Study on Deformation and Compensation for Micromilled Thin Walls With High Aspect Ratios

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Research Article

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Study on deformation and compensation for micromilled thin walls with high aspect ratios

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Abstract

In order to further improve the dimensional accuracy of micromilled thin walls with high aspect ratios, the machining process should be actively controlled. An active cutting force measurement and cutting parameter compensation device is developed to realize the real-time measurement of radial cutting forces and compensation of radial cutting parameters in thin wall cutting process. Firstly, based on the cantilever beam deformation theory, a mathematical model is established to calculate the deformation and cutting force of thin walls. By measuring the cutting force, the thin wall deformation in the cutting process could be estimated. Then, the obtained incremental thin wall deformation is to be compared with the compensation threshold, which is set at 0.5 μm. If the value of the incremental deformation is less than 0.5 μm, compensation will not be processed. Otherwise, the incremental deformation is used as the compensation value for iterative compensation, until the incremental deformation of the thin wall is less than 0.5 μm. At last, a contrast experiment is carried out. The experimental results show that the introduced device and method are feasible. Machining quality of the thin wall has been obviously improved in dimension precision after the cutting parameter compensations.

Key words: Thin wall, deformation, cantilever beam, cutting force measurement, cutting parameter compensation, dimensional error

1. Introduction

Thin wall parts with high aspect ratios are widely used in aerospace, electronics, die and other industries, the CNC machining method is generally adopted in the production of thin wall parts, among which high-speed milling is the most widely used one. The whole rigidity of thin wall feature is poor. Its deformation and the processing vibration phenomena are very obvious in the cutting process. Therefore, the study of high quality and high efficient processing technology of thin wall parts has important significance.

Wang has proposed a numerical control compensation method for thin wall parts machining to reduce the errors generated by the elastic deformation of workpiece. The machining deformation of thin wall parts was analyzed and calculated by using finite element analysis method. According to the experimental results, the deformation of the side wall was parabolic in the direction of the height, and the deformation of the top of the side wall was the largest one. In the direction of the length of the side wall, the deformation was the largest at the middle point and the smallest at both ends [1, 2]. Xue took genetic algorithm as the optimization tool and the milling deformation as the optimization goal, and proposed a synchronous optimization method that could improve the milling efficiency [3]. Sridhar obtained a combination of milling parameters for the minimum deformation of thin wall parts through orthogonal experiments [4]. Guo proposed a new house-building frame modeling method to simulate the machining deformation of complex multi-frame aluminum alloy thin wall parts [5]. Chen established multi-layer cutting model, multi-layer cutting deformation prediction model and deformation error compensation model for thin wall parts [6]. Bi proposed a simplified cutting layer model to simulate the milling process of aeronautical structural parts by comprehensively considering the influence of various factors, and revealed the deformation fundamental [7].

Lim proposed a method for compensating milling errors with ball-end milling cutters by using a controlled surface strategy. By this method, the machining errors caused by cutters were predicted using a surface generation model without the need for actual machining experiments. In order to adapt to different conditions of surface errors, error sensitive functions were defined when generating control surfaces [8]. Ratchev used two ways of single-level cycle and multi-level cycle to compensate the tool path based on the prediction of machining deformation. The single-level cycle only compensated the tool path once without considering the coupling effect between the change of tool point and machining deformation. In the multi-level cycle method, iterative calculation was carried out between the modified tool point, the cutting force model and the machining deformation until the machining surface error meets the given accuracy requirements [9]. Kant studied the relationship between the wall thickness of the parts and the milling force and the influence degree on the milling deformation for the size of thin wall parts. At the same time, the machining deformation in a certain time was calculated by the distribution of the milling force in the contact parts between the cutter and the workpiece [10]. Ratchev made a certain analysis on the influence factors of common machining deformation and conducted a study on the compensation of stratified errors in milling. In addition, the algorithm based on the principle that different machining paths will produce different cutting forces finds out the dynamic balance relationship between the two paths, thus improving the accuracy of thin wall size [11]. Hou aimed at the problem of cutting deformation in the process of thin wall parts machining, a learning control method on machining error compensation was proposed. Based on elastic deformation theory, the nonlinear function relationship between machining error and nominal cutting depth was established, and a general model of machining error compensation for thin wall parts was constructed by using the compensation idea, that is the calculation method of nominal cutting depth in the next cutting. The model realized the off-line learning of compensation coefficient and accurate control of machining error by using the feedback principle. Finally, the effectiveness of the model was verified by peripheral milling experiments [12].

In view of the local machining deformation of weak rigid thin wall structural parts, many scholars mainly studied the cutting force model, cutting parameters, cutting path and other issues. The cutting parameters and other process conditions are optimized by building a cutting model, which reduces the local deformation of the thin wall structure to a certain extent. However, the mentioned cutting parameter compensations are basically off-line optimization, and there are very limited on-online compensations studies. Consequently, there are still large spaces in improving the thin wall machining quality. On-line optimization requires changing the original tool path and generating a new machining program, resulting in relatively low efficiency. Therefore, a device for cutting force measurement and cutting parameter compensation is developed in this study. Based on the cantilever beam deformation theory, the mathematical model of thin wall deformation and cutting force is established. The thin wall deformation in cutting process can be calculated by measuring the cutting force. Then the deformation value is used as the compensation value by the cutting parameter compensation device to reduce the dimensional error caused by thin wall deformation.

2. Thin wall deformation mechanism and compensation device

2.1 Thin wall deformation mechanism

Fig. 1 shows the mechanism of thin wall deformation and the process of deformation compensation. As shown in Fig. 1(a), the elastic deformation of the thin wall is generated in the cutting process due to the cutting force perpendicular to the side surface of the thin wall, leading to that the actual radial cutting depth is less than the nominal radial cutting depth and resulting in machining errors. When the tool leaves the machined surface, the cutting force disappears and the thin wall recovers to form the actual machined surface as shown in Fig. 1(b). The difference between the actual machined surface and the nominal one is the residual material needs to be removed. The stiffness continuously reduces from bottom to top of the thin wall. It is unreasonable to use the maximum workpiece deformation to define compensation value. Therefore, the incremental amount of deformation is used to identify the compensation value in this study. Through radial cutting parameter compensation for the thin wall, the incremental amount of deformation decreases continuously until the dimensional accuracy is realized, as shown in Fig. 1(c). During the compensation process, the error between the actual machined surface and the nominal machined surface is continuously reduced, as shown in Fig. 1(d).

2.2 Cutting force measurement and cutting parameter compensation device

The machining error is mainly due to the elastic deformation of thin wall caused by cutting forces. The greater the cutting force is, the greater the deformation of thin wall will be. Therefore, the cutting force can be reduced by reducing the cutting parameters, so as to indirectly reduce the deformation of thin wall. However, this will greatly reduce the machining efficiency. Therefore, a device of cutting force measurement and cutting parameter compensation is developed in this study. It can measure the radial cutting force perpendicular to the thin wall that generated in the thin wall cutting process. Then, the radial cutting parameter is compensated according to the value of the cutting force. By this way, a relatively reasonable machining efficiency could be assured.

Fig. 2 shows the three-dimensional structure diagram of the designed cutting force measurement and cutting parameter compensation device. It is mainly composed of two components, the cutting force measurement component and the cutting parameter compensation component. The cutting force measurement component is composed of a piezoelectric sensor, two guide rails and slides. The main parameters of the sensor are shown in Table 1. The cutting parameter compensation component is composed of a linear motor, two guide rails and slides, and a grating ruler.

