the cutting forces are not measured each time the tools are replaced until the second cutting experiment during which they are independently measured thrice by using the same cutting parameters.

5.2 Experimental results and analysis

In the experiment, the entire helical end-milling cutter, which functions as a tooth in the milling–milling machining method, uses the same cutting parameters as those used in face milling cutters. In the experiment, a_{ef}=0.2 mm; the values of a_p and v_c are changed, and the cutting forces of the face milling and milling–milling machining methods are measured. The comparison of the cutting forces of the *x*-, *y*-, and *z*-axes of the face milling and milling–milling machining methods is shown in Fig. 11a–c, respectively.

The experimental results reveal significant decreases in the *x*-, *y*, and *z*-axes directions of the milling–milling machining method. As the analyses in Sections 4.1 and 4.2 show, the decrease in cutting force can be summarized as follows. The cutting force of the helical end-milling cutter in the milling–milling machining method is lower than that of the straight edge cutter in the face milling method. Under the same cutting parameters, the actual cutting layer thickness of the milling–milling machining method is smaller than that of the face milling method. The cutting force decrease is the comprehensive effect of the aforementioned two aspects. The findings prove that the milling–milling machining method is better than the conventional face milling method.

6 Conclusions

1. Based on the concepts of composite machining, wear ideological homogenization, and orderly multi-edge machining, we propose an innovative processing method, i.e., the milling–milling machining method. Similar to the turn-milling method, the proposed method is also an implementation form of composite machining.
2. The milling–milling machining method combines the advantages of face milling and helical end-milling cutters. It uses the synthesis motion of these two cutters to complete surface processing and, thus, effectively reduce cutting force, increase tool life, and improve machining efficiency. The milling–milling machining method exhibits the advantages of a large milling area with a large diameter face milling cutter, a low cutting force, as well as a stable and highly efficient cutting process of a helical-end cutter. The outstanding achievements of face milling and helical end-milling cutters can be applied directly to the milling–milling method. The wavy edge or variable pitch end-

milling cutter can be applied directly to the milling–milling machining method.
3. The milling–milling machining method can be classified into variable speed and different direction types. A portion of the milling force is offset in up–down milling–milling.
4. The milling–milling machining method, which has multiple implementation forms, can be achieved by combining electrical aspects. This approach is flexible because each helical end-milling cutter on the cutter body can have the same or varying speeds and directions.
5. We compare the milling–milling machining method and the common face milling method from the perspective of cutting forces. The experimental results show that the cutting force of the milling–milling machining method is considerably decreased compared with those of the conventional method.

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