



An accuracy evolution method applied to five-axis machining of curved surfaces

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Abstract

Currently, some high-value-added applications involve the manufacturing of curved surfaces, where it is challenging to achieve surface accuracy, repeatability, and productivity simultaneously. Among free-form surfaces, curved surfaces are commonly used in blades and airfoils (with a teardrop-shaped cross-section) and optical systems (with axial symmetry). In both cases, multi-axis milling accuracy directly affects the subsequent process step. Therefore, reducing even insignificant errors during machining can improve the accuracy in the final production stages. This study proposes an “evolution” method to improve the machining accuracy of curved surfaces. The key is to include compensation for the machining error after the first part through profile error measurement. Thus, correction can be applied directly after the manufacturing programming is fully developed, achieving the product with the minimum number of iterations. Accordingly, this method measures the machining error and changes only one key parameter after the process. This study considered two cases. First, an airfoil in which the clamping force was corrected; the results were quite good with only one modification in the blade machining case. Second is an aspherical surface where tool path correction in the Z-axis was applied; the error was effectively compensated along the normal vector of the workpiece surface. The experimental results showed that the surface accuracy increased from 44.4 to 4.5 μm , and the error was reduced by 89.9%, confirming that the accuracy of the machine tool and process had achieved “evolution.” This technical study is expected to help improve the quality and productivity of manufacturing highly accurate curved surfaces.

Keywords Aeronautical blade · Multi-axis machining · Geometric deviation compensation · Machining accuracy evolution · Axisymmetric aspheric surface · Error compensation

1 Introduction

This study approaches the common industrial problem of manufacturing complex curved surfaces in multi-axis machining centers with the same order of magnitude of precision as the manufactured parts. High-added-value components are commonly desired in applications such as turbomachinery and high-precision aspheric optical surfaces. Corrective measures or the so-called evolution-based method is necessary to achieve manufactured parts

according to customer requirements without changing all tool-path programming and processes. On the contrary, the entire process must vary, even when the geometrical position of the tool center point (TCP) and tool axis orientation are directly calculated by all commercial software with five-axis capabilities [1]. However, it requires skilled programmers and cannot be directly performed in workshops. Machinists usually apply a corrective method that involves the use of correction tables based on the previous performance and behaviors of machine tools. The practical parading is usually “the second part will be the right part,” instead of the more idealistic “first part-right part.” It is important to make a proper definition of the process, thus provide essential means for process control and its optimization [2].

Aerodynamic profile parts (airfoils, blades, blisk, and NGVs) are important components in aeronautics because a jet engine is composed of many such parts to drive and direct

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the airflow. They are usually manufactured by milling the starting blocks or investment casting process. Nevertheless, it is necessary to perform different finishing operations to achieve higher accuracy. This study considers the case of a thin-walled part; it is important to analyze the clamping of the part as it can induce deformations in the machining process. From an academic perspective, several studies have been conducted on the effects of clamping on machining, and different clamping devices have been developed to avoid deformations [3]. Jian-Hua et al. [4] designed a clamping system in which stresses can be released during machining. This is an adaptive double-sphere system that is adjusted to produce stress-free clamping, thus avoiding induced location errors. Wang et al. [5] used a low-melting-point alloy to clamp and support thin-walled parts. Meshreki et al. [6] introduced a new concept to optimize clamping capability by designing a model that predicts the dynamics of complex thin-walled aerospace structures under sinusoidal impact and machining loads. Li et al. [7] presented a method to determine the optimal clamping forces for a multiple fixture subjected to quasi-static machining forces to reduce the impact on both the accuracy and location error of the part.

However, axisymmetric aspherical surface components are important optical components. Five-axis or four-axis milling is the first process stage, and milling accuracy directly impacts the subsequent grinding and polishing processes. Even small processing errors in milling can significantly reduce the grinding and polishing times.

There are two main ways to ensure high machining accuracy.

1. The first method involves using machine tools with higher accuracy than the workpiece required. This is called the “motherhood” principle, which involves using a high-precision machine that produces high-precision parts [8]. However, the use of high-precision machine tools directly increases manufacturing costs. The usual drawback in daily production is that many companies that have good machines aspire to offer services in the niche of high-value-added applications and need a solution for trial-error methods, obtaining a clear methodological approach.
2. Considering this, an alternative is to improve the machining accuracy through error compensation technology on machine tools whose precision is of the same order of magnitude as the workpiece to be produced. This approach is known as the “evolution” principle. The main processes of error compensation operations for improving machining accuracy include volumetric error modeling, measurement, compensation [9, 10], and verification of machining accuracy through specific machining tests [11].

Researchers have demonstrated that various error sources adversely affect the nominal accuracy of machine tools [12]. However, most existing studies focus on single-error modeling methods, such as machine tool geometric error modeling, tool wear error modeling, and thermal error modeling, as the main research direction. Rahman et al. [9] established a quasi-static comprehensive spatial error model of multi-axis computer numerical control (CNC) machine tools, including errors in geometry, thermal deformation, rotary axis, and elastic deformation of machine tool components based on a homogeneous coordinate matrix. Ferreira and Liu established an error model for a three-axis machine tool by using rigid-body kinematics and small-angle error assumptions [13]. Cho et al. used an on-machine measurement system to measure the error size, and then used an artificial neural network model to train the data to achieve error compensation [14, 15]. He et al. used an online inspection system to measure the error of a fixture system and compensated for the error [16]. Choi et al. configured an online detection method for three-axis CNC machine tools, established an error analysis and compensation method, and modified the tool position file using an algorithm to reduce machining errors [17]. Gdula [18] proposed an adaptive five-axis machining strategy for turbine rotor blades, considering the variable curvature radius and change in the mill axis orientation. The selection method of the milling tool paths using the predicted value of the cutting forces as a decision criterion was proposed to minimize the dimensional errors of a complex surface [19].

In practical applications, it was found that the norm of the error vector is a comprehensive concept of the tool center point [20]. However, the accuracy of the volumetric error model strongly depends on the error propagation scheme and accuracy of the geometric error measurement and identification [21]. In addition, thermal-induced errors are more complex, thus posing a significant challenge to volumetric error modeling [22]. Usually, machining accuracy can be effectively improved offline by modifying the machining programs according to the nominal or reconstructed three-dimensional (3D) model based on the measurement data acquired with a laser scanner or coordinate measuring machine [23, 24]. Existing research shows that a comprehensive error in locating the machining center is an extremely complex problem, resulting in several studies focusing on establishing an integrated model to represent it.