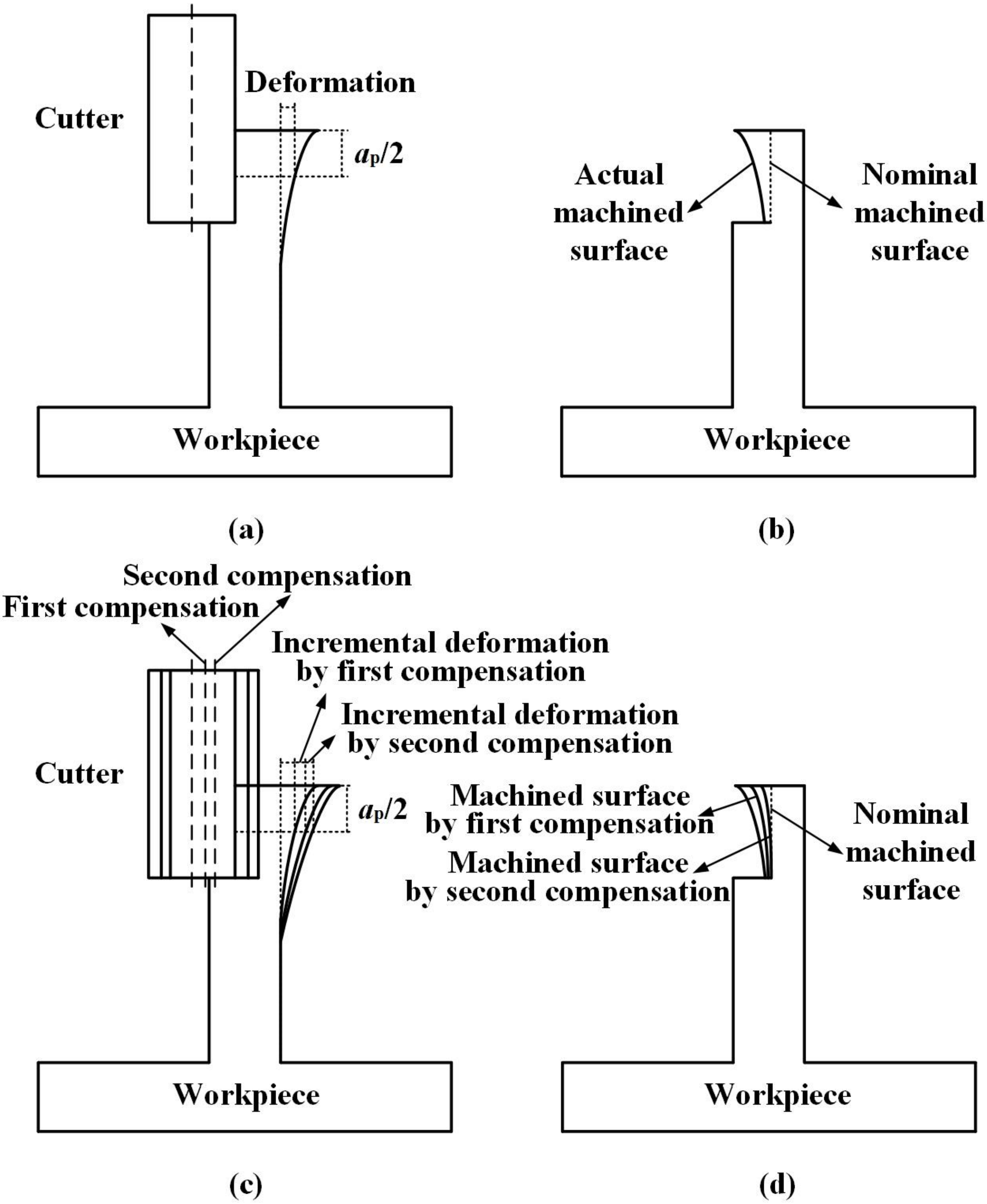
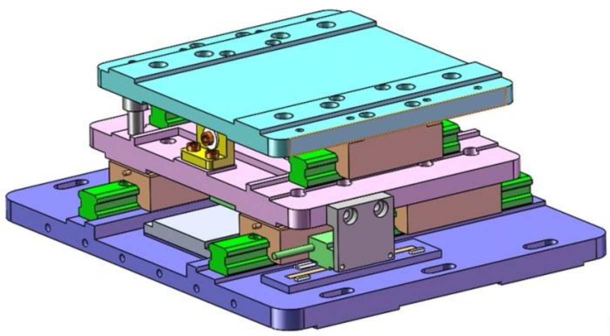
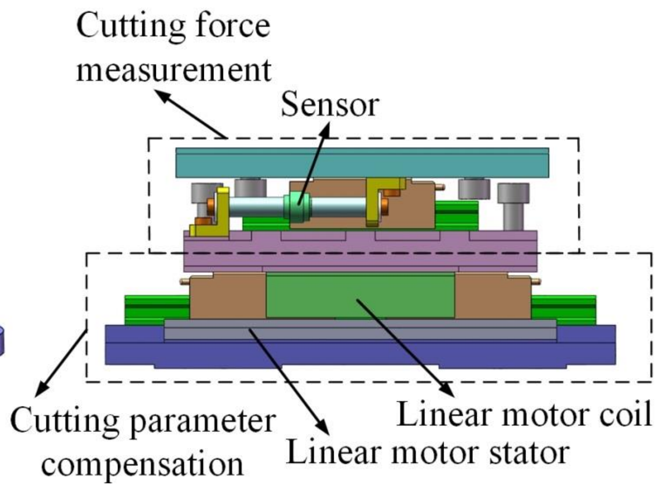


Fig. 1 Schematic view of thin wall deformation and compensation process.



(a) Schematic view



(b) Sectional view

Fig. 2. The designed cutting force measurement and cutting parameter compensation device.

Table 1. The parameters of the sensor.

Capacity	Resolution	Combined Error	Stiffness	Operating Temperature	Sensitive Material	Shell Material
-50~50 N	0.001 N	0.5% F.S	>10 KN/μm	-50~120 ℃	Quartz	Stainless Steel

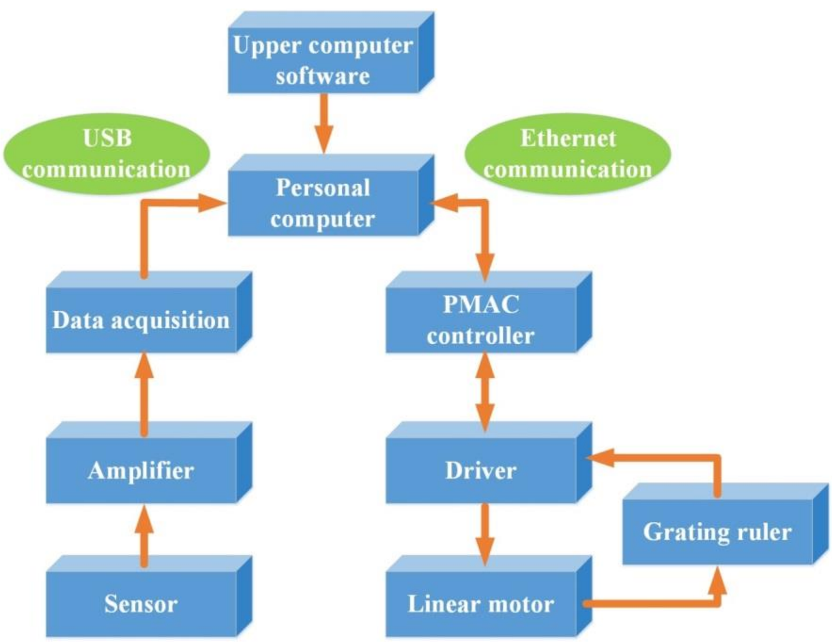


Fig. 3. Control system diagram of the proposed device.

Fig. 3 shows the control system diagram of the proposed device, which is also mainly divided into two components. The force signal is amplified and transmitted to the computer after A/D conversion from the USB port and processed by the upper computer to get the final measured cutting force value. The upper computer sends the motion instruction to the PMAC controller through the Ethernet port. The linear motor is used to realize the desired movement through the driver and the compensation is realized. The resolution of the motion system is 0.1 μm and the positioning accuracy is 0.5 μm.

The working principle of the proposed device is shown in Fig. 4. The spindle is fed in the direction parallel to the thin wall, and the cutting force measurement system is used to measure the radial cutting force perpendicular to the thin wall in the thin wall cutting process. After reading and processing the cutting force, the upper computer outputs the command to PMAC controller. The device can realize the linear motion perpendicular to the thin wall direction, so as to realize the compensation of the radial cutting parameter.

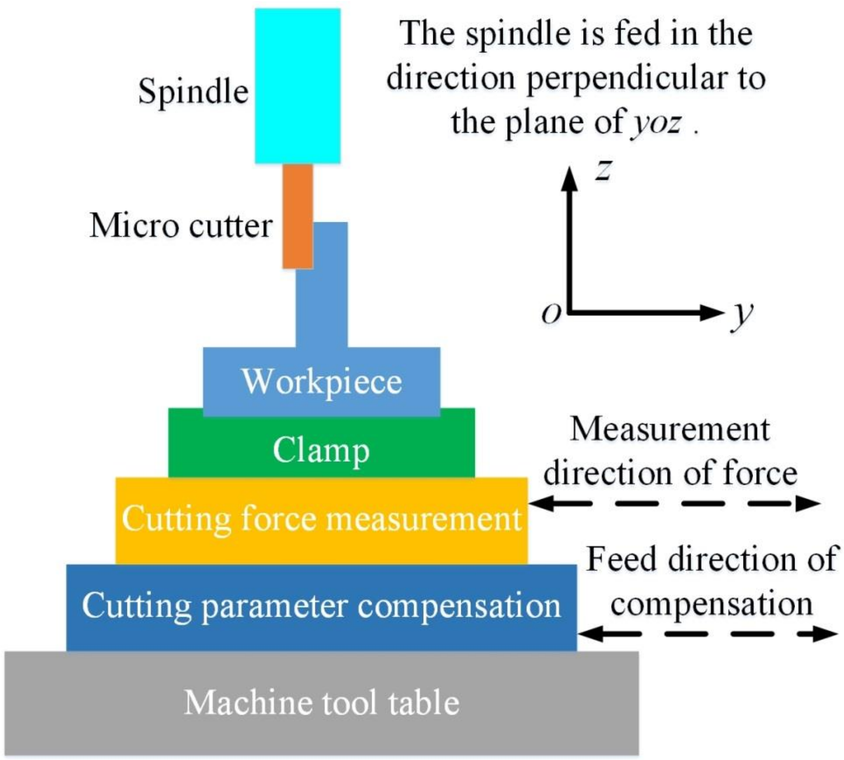


Fig. 4. Working principle of the proposed device.

3. Thin wall deformation model and compensation method

3.1 Thin wall deformation model

A stable cutting load is obtained by extracting the peak value of the cutting force of several successive cycles, which is applied as the concentrated load on the thin wall. The elastic deformation process of the thin wall under the cutting force could be regarded as the deformation process of the cantilever beam.

In the actual cutting process, the lower part of the thin wall is fixed by the clamp, and the upper part is suspended. The thin wall is simplified into the cantilever beam structure as shown in Fig. 5. It is assumed that the height, the thickness and the length of the thin wall is l, h, and b, respectively. The concentrated load F acts on the top of the thin wall.