Therefore, there are some approaches for improving machine tools and machining processes; however, a global approach is required to achieve a better definition. The proposed idea is an evolution method that considers the change in only one factor after the development of CNC programs. Despite being two pieces of very different applications, both cases have the same objective, which is to develop a methodology by which the

errors of the first manufactured part lead to a more accurate second part with minimal changes.

Two types of error—systematic and random—may occur. A systematic error is the result of a miscalibrated machine/system or a measuring technique which always results in the measured value being larger (or smaller) than the “true” value. Therefore, it can be compensated for or eliminated. However, random errors imply uncertainty and must be resolved statistically. Many machine/machining problems are related to systematic errors; therefore, measuring the first manufactured part provides the errors and useful information to compensate for them in manufacturing the second part. This is a basic idea in many workshop practices and the main aim of the proposed methodology in this study.

2 Proposed methodology for accuracy improvement in multi-axis machining

This study proposes a practical accuracy-enhancement method for multi-axis machining. This method seeks to improve machining accuracy without requiring complex models. The methodology includes an iterative process that treats the problem as a *one-degree-of-freedom* system. This method is defined as an *accuracy-based evolutive method* (ABEM). Therefore, a single-system feature is defined as an input variable (i.e., cutting speed) to modify the surface errors (output variable), whereas the other system features (machine, clamping, programming method, and cutting conditions) remain unchanged. As the main

idea, the total sum of errors induced by all variables is assumed to be within a single integral systematic error. This integral error is compensated for by using one chosen variable. Therefore, the method is useful for systematic deviations but does not reduce the process uncertainties owing to repeatability.

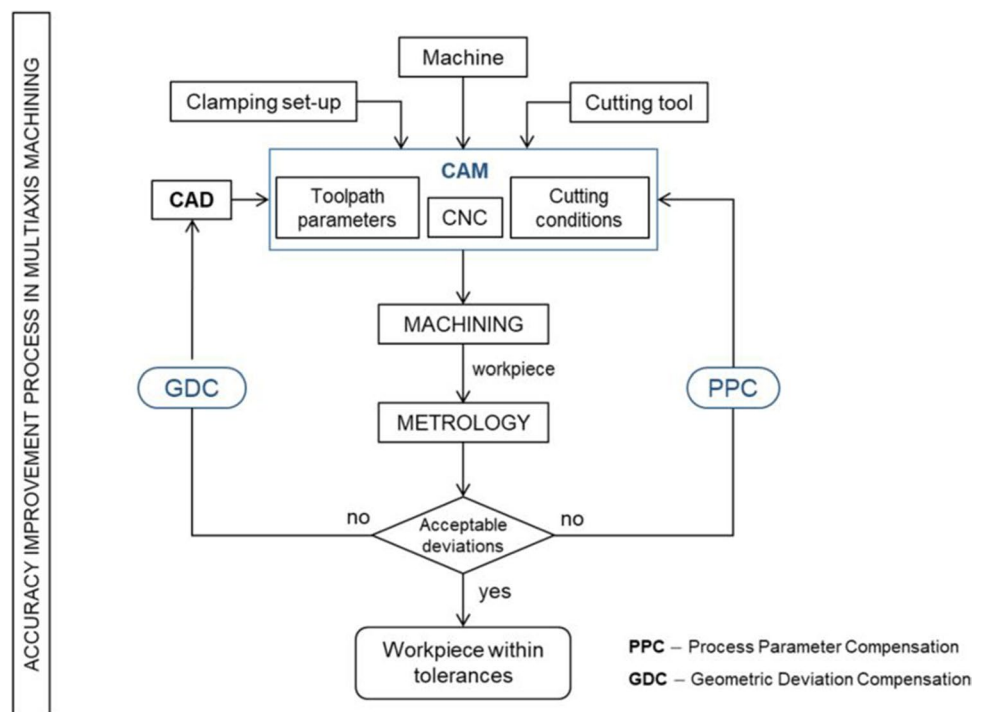
The main advantage of this method is that it realizes a production process through which the desired geometry is obtained with the tolerances required, according to the design. This study is more oriented toward the industry because it includes the verification of the obtained geometry (Fig. 1).

Two methods for machining error compensation for curved surfaces are proposed.

- The first method is *process parameter compensation* (PPC), which compensates for the total error by modifying the variable of the cutting process with the highest effect on the error. Therefore, it is necessary to analyze all possible causes of error and identify the variable with the highest effect.
- The second method is *geometric deviation compensation* (GDC), which involves modifying the part geometry by toolpath compensation based on the measured deviations in the first workpiece, maintaining fixed path programming parameters and process variables.

The above methodology is applied and demonstrated in two different multi-axis machines for different machining applications.

Fig. 1 Accuracy-based evolutive method (ABEM) for precision improvement in multi-axis machining