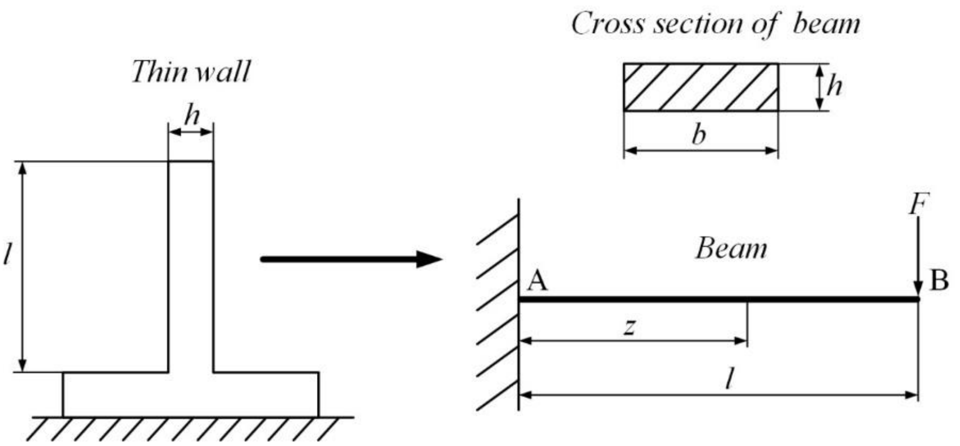


Fig. 5. Diagram of the thin wall simplified as a cantilever beam.

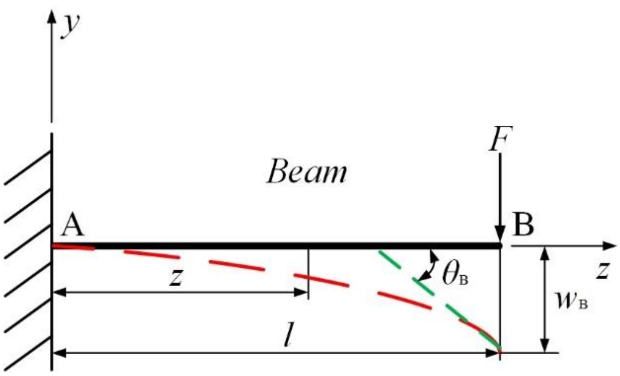


Fig. 6. Diagram of beam deflection.

The coordinate system is established as shown in Fig. 6. The bending moment on any cross section can be calculated by Eq. (1).

$$M=-F\cdot(l-z) \tag{1}$$

Where, z is a position on the cantilever beam, F is the cutting force generated in the thin wall cutting process perpendicular to the thin wall direction, l is the length of the beam, M is the moment at position z.

Eq. (2) is the approximate differential equation of the deflection line.

$$\frac{d^2w}{dz^2}=\frac{M}{EI} \tag{2}$$

Where, w is the deformation of a certain position of the cantilever beam, E is the elastic modulus of the workpiece material, and I is the moment of inertia of the workpiece.

Eq. (3) can be obtained by simplifying Eqs. (1) and (2).

$$EIw''=M=-F\cdot(l-z) \tag{3}$$

Eqs. (4) and (5) can be obtained by integrating Eq. (3).

$$EIw'=\frac{1}{2}Fz^2-Flz+C \tag{4}$$

$$EIw=\frac{1}{6}Fz^3-\frac{1}{2}Flz^2+Cz+D \tag{5}$$

Where, w' is rotation angle, w is deflection, C and D are the integral constants.

Since A side is fixed, both rotation angle w_A' and deflection w_A are 0, that is, Eqs. (6) and (7) can be obtained when z=0.

$$w_A'=\theta_A=0 \tag{6}$$

$$w_A=0 \tag{7}$$

The boundary conditions Eqs. (6) and (7) are substituted into Eqs. (4) and (5) respectively, then the Eqs. (8) and (9) can be obtained.

$$C=EI\theta_A=0 \tag{8}$$

$$D=EIw_A=0 \tag{9}$$

Then the integral constants C and D are substituted back into Eqs. (4) and (5), and the equations of rotation angle Eq. (10) and deflection line Eq. (11) are obtained.

$$EIw'=\frac{1}{2}Fz^2-Flz \tag{10}$$

$$EIw=\frac{1}{6}Fz^3-\frac{1}{2}Flz^2 \tag{11}$$

The Eq. (10) and Eq. (11) can be simplified as Eq. (12) and Eq. (13), respectively.

$$w'=(\frac{1}{2}z-l)\cdot Fz/EI \tag{12}$$

$$w=(\frac{1}{6}z-\frac{1}{2}l)\cdot Fz^2/EI \tag{13}$$

According to Eq. (13), the amount of deformation w is related to the size of the cutting force F and the cantilever stress position z for the same cantilever.

The moment of inertia of rectangular section is defined, as shown in Fig. 7 and Eq. (14). In this study, moment of inertia is changing as the cutting process, not as a fixed value, it is necessary to establish a function between moment of inertia with cutting processing.

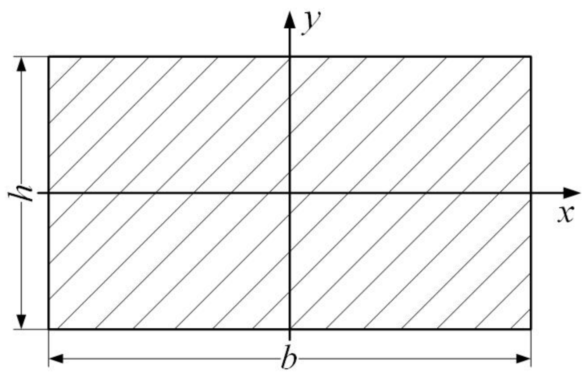


Fig. 7. Diagram of standard rectangular moment of inertia.

$$I_z=\int_{-h/2}^{h/2} by^2\, dy=bh^3/12 \tag{14}$$

Fig. 8 shows the thin wall shape change in the process of cutting. According to the definition of moment of inertia, the coordinate system is established. Thin wall can be divided into two parts along the Z-axis direction according to the axial cutting depth location of the thin wall as shown in Fig. 9. Then, the moment of inertia of the two parts are calculated respectively. The mean value of the two moment of inertia works as the actual moment of inertia.

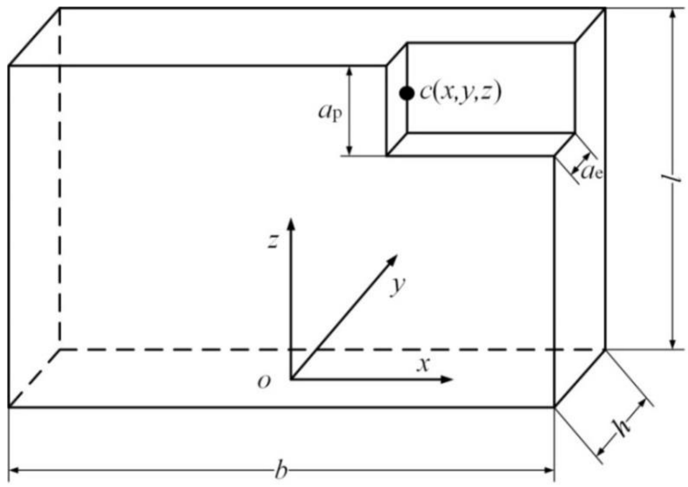
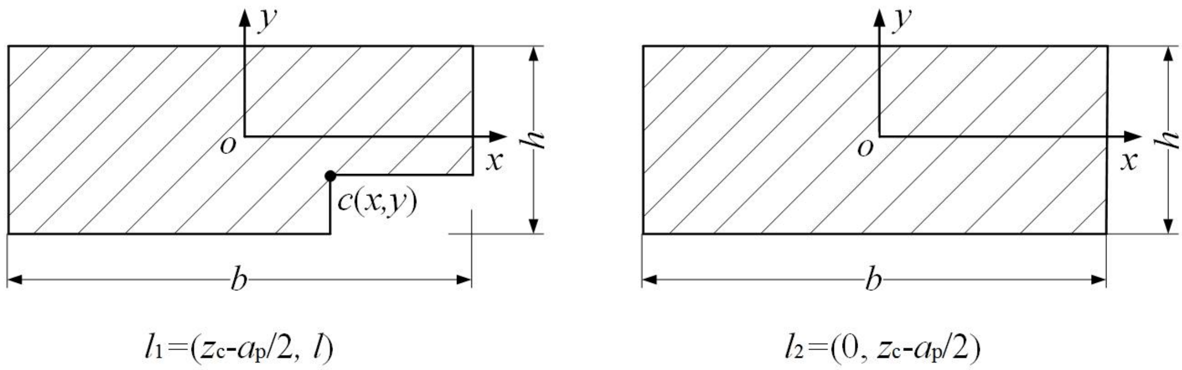


Fig. 8. Diagram of thin wall shape change.



(a) Section one

(b) Section two

Fig. 9. Diagram of different sections.

According to the definition of the moment of inertia in Eq. (14), the moment of inertia of section one and section two can be respectively expressed as follows.

$$I_1=\int_{-h/2+a_e}^{h/2} by^2\,dy+\int_{-h/2}^{-h/2+a_e} (x_c+b/2)y^2\,dy \tag{15}$$

$$I_2=\int_{-h/2}^{h/2} by^2\,dy \tag{16}$$

The Eqs. (15) and (16) are integrated along the Z-axis. Then the average value is calculated as the average moment of inertia of the thin wall, which can be expressed as:

$$I_{\mathrm{ave}}=(\int_{z_{\mathrm{c}}-a_{\mathrm{p}}/2}^{l} I_1\, dz+ \int_{0}^{z_{\mathrm{c}}-a_{\mathrm{p}}/2} I_2\, dz)/l \tag{17}$$

Therefore, the actual equation of the deflection line can be expressed as:

$$w=(\frac{1}{6}z-\frac{1}{2}l)\cdot Fz^2/EI_{\mathrm{ave}} \tag{18}$$

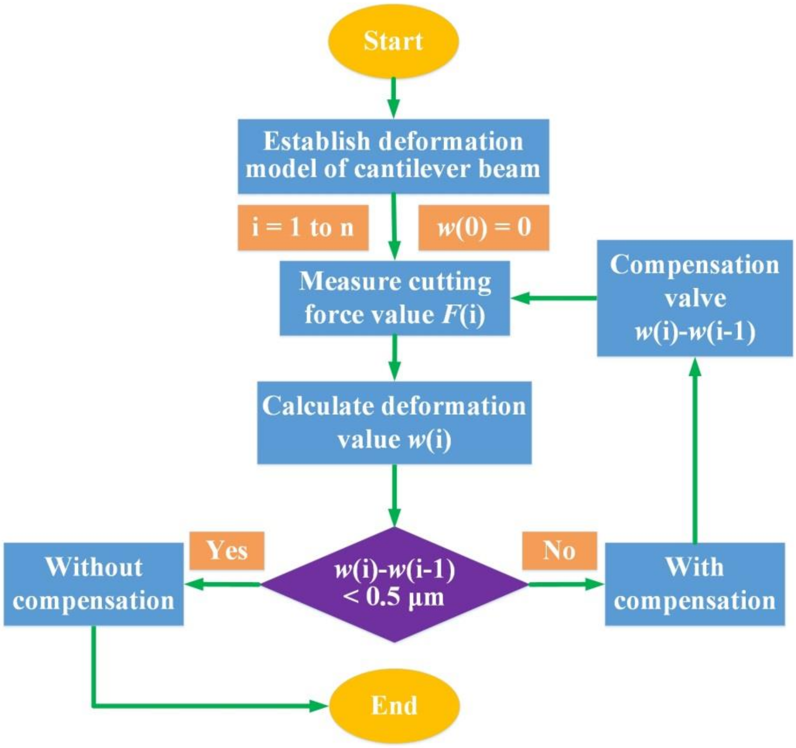


Fig. 10. Thin wall deformation compensation process.

3.2 Compensation method

The iterative method is adopted to conduct thin wall deformation compensation. Based on the established deflection equation, the cutting force is measured firstly. Then, the value of the deformation is calculated according to the deflection equation and compared with the threshold. If the incremental deformation value is less than 0.5 μm, the compensation is not performed. If the incremental deformation value is greater than 0.5 μm, it is necessary to compensate. After the compensation is completed, the cutting force is measured again and the deformation value is also calculated. The compensation is stopped until the incremental deformation value is less than 0.5 μm. The specific compensation process is shown in Fig. 10.

4. Contrast experiment

In order to verify the reliability of the model and whether the dimensional errors are reduced after the cutting parameter compensation, the contrast experiments with and without compensations are conducted using the introduced device.

4.1 Experiment setup

The CNC milling machine tool CarverPMS23_A8 is selected to conduct the micromilling experiments, as shown in Fig. 11. The programming resolution for each linear axis is 0.1 μm. The maximum rotation speed of spindle is 36, 000 min^{-1}. The cutting force measurement and cutting parameter compensation device is fixed on the worktable of the machine tool. The workpiece is fixed on the proposed device through the clamp.

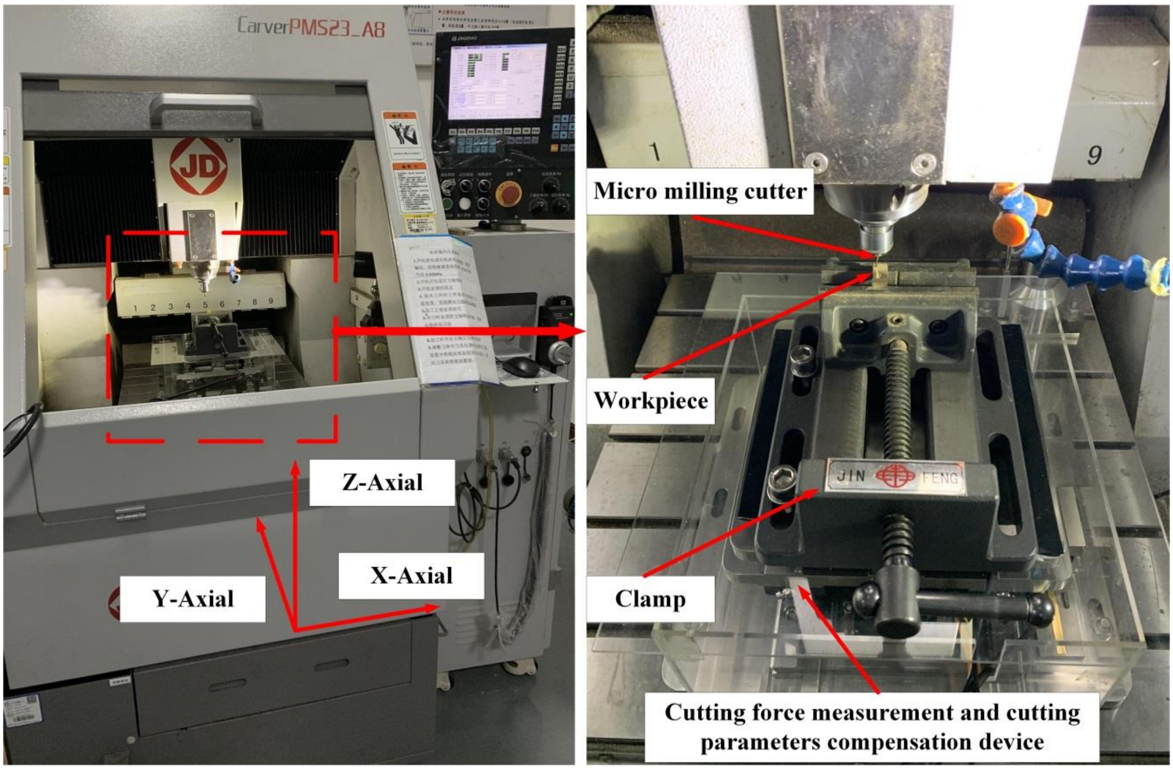


Fig. 11. Experiment setup.

The feed per tooth is directly related to the phenomenon of minimum cutting thickness, and has a great influence on the micromilling force and machining quality due to the size effect in microcutting processes. Therefore, the feed per tooth is an important parameter in the micromilling process. In this study, the main purpose is to study the relationship between milling force and deformation of the thin wall. Considering the size effect in the microcutting process, the nonlinear force increase due to ploughing should be avoided. Therefore, the feed per tooth should be carefully selected and greater than the minimum undeformed chip thickness. The cutting parameters are determined as shown in Table 2 based on previous studies [13-18]. The attributes of the tool and workpiece used in the experiment are shown in Table 3 and Table 4 respectively.

Table 2. The micromilling parameter selection for high aspect ratio thin walls.

No.	Thin wall width (μm)	Thin wall height (μm)	a_e (μm)	a_p (μm)	f_z (μm/z)
1	80				
2	100	800	50	200	1.6
3	120				

Table 3. The properties of the micromilling cutter.

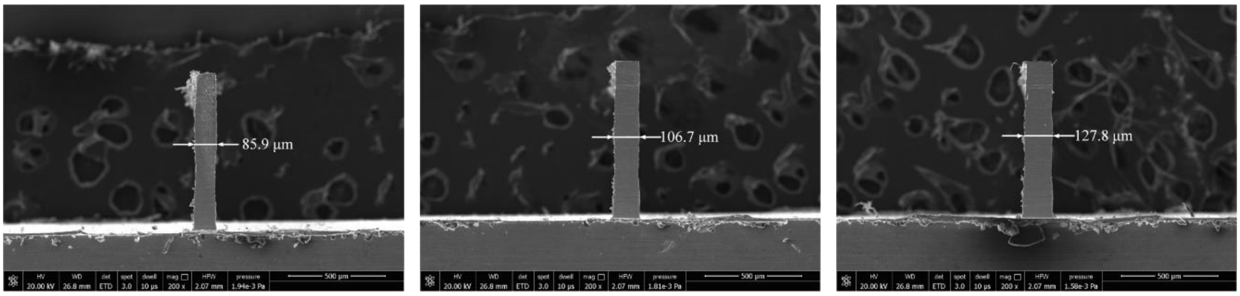
Diameter	Spiral Angle	Cutting Edges	Cutting Edge Radius	Matrix	Coating
1 mm	35°	4	5 μm	Carbide	TiAlN

Table 4. The material properties of the workpiece.

Material	Elastic Modulus (N/mm^2)	Shear Elastic Modulus (N/mm^2)	Poisson Ratio	Thermal Conductivity (W/(m•K))	Specific Heat (J/(kg•K))	Density (Kg/m^3)
H59 Brass	100000	37000	0.33	110	390	8500

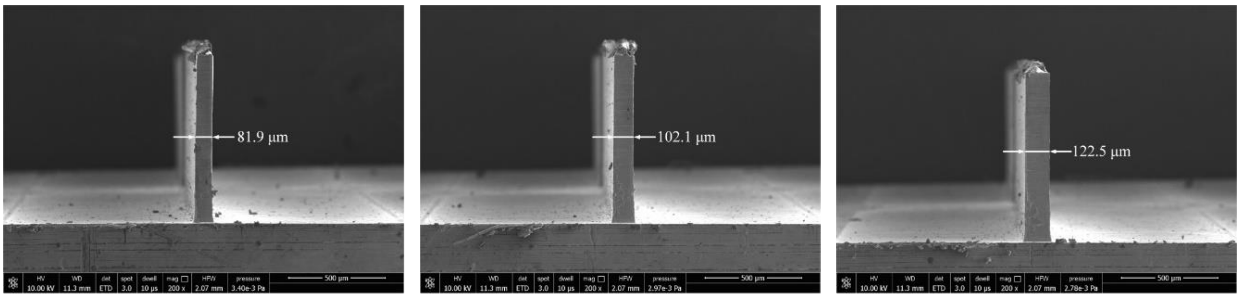
4.2 Results

The actual thicknesses of thin walls are measured by scanning electron microscope (Model: quanta 250) after micromilling. Fig. 12 and Fig. 13 show the thin wall measurement results without and with compensations, respectively. All measurements are averaged by measuring at least six positions.