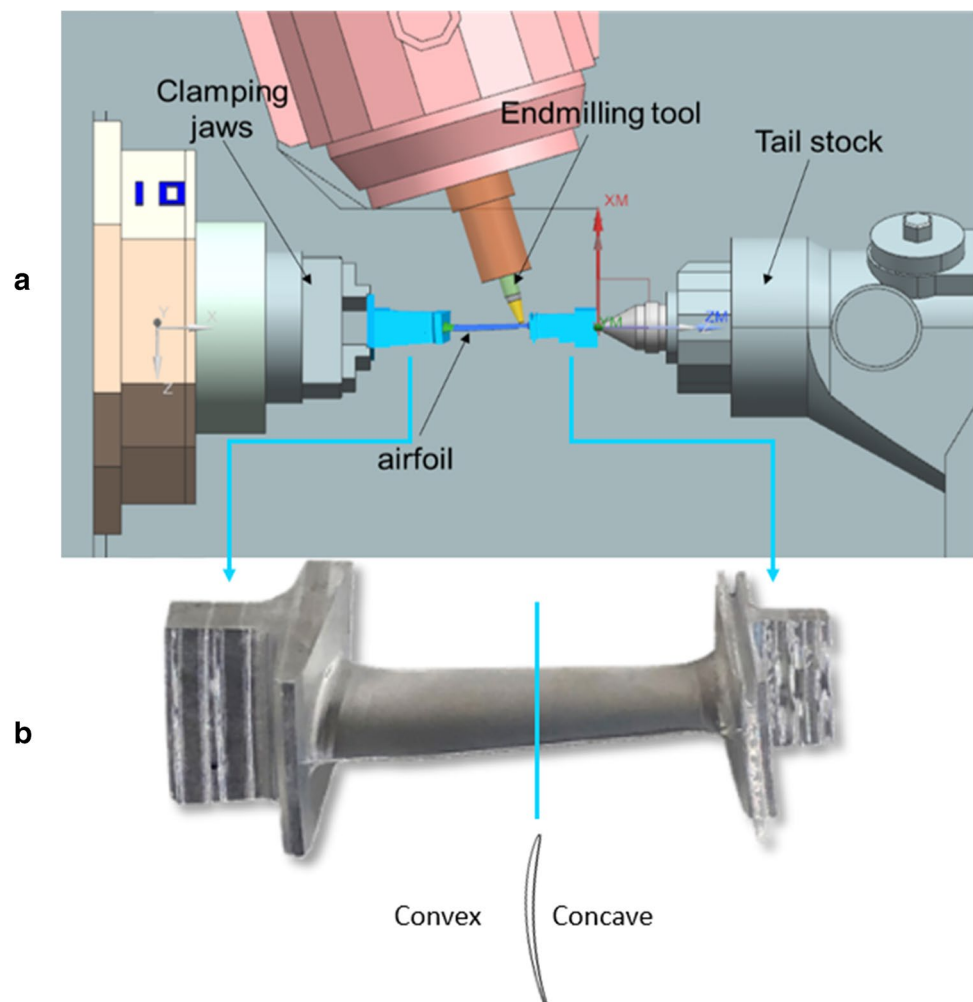


The first case uses PPC for machining an aeronautical part (nozzle guide vane), and the second uses GDC for machining an optical application part requiring high precision.

3 Case A: aerodynamic profile part machining

The workpiece was a nozzle guide vane (NGV), composed of two extreme ends (one at the root and the other at the blade tip) joined by a long middle low-thickness vane with an aerodynamic profile. The vane area can be considered a thin wall with a complex surface and a drop-like cross-section (see Fig. 2). The slenderness and low rigidity of the workpiece presented a serious problem when finishing the surface, affecting the following aspects [25–27]. The forces generated in the cutting process, especially those perpendicular to the blade axis component, produced a bending force.

Fig. 2 a NGV machining setup. b Finished blade and cross-section



1. Compressive clamping forces can induce severe deformation in the workpiece. The tailstock pressure resulted in a compressive force. The tailstock was used to increase rigidity through additional support; however, it also introduced a dangerous compressive force. A shift was observed in the manufactured part upon removing the tailstock. This was supported by measurements.

The material used was Al7075 T651, and the component was manufactured for the cold test of a new turbine.

4 Process parameter compensation (PPC) for the airfoil case

The manufacturing process followed is described as follows.

- Step 1. The initial blank was placed on a turn-milling multi-axis machine, and all operations were performed in succession. The extremes were clamped between the chuck and tailstock, and the final machining step involved

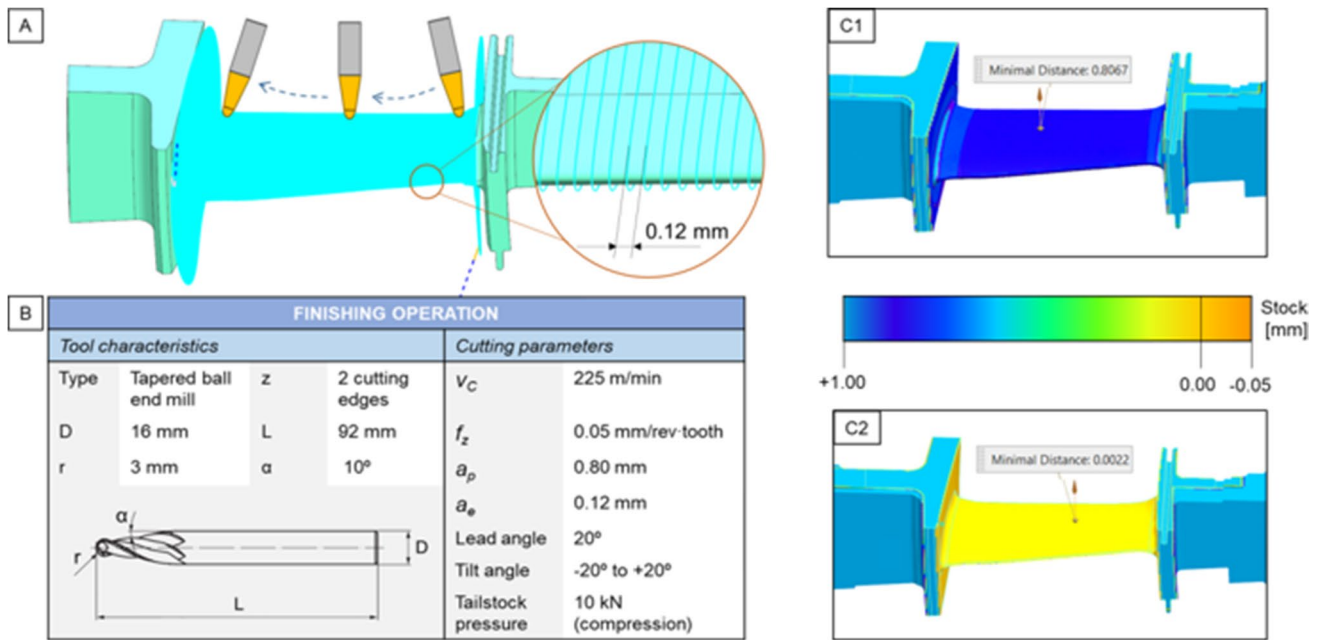


Fig. 3 Finishing operation: **a** Tool path. **b** Tool characteristics and cutting parameters. Theoretical material stock **c1.** before and **c2.** after finishing