(a) W = 80 μm (b) W = 100 μm (c) W = 120 μm

Fig. 12. Results without radial cutting parameter compensation.



(a) W = 80 μm (b) W = 100 μm (c) W = 120 μm

Fig. 13. Results with radial cutting parameter compensation.

Table 5. Comparison of relative dimensional errors.

No.	Nominal thickness (μm)	Thickness without compensation (μm)	Relative dimensional errors	Thickness with compensation (μm)	Relative dimensional errors
1	80	85.9	7.38%	81.9	2.38%
2	100	106.7	6.70%	102.1	2.10%
3	120	127.8	6.50%	122.5	2.08%
Average	100	107.2	6.86%	102.2	2.19%

4.3 Result analysis

It can be seen from Fig. 12 that the thickness of the thin wall without compensation is not uniform. But from Fig. 13, the thickness of the thin wall after radial cutting parameter compensation is relatively uniform. The experimental results show that the dimensional errors of the thin walls have been significantly reduced. The average relative error has been reduced from 6.86% to 2.19%. The machining quality has a relatively obvious improvement in dimensional accuracy after the cutting parameter compensation. It is undeniable that the size of the thin wall still has a certain error due to various reasons such as the positioning errors of both the proposed device and the machine tool, etc.

As shown in Fig. 12, the dimension errors of the three thin walls don't appear the situation that the thickness at the top is significantly larger than that at the bottom as shown in Fig. 1. Possible reasons are discussed as follows.

After the first layer is cut, the elastic deformation of the thin wall is recovered. Part of the material is not removed due to the deformation. After the second layer is cut, since the thin wall stiffness of the second layer is greater than that of the first layer under the same process conditions, the deformation of the second layer will be less than that of the first layer in the cutting process.

Therefore, the residual material of the first layer will be partially removed at this time. Similarly, when the third layer is cutting, the residual material of the first layer and the second layer will be partially removed too. Furthermore, when the fourth layer is cutting, the residual material of the previous three layers will be partially removed. The material removal amount from top to bottom of each layer is increasing in this cutting situation. Therefore, the tool constantly removes the uncut part of the material on the upper layer in the process of layered cutting, and the final thin wall will not appear obvious shape error on the whole, but there will be a certain error on the dimension. Axial laminated milling can improve the shape accuracy of thin wall parts, but it is difficult to reduce the dimensional errors.

5. Conclusions

Based on straight thin wall micromilling experiments, the micromilling strategies and the proposed device for radial compensations in micromilling of thin walls have been successfully evaluated. The contrast experiments show that the dimensional errors of the thin wall are significantly reduced after the radial cutting parameter compensations. The average relative error has been reduced from 6.86% to 2.19%. The dimensional accuracy of the thin wall has been greatly improved and the shape accuracy of the thin wall has been guaranteed compared with that without compensations. Experimental results show that the established cantilever beam model is reliable, which can be used to compensate the radial cutting parameter in the thin wall micromilling process.

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Data availability All data generated or analyzed during this study are included in this published article.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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Figures

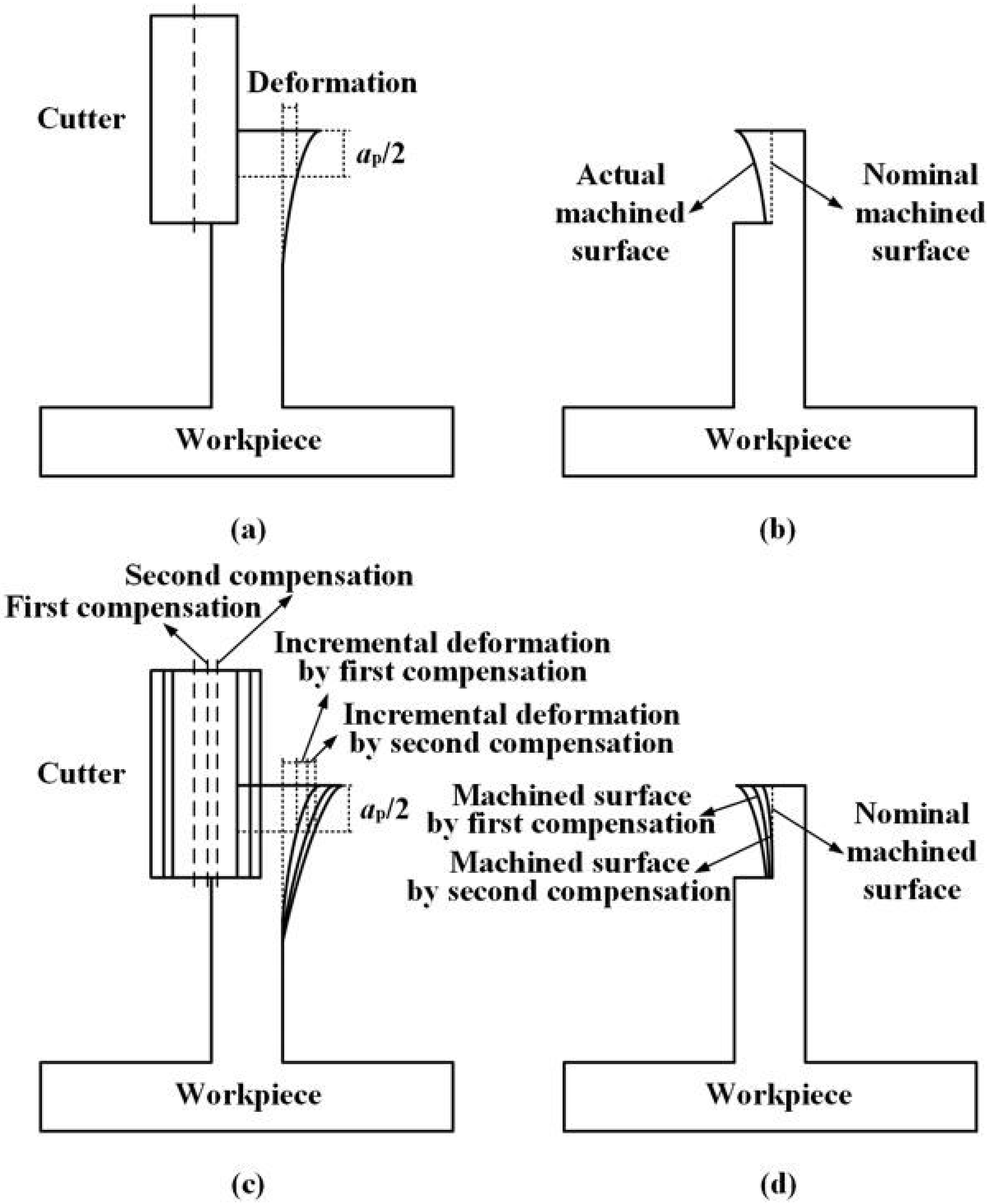


Figure 1

Schematic view of thin wall deformation and compensation process.

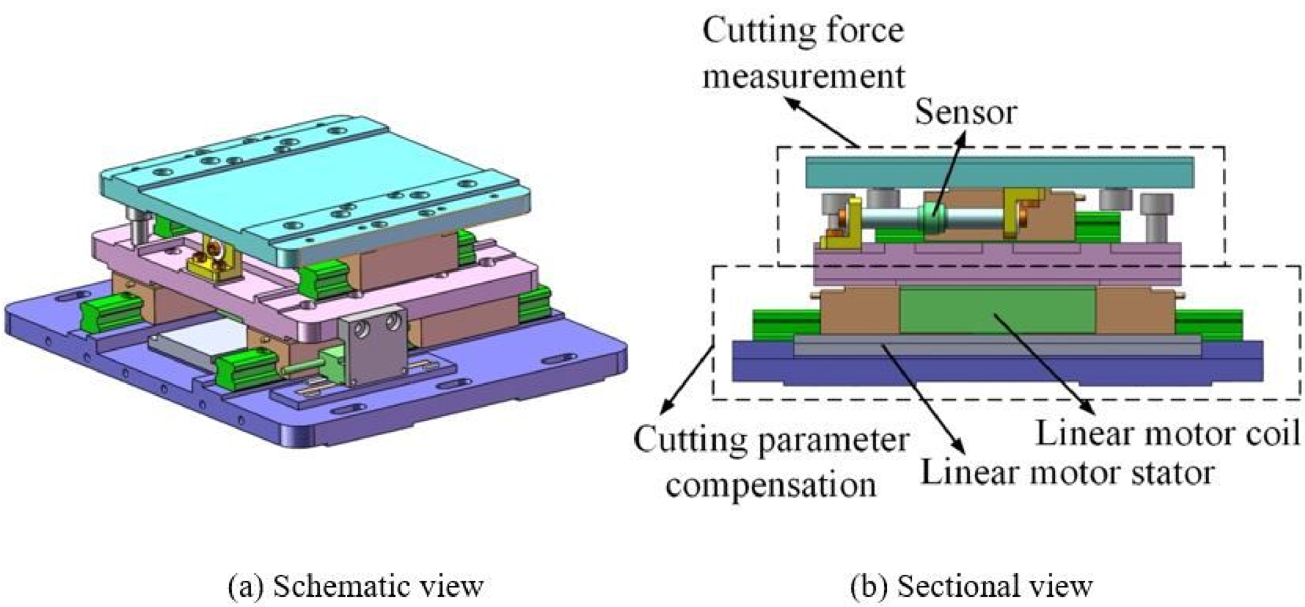


Figure 2

The designed cutting force measurement and cutting parameter compensation device.