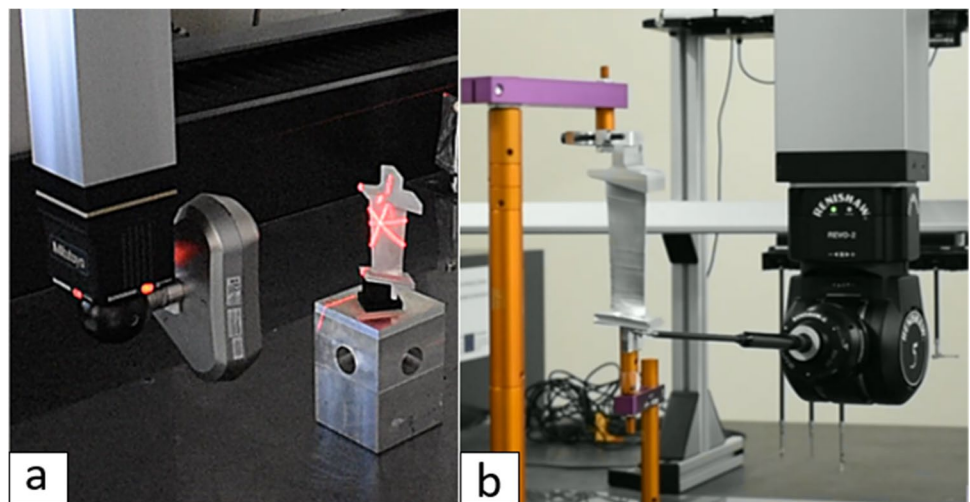
cutting off both ends. The initial prismatic block measured $54 \times 72 \times 210$ mm.

- Step 2: Machining programs were executed. In the roughing step, three-axis operations are performed, whereas semi-finishing and finishing were based on rotating turn-milling passes from right to left (helical tool path). The finishing tool path and cutting parameters are shown in Fig. 3. Along the last finishing procedure, the tailstock pressure visually deforms the part, due to the thinness of the part.
- Step 3. The part was measured using a laser scanner and CMM at a stable temperature of 20 °C and with a specific fixture to ensure measurement repeatability (see Fig. 4).

- Step 4. The error distribution in each part was analyzed, and the variable with the greatest influence on the deviation was detected. In this case, tailstock pressure was found to be the major influence, considering that deformation has been appreciate during the machining process, and is therefore used to improve the production of the next part. Initially, the load was approximately 10 kN.
- Step 5. The second and successive parts were manufactured using the newly defined values. Subsequently, they were measured to verify that the change improved the blade accuracy and satisfied the designed tolerances.

As this process is used to manufacture and measure a part to observe the errors to be corrected, this methodology is

Fig. 4 Blade measurement at the CMM **a** by optical scanner **b** by contact



corrective and not preventive. Therefore, a greater effort is required in terms of machine material but a lesser effort in terms of instrumentation. It improves precision without the need for investment in higher-precision machines, and a part is manufactured within the desired tolerances, as measured using different measuring systems.

5 Results obtained from PPC method

An aerodynamic profile part was machined on a multitasking machine (Fig. 2), which combines the capabilities of high-power turning and a full-function machining center to produce complex parts. The machine allows the regulation of the tailstock pressure. The cutting tools used were nose ball end milling tools ($\varnothing 20$ mm), which provided the necessary rigidity to guarantee that the deviations generated in the part during machining were not because of the tool.

After machining, measurements were performed on a Crysta® APEX S-9106 coordinate measuring machine with a workspace of $900 \times 1000 \times 600$ mm³ and a resolution of 0.1 μ m. It was equipped with temperature compensation software, and the temperature was maintained at 16–26 °C. Regarding tolerances, free-form vane surfaces must be less than 200 μ m in terms of precision. Therefore, a laser scanner was proposed. An optical scanner (Fig. 4a),

which has a scanner error of 17 μ m, was used in the coordinate-measuring machine to inspect the aerodynamic profile part. Therefore, the part-machining error was greater than the laser and CMM system uncertainty; however, it was also verified through touch probe contact measurements (Fig. 4b). In practical applications, optical scanners can be directly implemented in the machine tool without the need for unclamping the workpiece.

The results are shown in Fig. 5 by analyzing the part surface. Thus, profile deviations produced during manufacturing are observed in Fig. 5a. An increase in deflection was observed in the Z-direction. This deflection occurred due to excessive tailstock pressure. Therefore, the tailstock pressure was found to be the key process parameter to vary; thus, by reducing the tailstock pressure, the deviations generated in the part were reduced, as observed in Fig. 5. The final tailstock force was compressive but lower than 1 kN.

Therefore, during the practical application, as the tailstock is only rotary support, low values of the tailstock pressure are used to make the long blade stiffer. The Z-axis cutting force component did not include a significant source of inaccuracy, and the tool paths were the same in all process iterations.

Once the manufacturing process was defined, several NGVs were machined, and a good repeatability of the process was observed, as the maximum errors remained