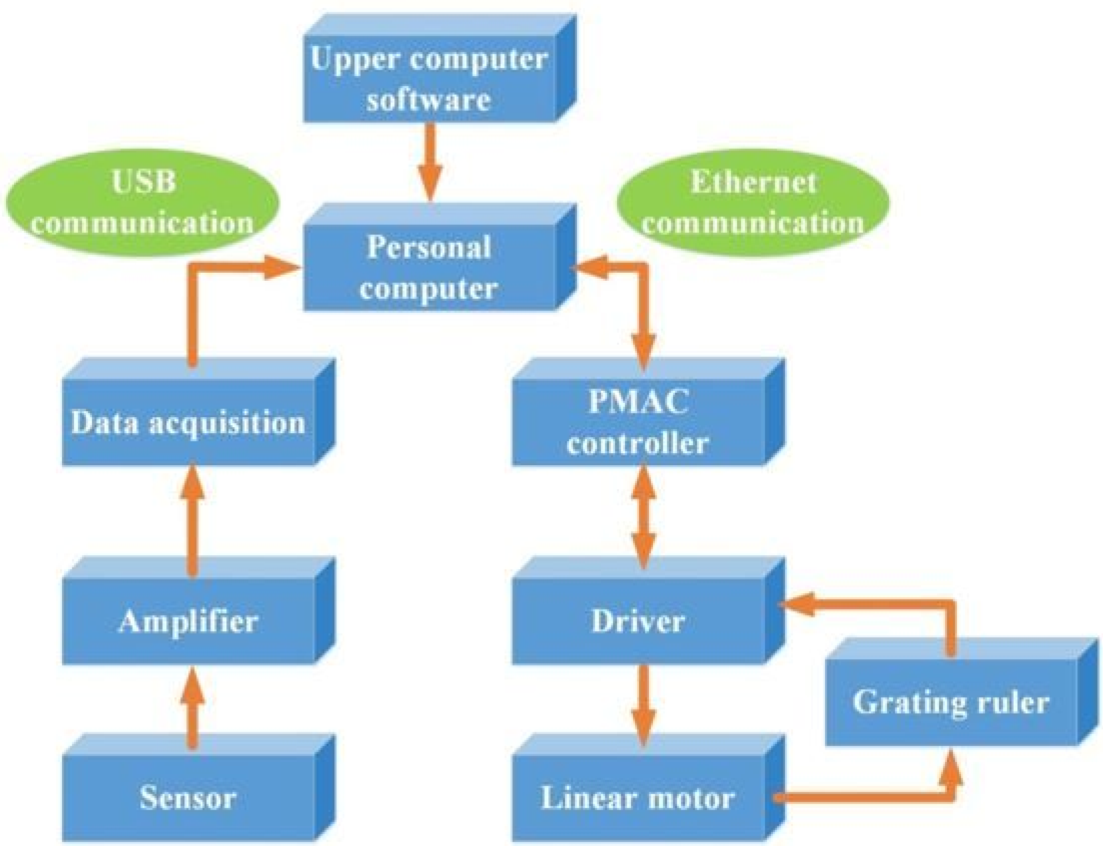


Figure 3

Control system diagram of the proposed device.

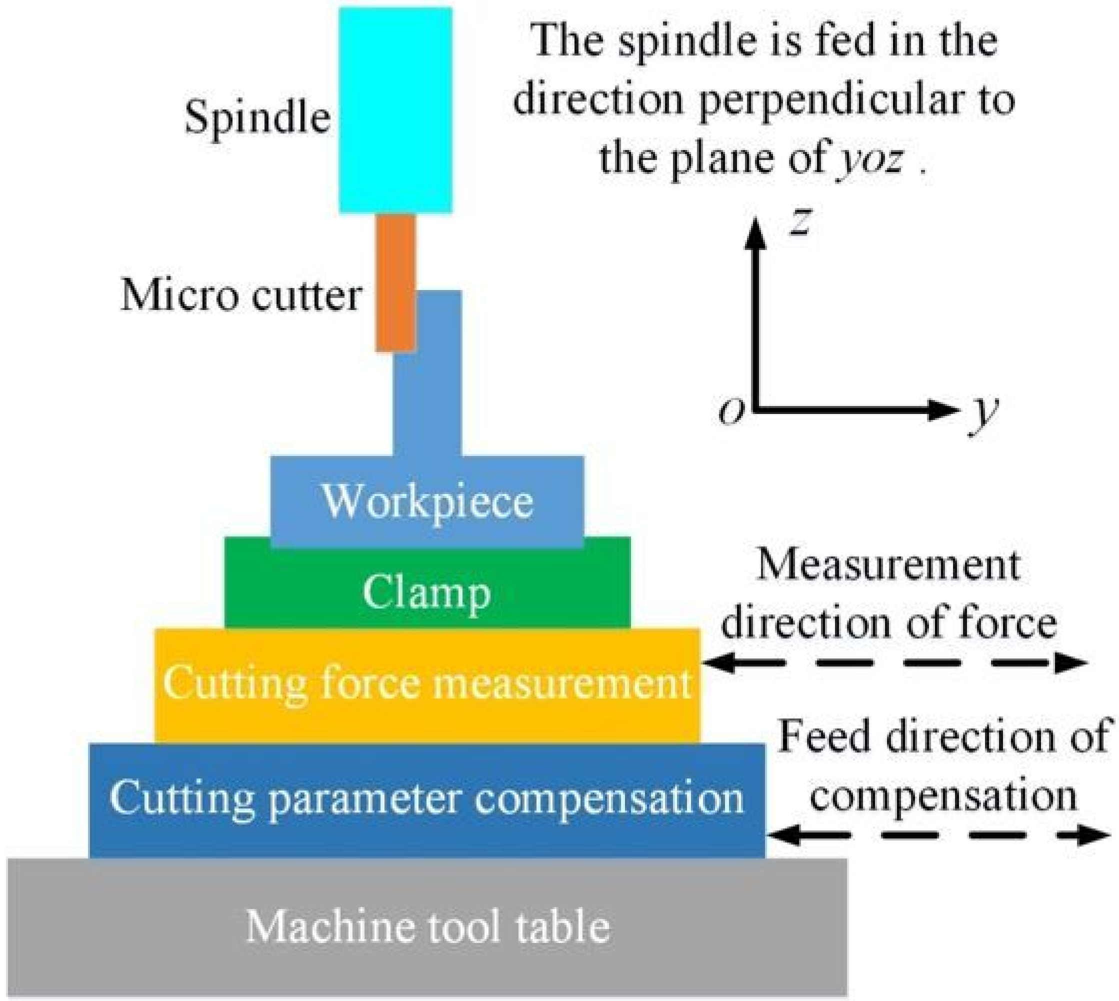


Figure 4

Working principle of the proposed device.

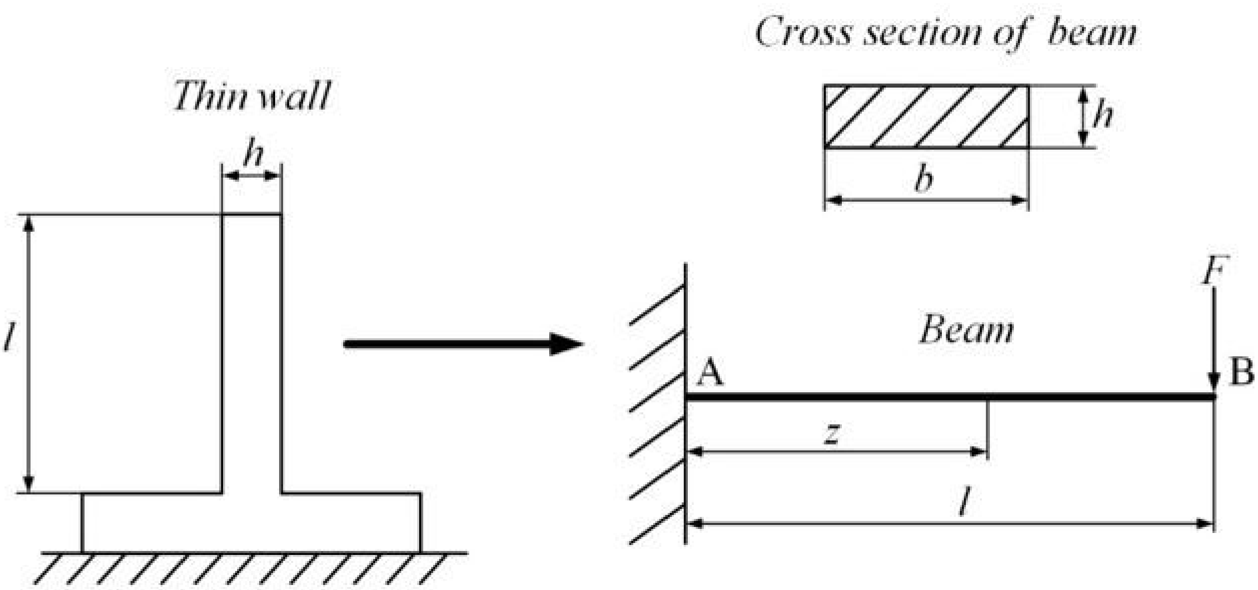


Figure 5

Diagram of the thin wall simplified as a cantilever beam.

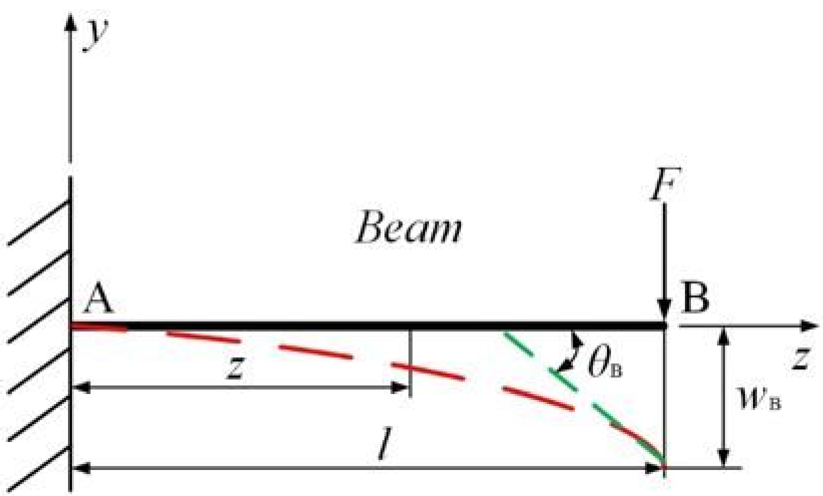


Figure 6

Diagram of beam deflection.

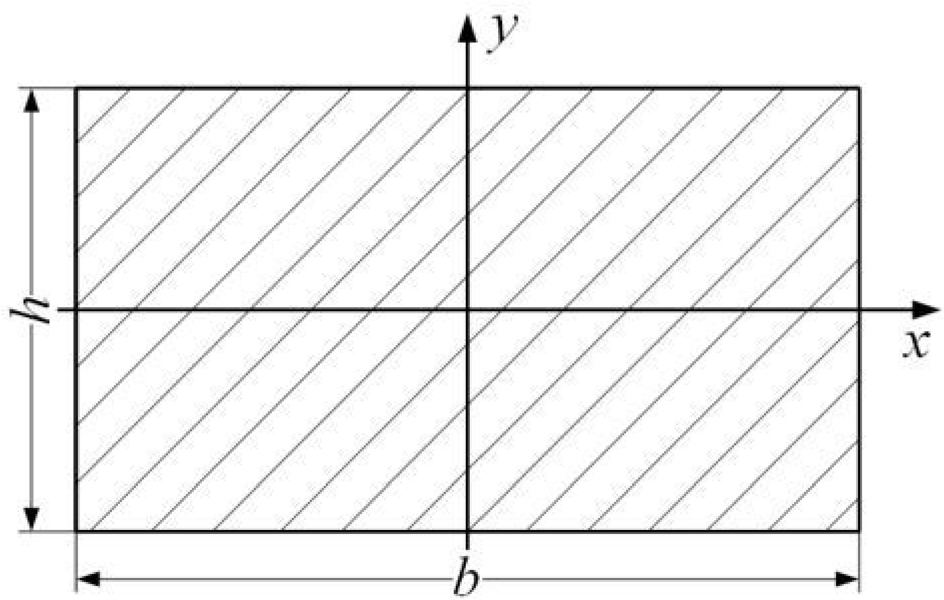


Figure 7

Diagram of standard rectangular moment of inertia.

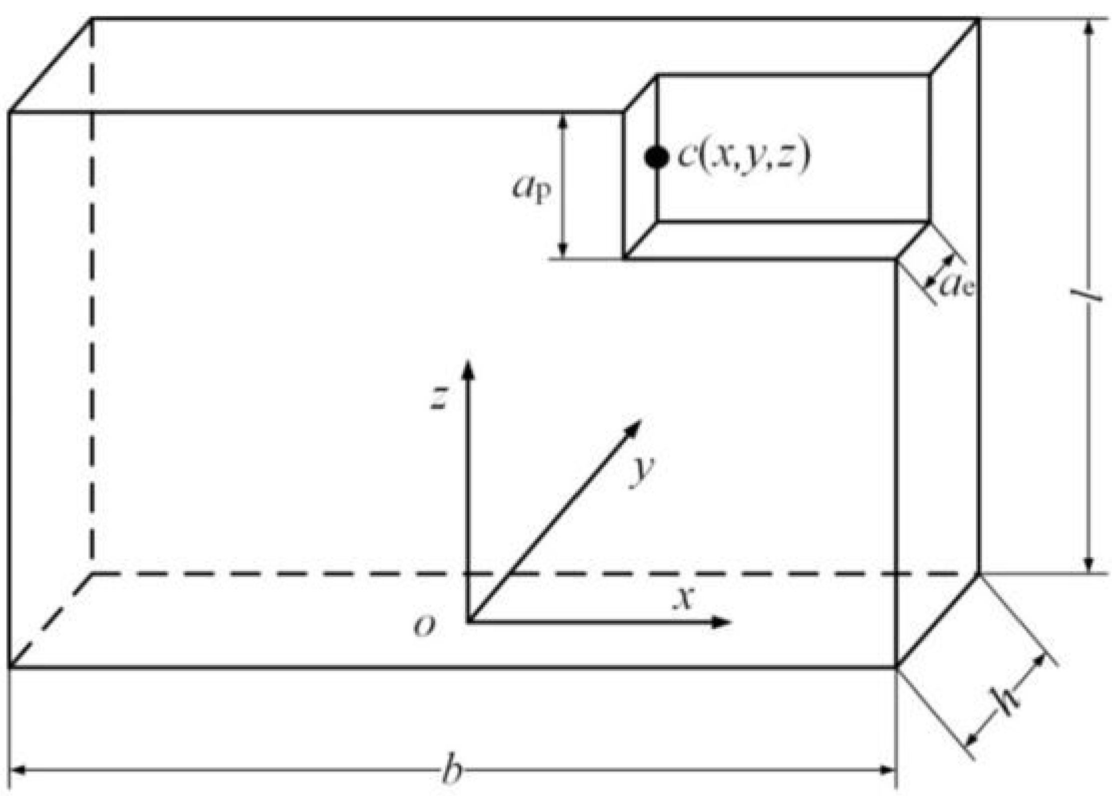


Figure 8

Diagram of thin wall shape change.

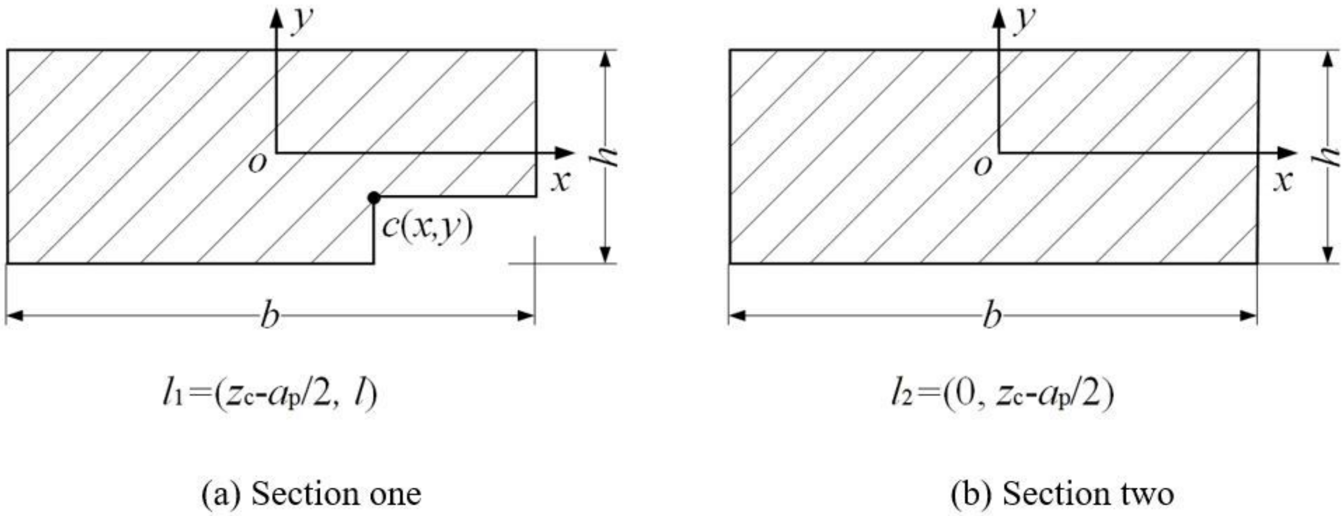


Figure 9

Diagram of different sections.