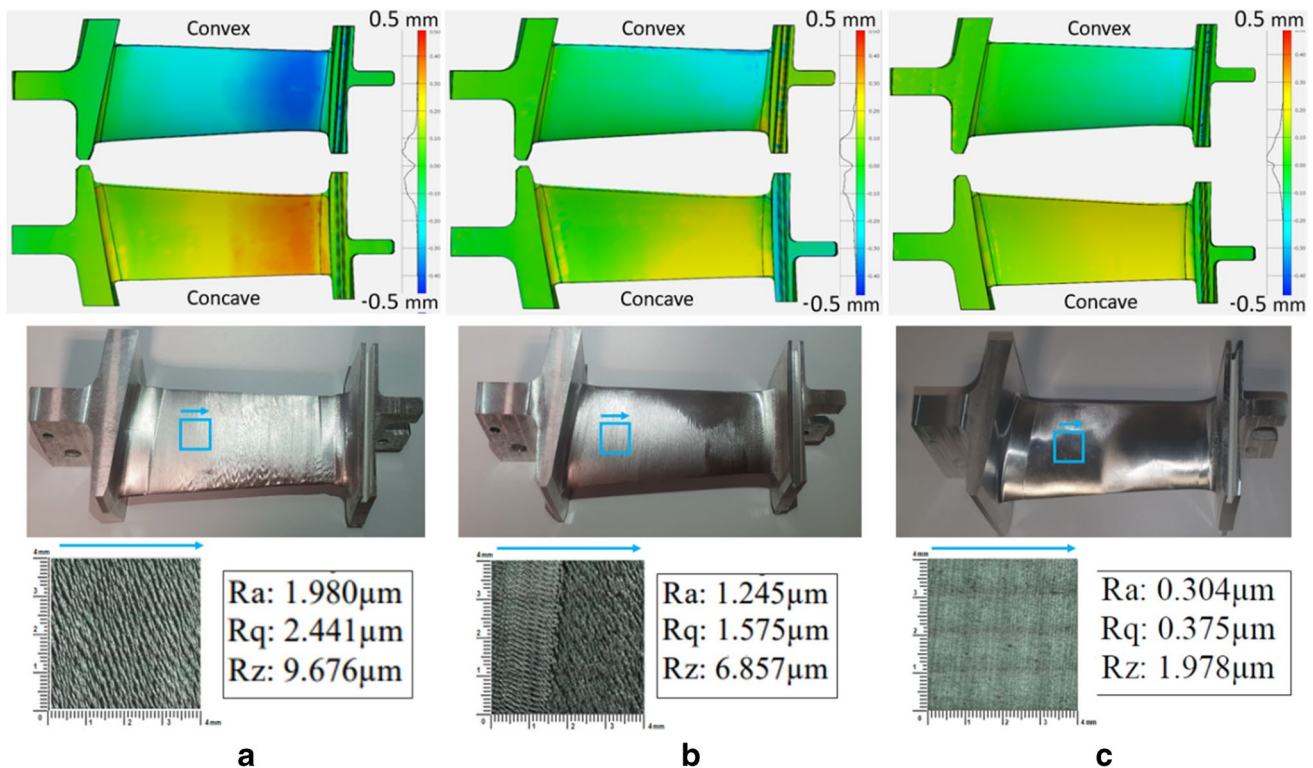


Fig. 5 Measured results **a** without manufacturing error compensation, **b** partial reduction of the tailstock pressure, **c** tailstock pressure reduction

constant between ± 0.125 and ± 0.150 mm, which is a significant improvement; furthermore, all the parts were manufactured within the specified tolerances.

We compared our results with those of Jian-Hua et al. [4] who designed a clamping system that allows released stresses during machining. Although they are completely different processes, Jian-Hua et al. corrected the part while it was manufactured; in our case, a part is first manufactured, and it is during the manufacture of the next part that the modification of the process is incorporated to obtain the results. Both studies show the importance of the clamping method, which is essential for obtaining results within tolerances. Li et al. [7] also focused on the importance of analyzing the optimum clamping forces and developed an algorithm that optimizes the fixing process of the workpiece.

6 Geometric deviation compensation (GDC) for the aspheric surface

The reported axisymmetric aspheric workpiece made of K9 glass can be expressed using the following formula [28]:

$$Z = \frac{cr^2}{1 + \sqrt{1 - (1 + k)c^2r^2}} + Ar^2 + Br^4 + Cr^6 + Dr^8 \quad (1)$$

where $r^2 = x^2 + y^2$ and $c = 1/R$. The quadratic equation of the datum plane in an axisymmetric aspheric workpiece is

$$Z = \frac{cr^2}{1 + \sqrt{1 - (1 + k)c^2r^2}} \quad (2)$$

where c is the curvature, r is the radial coordinate, and k is the taper factor. The workpiece exhibits a hyperboloid feature when $k < -1$. The offset of the aspheric surface from the base quadric surface can be expressed as $\Delta z = Ar^2 + Br^4 + Cr^6 + Dr^8$, where **A**, **B**, **C**, and **D** in Eq. (1), are constants.

The following parameters are applied : $R = 96.026$, $k = -2.0780$, $A = -7.22 \times 10^{-08}$, $B = -4.96 \times 10^{-12}$, $C = 1.39 \times 10^{-15}$, and $D = -5.43 \times 10^{-19}$; $r = \pm 60$ mm. The generatrix data of the axisymmetric aspheric surface can be calculated from the above data. A three-dimensional surface was generated by rotating the curve around the rotation axis, as shown in Fig. 6. In this study, a bronze-sintered diamond grinding wheel was used to machine the workpiece.

7 Results with the GDC

The GDC method involves a tool-path coordinate variation to generate modified tool paths. In industrial milling processes, the programming method, tools used, external

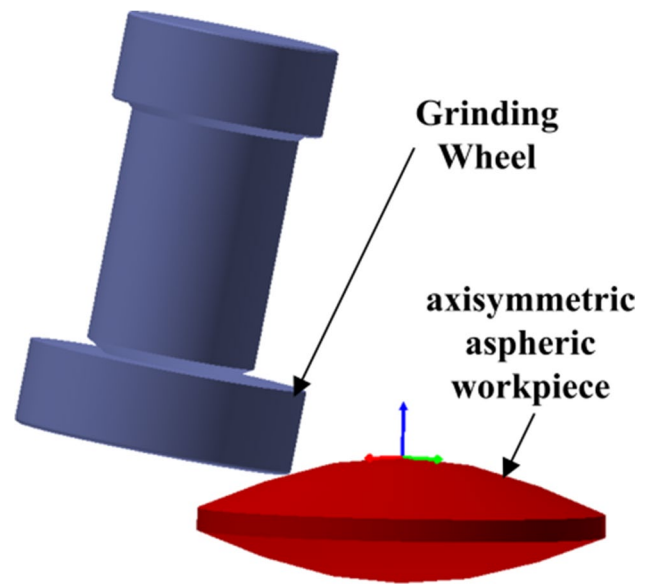


Fig. 6 Multi-axis machining of the axisymmetric aspheric workpiece

temperature changes, clamping method, and installation position of the workpiece in the machine tool are approximately identical; therefore, the systematic machining error of the workpiece should be essentially the same if parts are produced under similar conditions. Based on this, the workpiece machining error obtained under the same processing conditions can be compensated for by the GDC method. Therefore, the machine tool error, thermal error, grinding wheel wear, and other errors can be effectively compensated for by considering the total systematic deviation.