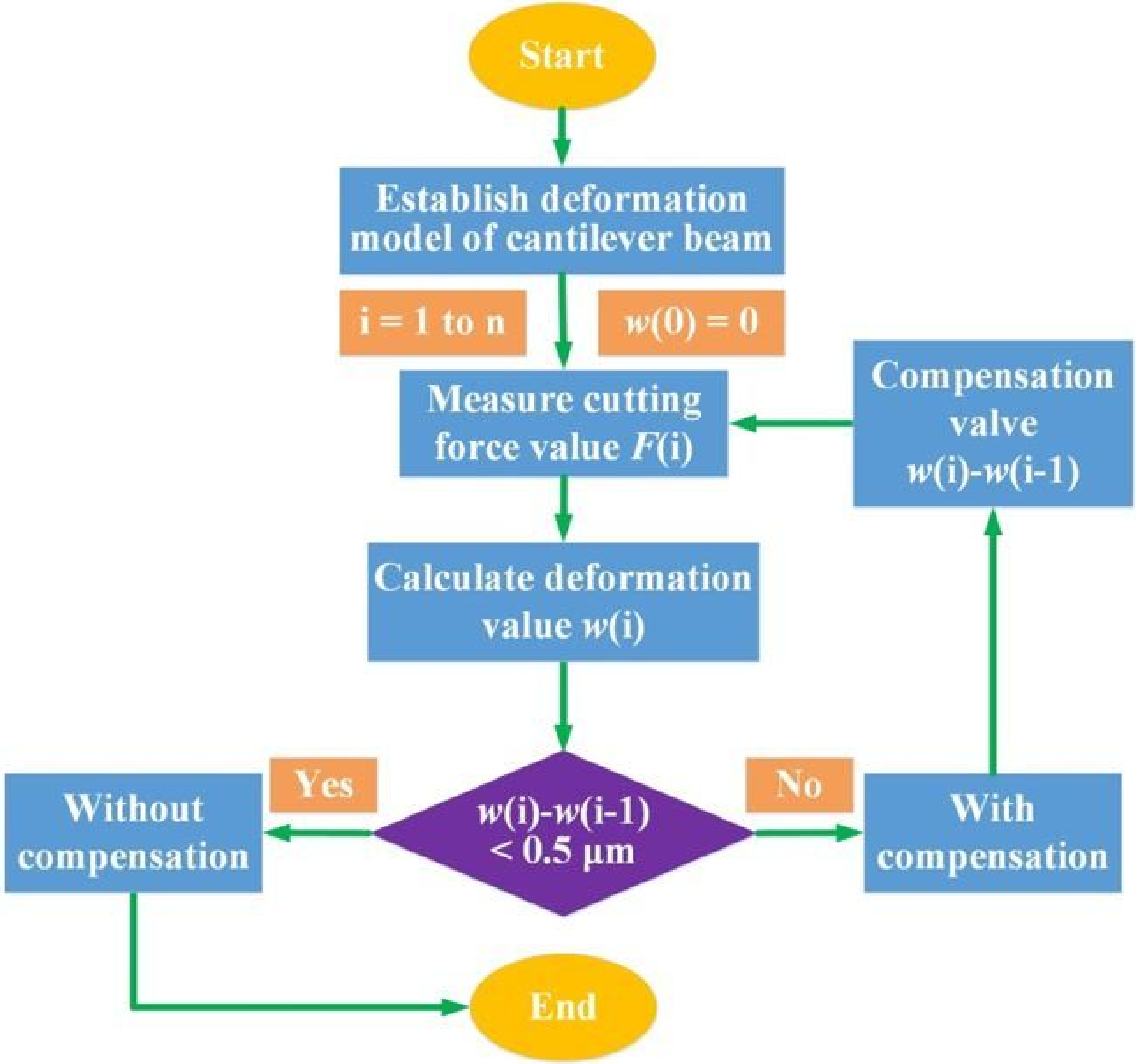


Figure 10

Thin wall deformation compensation process.

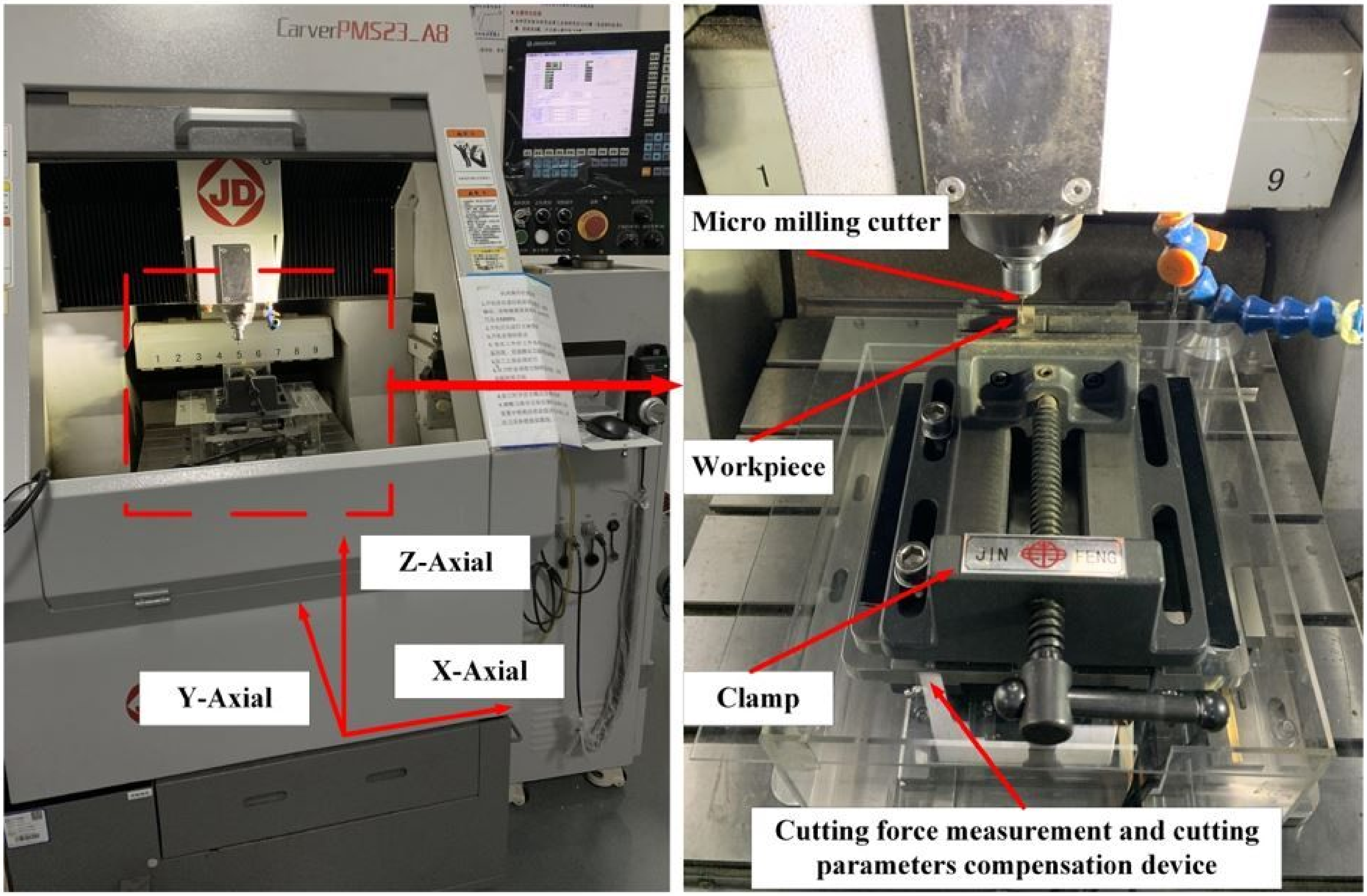


Figure 11

Experiment setup.

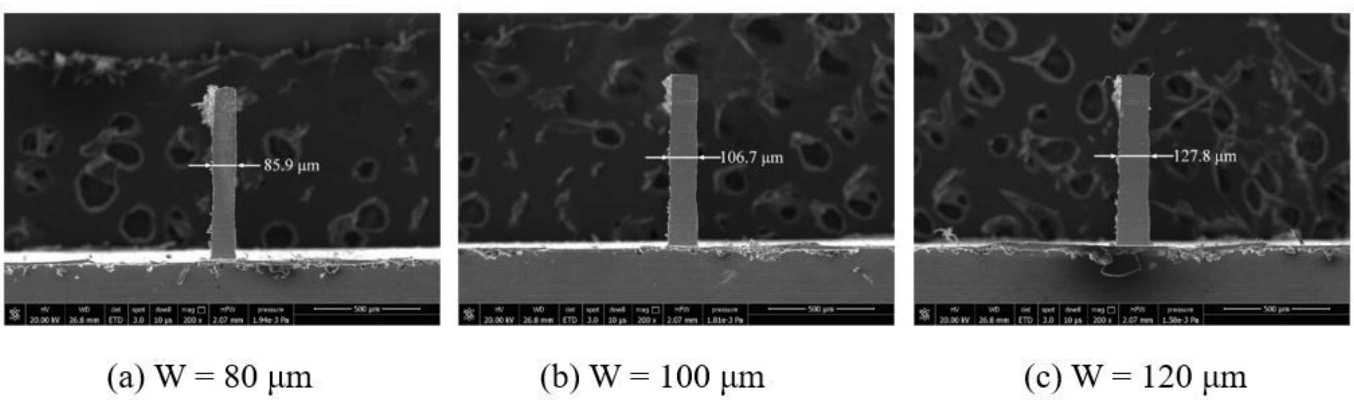
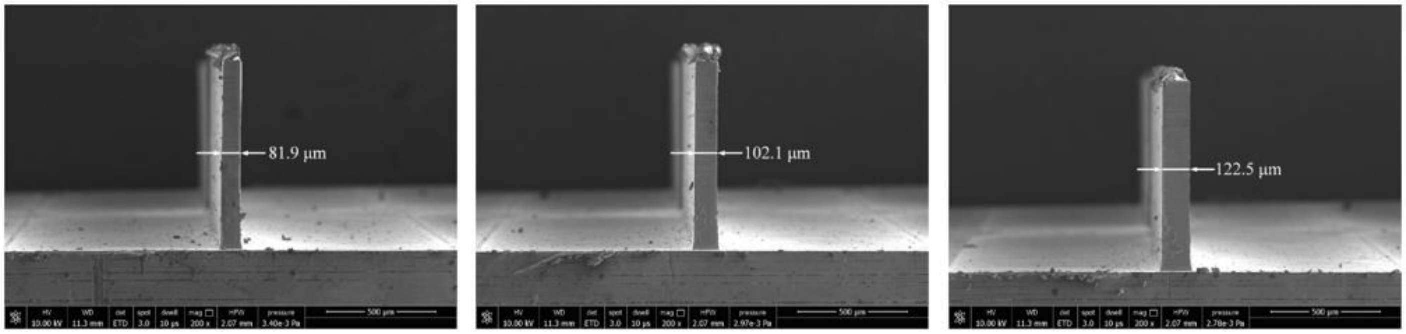


Figure 12

Results without radial cutting parameter compensation.



(a) W = 80 μm (b) W = 100 μm (c) W = 120 μm

Figure 13

Results with radial cutting parameter compensation.