7.1 Implementation of GDC method for machining error

- Step 1. The cutting speed, feed rate, and depth of cut in rough machining were 6000 rpm, 1500 mm/min, and 0.5 mm, respectively. According to workpiece processing technology, the workpiece is finished first, leaving a certain allowance for the surface of the workpiece to be finished. In addition, there should be a sufficient machining allowance for subsequent compensation machining.
- Step 2. The workpiece was accurately measured after processing in a constant-temperature environment using a CMM machine, and the best-fitting method was used to process the measured data to obtain the best machining error value of the workpiece. Furthermore, the measurement error of the workpiece must include the measurement value of the normal vector at the measurement point.
- Step 3. The coordinates of the machining point along the normal vector of the workpiece measurement point were reverse-compensated, corresponding to the sur-

face of the workpiece, through reverse compensation of the machining error. This was achieved using the final CNC code.

- Step 4. The compensated coordinate point file was imported into the 3D modeling software to generate the modified tool paths. The cutting speed, feed rate, and depth of cut in finish machining were 6000 rpm, 1500 mm/min, and 0.1 mm, respectively.
- Step 5. The workpiece error was measured after compensation and checked with respect to the tolerances.

In Fig. 7, the blue line represents the original generatrix of the axisymmetric aspheric workpiece with a radius of 60 mm. After the form error measurement, the machining error (unit: μm) was decomposed in the normal direction, as indicated by the arrows. Subsequently, the new generatrix, which includes all arrow endpoints, was derived.

7.2 Results with the GDC method

The axisymmetric aspherical parts were machined by the five-axis machining center of HSC 75 linear. Each linear axis can achieve a 5- μm -positioning accuracy and 3- μm -repeated positioning accuracy. The B-axis can achieve a swing angle of $+10^\circ$ to -110° . The C-axis can realize any rotation within the range of $0\text{--}360^\circ$.

The surface accuracy of axisymmetric aspherical parts was inspected by the Hexagon Leitz Infinity coordinate measuring machine (CMM), which can realize a measurement error “ E ” value of $0.3 + L/1000$ (μm) at any position within the $1200 \times 1000 \times 700$ mm³ space range.

1. Specific requirements for the experimental processing of the workpiece

The processed axisymmetric free-form surface roughcast has an allowance of not less than 1 mm on each side, as

shown in Fig. 8a. The surface accuracy of the workpiece after milling and grinding should not be greater than 5 μm .

2. Processing and analysis

The processed axisymmetric aspheric workpiece is illustrated in Fig. 8b. The surface-shape accuracy after processing is 44.4 μm , as shown in Fig. 8c. The error of the workpiece includes the geometric error of the machine tool, thermal error, wear error of the grinding wheel, and other errors. The superposition of these errors results in a workpiece machining error that is significantly greater than the accuracy of the machine tool itself. Although the precision of the machine tool is high, and the machine tool is equipped with a real-time thermal error compensation system, it is extremely difficult to precisely machine a surface accuracy of less than 5 μm . During the processing of a surface shape, the accuracy requirements of the workpiece surface can be satisfied only through error compensation. Thus, the principle of “evolution” is employed to machine high-precision workpieces on low-precision machine tools.

The coordinate point data in the measurement result files are extracted and calculated. The data includes the coordinates of the corresponding measurement point and the normal-vector value of the point on the surface. In addition, the error value of this point after the best-fit process is included. The application of the best fit in the measurement is very important because after the workpiece is re-installed on the CMM, it cannot be completely consistent with the clamping during processing. Using the best-fitting algorithm can effectively reduce the measurement error caused by the clamping factor. The error is decomposed to the theoretical coordinate point according to the normal vector and reverse compensation. Subsequently, the new coordinate value after compensation is calculated.

In the GDC processes, the following points must be considered.

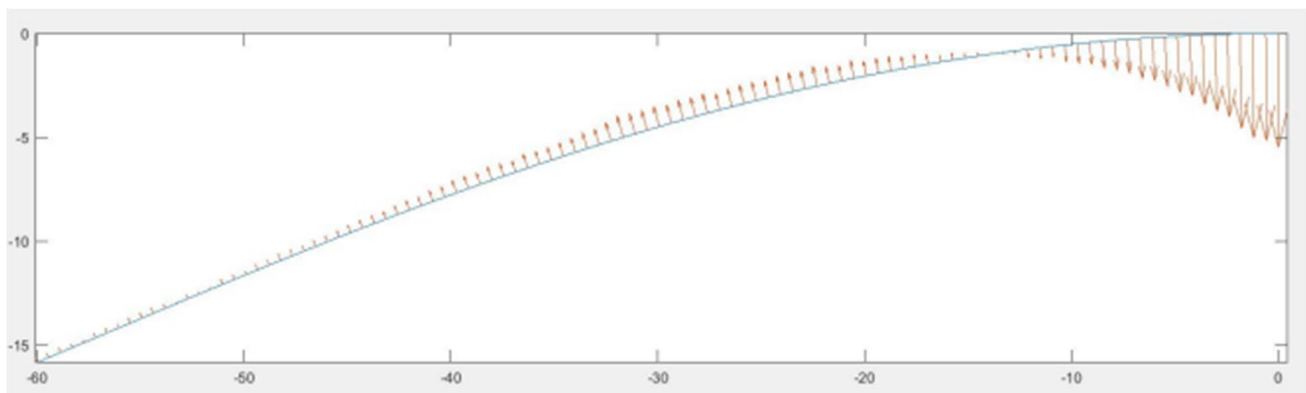
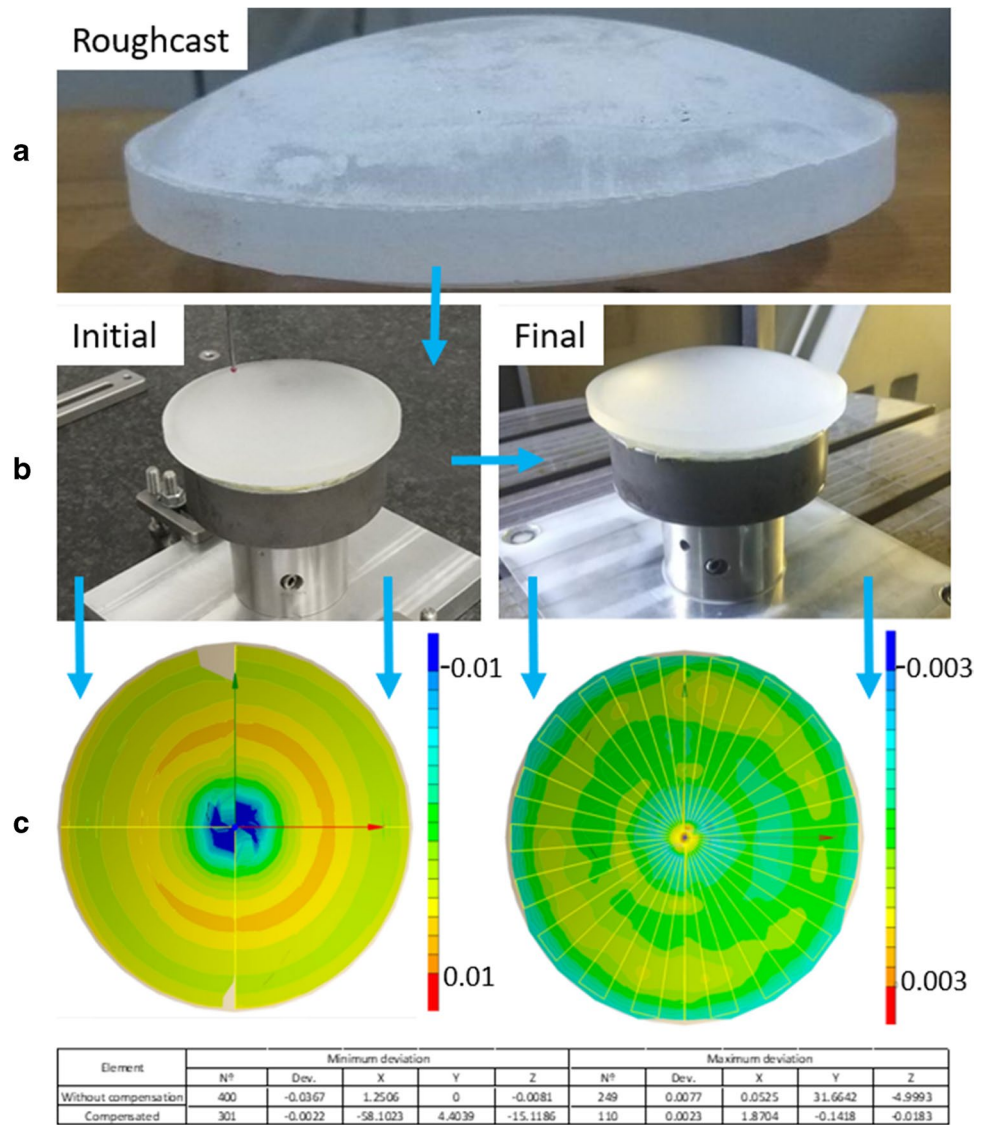


Fig. 7 Schematic of error compensation direction

Fig. 8 **a** Axisymmetric free-form surface roughcast part; **b** roughcast before and after GDC; **c** measured results without GDC (left, unit: mm). Measured results with GDC (right, unit: mm)



1. The clamping positions should be identical:

When the workpiece is clamped again, the position of the workpiece in the machine tool must not be changed. If the installation position in the machine tool changes significantly, the effect of the compensation processing will be poor.

2. The machining allowances should be identical:

During machining, it is necessary to ensure that the machining amount of the last completed machining and that after compensation are the same. At this time, the deformation of the processing system will be different because of the different processing amounts; therefore, the same processing amount is an important factor to ensure the compensation of the processing effect.

3. The programming settings should be consistent:

The coordinates obtained after the compensation of the machining error should be used to remodel using the 3D modeling software and regenerate the machining program with the new model. The machining program during the regeneration process must be consistent with parameters such as the machining step of the first finishing program.

4. The processing parameters should be identical:

The machining parameters used during machining should be consistent with those used for the first finishing. That is, the same speed and same feed should be used. If the parameters are different, the deformation of the processing system will be different, resulting in unsatisfactory compensation

processing results. Therefore, these parameters should be consistent.

5. The ambient temperatures should be the same:

When compensating for machining, we try to ensure that the temperature change is the same as that in the first finishing process. To meet this requirement, it should be processed in a constant-temperature environment. If there is no environment for constant-temperature processing, one can choose the same time of the day and duration to complete the finishing and processing of the workpiece after compensation. If there is no constant-temperature environment compensation, the effect of compensation after processing will change to a certain extent.

To satisfy these processing conditions, the axisymmetric aspheric workpiece is processed again. The finished workpiece is shown in Fig. 8c left. Finally, after error compensation processing, the final surface-shape accuracy is $4.5\ \mu\text{m}$. Thus, the processing requirements of the workpiece are satisfied. The workpiece after machining and measurement results is shown in Fig. 8c right.

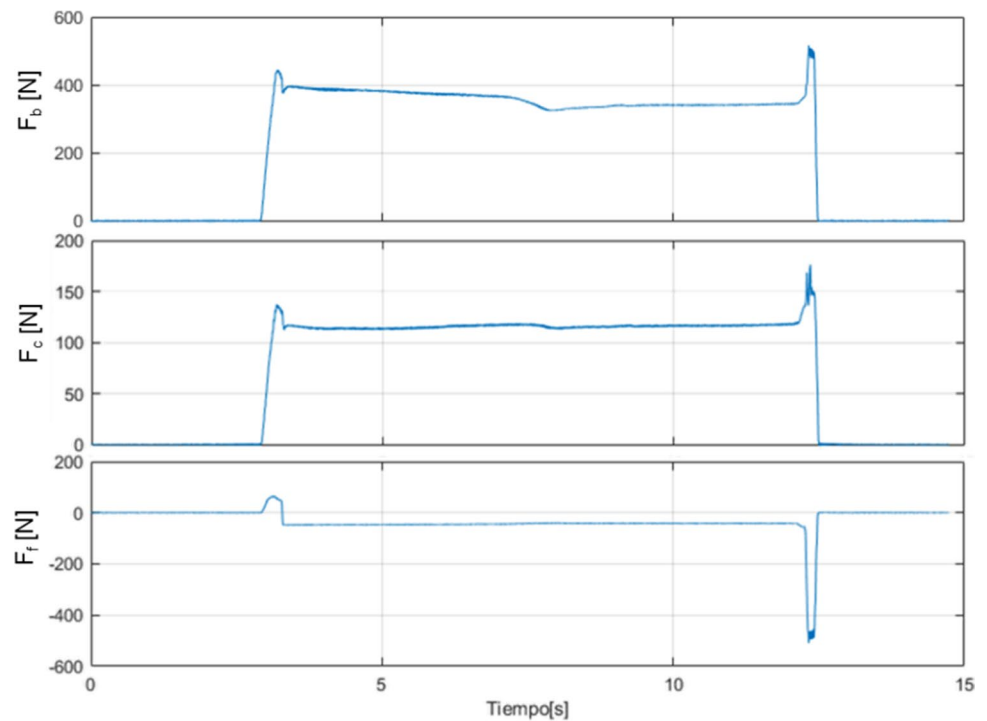
8 Other examples

Table 1 offers other two examples recently solved by the proposed method, specifically the PPC. The first row shows a blade manufactured in IN718 by DED (direct energy deposition). DED is an additive manufacturing method that uses a coaxial powder deposition nozzle and a laser (3 kW in this case) focused on the powder concentration point. Following a defined toolpath of the focus point, the blade is built up layer by layer. Precision is far from the required one, so milling is the consequent finishing operation. Milling toolpaths surround the blade shape and apply milling layer by layer from top to bottom. The end-milling tool was a $\varnothing 12$ -mm diameter carbide one (grade S10). Cutting speed V_c was 30 m/min. The main problem observed in the workshop was the thin-wall deformations originated by cutting force (force component perpendicular to the piece wall); therefore, feed per tooth was the selected parameter to vary because cutting force depends linearly on chip section. The final value was 0.07 mm, 30% lower than the initial value. The final precision was about two-hundredths of a millimeter.

Table 1 Two cases solved by PPC

Case	Parameter to control	Initial value	Workshop value
 <p><i>3D printed Blade in In718</i></p>	Cutting forces produce thin-wall deformation	Feed per tooth: 0.1 mm	Feed per tooth: 0.07 mm
 <p><i>Hard turning of broaching tool with ceramics insert</i></p>		Feed per revolution: 0.2	Feed per revolution: 0.105

Fig. 9 Cutting force components for the final feed per revolution of the second row, hard turning using ceramics. F_c (tangential cutting force, lathe Y-axis) and F_b (transverse force, X-axis) cause shaft deformation or vibrations



The second row shows the turning of a broaching tool shank made in tempered steel HSS ASP23, a chromium-molybdenum-tungsten-vanadium alloyed high-speed steel, using ceramic inserts. The main problems were transverse shaft vibrations, which also were originated by high cutting forces, so feed per revolution was the selected parameter to vary. Ceramic insert was MITSUBISHI®, geometry SNGA 120,408 T01025 ZC7, cutting speed was 120 m/min, and depth of cut was 0–0.5 mm feed per revolution. Final value was 0.15 mm; Fig. 9 shows the final components of cutting force. In summary, by modifying only one parameter, both cases were solved.

9 Conclusions

This study proposes a technical method to define better machining practices using a compensation method, considering the use of machine tools with the same order of magnitude of precision as the manufactured parts. The objective is to change as few parameters or program modifications as possible, with the second produced part being the correct one, i.e., within the specified tolerances and satisfying other requirements. The proposed solution offers two sub-methods. The first method is the *process parameter compensation* (PPC) method, which involves compensating for the error by modifying the cutting process parameter that has the greatest influence on the error. The second method is the *geometric deviation compensation* (GDC) method, which involves modifying the part profile by surface tool path compensation

based on the measured deviations in the workpiece while maintaining other process variables constant.

Two examples are presented for curved surfaces and high-value-added applications. First, an airfoil was machined using a turn-milling platform. The practical solution was the correct definition of the clamping systems and their force; the final errors were less than 100 μm in very slender thin-wall vanes.

Second, by processing the axisymmetric aspheric surface of a K9 glass, a workpiece with a surface-shape accuracy of 44.4 μm was processed by the compensation method. Consequently, the surface-shape accuracy improved to 4.5 μm , and the compensation efficiency of the surface-shape accuracy reached 89.9%.

This method has the following advantages.

1. This method can be easily implemented in current workshops. As there are many types of machine/machining errors in the actual processes, each source may cause machining errors in the workpiece. Additionally, the magnitude and direction of each error can increase or decrease the total error. Thus, the resultant machining error is the superposition of various sources during the processes, which are extremely difficult to correct separately. By collecting the scanned workpiece data point cloud to be processed and defining only one key parameter to modify, a practical solution is proposed regardless of the sum of errors but considering the total value.
2. The main aim is to make the smallest modifications possible while maintaining all the previous process prepa-

rations and global tool path programming. The method attempts to eliminate the necessity of reprogramming, starting from CAD/CAM, which is a solution at the workshop level useful for small companies.

3. This method does not require a complex mathematical model for machining error compensation. Typically, the study of error compensation requires establishing mathematical models for each corresponding error source. Significant data collection and regression analysis are required.
4. This accuracy-based evolutive method (ABEM) uses model-free machining error compensation (or evolution) through a single first-part measurement. The second part satisfies the specified tolerances and quality requirements. The second part must be produced after the first in the same machine/clamping/cutting tool system. This is common in current workshops; machinists examine the variations when some parts are not within the desired tolerances. Process variations can be easily implemented in workshops, for instance, a parameter modification (f_z , v_z , other parameters), some utilities to compensate for some program coordinates (a port processor of coordinates), and a work-holding parameter (pressure), thus eliminating the entire process change. The test and trial approaches must be based on the proposed method, which requires only one iteration. Uncertainty because of the lack of repeatability is not resolved, but systematic errors can be reduced, thus improving accuracy.

The proposed method for curved surfaces, which are widely used in aviation and optical imaging fields, has some constraints and potential in practical production. The manufacturing of curved surfaces should meet high standards regarding not only profile deviations but also machining efficiency after finishing machining. Nevertheless, machining deviation usually requires additional time for the desired profile, thus not only hindering high-quality processing but also increasing manufacturing costs. In practice, profile deviation measurement is mandatory, which affects productivity to some extent; however, it is significantly helpful for industrial production facing machining accuracy issues as it can help improve product yield.

Furthermore, data acquisition techniques, learning capabilities via artificial intelligence, and extensive applications in machining centers should be developed so that they can be applied to the online profile deviation measurement system, thus realizing the adaptive adjustment target of the processing parameters on the machining accuracy evolution for curved surfaces.

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Declarations

Competing interests The authors declare no competing interests.

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