

# Active Tool Wear Compensation for Enhanced Surface Integrity and Geometric Accuracy in High-Speed Freeform Machining of C45 Steel

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## Keywords:

Tool wear compensation  
Friction control  
Surface integrity  
On-machine metrology  
Freeform surface milling  
C45 steel

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Received: 6 April 2026

Revised: 5 May 2026

Accepted: 2 June 2026



## ABSTRACT

As advancements continue in precision engineering, the management of complex tribological interactions—specifically friction, progressive tool wear, and thermo-kinematic deviations - remains a critical challenge in achieving precise geometric accuracy and high surface integrity on complex freeform three-dimensional shapes. This research examines the tribological aspects of high-speed surface milling of ductile medium-carbon C45 steel using a comprehensive closed-loop machining framework. To control high friction at the tool-chip interface and to mitigate the formation of built-up edge (BUE), the process was optimized through specific cutting and lubrication strategies. A key innovation of this study is the implementation of an active feedback loop, utilizing advanced macro programming integrated with automated on-machine metrology, which facilitates real-time monitoring and dynamic compensation for progressive tool wear and thermal expansion. The tribological and geometric performance was rigorously evaluated using 3D profilometry, contact surface measurement, and dynamic wear analysis. Experimental data revealed that active wear compensation notably minimized setup uncertainties—from 0.03 mm to 0.003 mm—and preserved highly accurate three-dimensional contours with an average profile deviation of 17 micrometers (ranging from 12 to 20 micrometers). Furthermore, the optimized control of friction and tool kinematics resulted in an exceptional surface roughness ( $R_z$ ) of 4.37-5.14  $\mu\text{m}$ , nearly eliminating mesh artifacts and reducing the need for manual post-polishing by up to 70%. These findings offer a robust, data-driven method for enhancing surface integrity and extending tool life in smart manufacturing processes that demand continuous, high-precision production.

## 1. INTRODUCTION

There is a growing need for aerodynamic and hydrodynamic parts in modern manufacturing, especially in the automotive, medical, and aerospace industries. These parts often feature complex features such as curved edges, thin walls, deep cavities, and freeform 3D surfaces. Such shapes are challenging for CNC milling machines, which must meet high standards for movement, accuracy, and surface finish. During machining of curved surfaces, cutting loads and resistance change in complex ways depending on the tool's position and angle. These modifications may induce tool vibrations and bending, resulting in shape inaccuracies, rougher surface finishes, and reduced consistency in outcomes, particularly in challenging regions. Heat generated during machining also causes components such as spindles and ball screws to expand, shifting the tool's position and increasing the likelihood of errors when working on complex shapes.

Traditional machining frequently employs coordinate measuring machines (CMMs) for inspection and manual alignment post-machining. Nevertheless, this methodology presents several disadvantages, including prolonged machine downtime, increased susceptibility to human error, and reduced responsiveness to tool wear. Should issues be identified only after machining, costly components may need to be discarded or re-clamped, thereby increasing the likelihood of additional errors. To address these issues, integrated methods are needed to reduce errors and stabilize the process.

Numerous studies have investigated factors affecting surface quality and geometric accuracy in machining. C45 medium-carbon steel is frequently utilized by mechanical engineers, and significant research has focused on optimizing its machining processes to enhance productivity and surface finish [1-3]. Feed per tooth and lubrication conditions are critical determinants of surface roughness, with experimental results and ANOVA analyses indicating statistically significant interactions; flood lubrication typically yields lower roughness than dry cutting. [4]. Recent research has emphasized the role of tool materials and coatings in extending tool life and improving

surface finish. Experiments with PVD- and CVD-coated inserts demonstrated that insert type primarily influences tool durability, whereas spindle speed and depth of cut substantially affect Ra values. Optimal machining conditions were identified at a spindle speed of 400 m/min, a depth of cut of 0.5 mm, and the use of cermet-coated inserts, highlighting the potential of AI-based methods for forecasting and optimizing C45 machining performance [5]. Grey Relational Analysis and ANFIS modelling have been applied to simultaneously optimize machining parameters. Tool orientation is also crucial in five-axis machining; adjusting tilt and lead angles relative to the surface normal improves transverse roughness and reduces contact zones at zero cutting speed. For C45 steel, optimal Rz values on inclined surfaces generally range from 3 to 6  $\mu\text{m}$ , establishing a benchmark for quality [6].

Comparative studies of milling techniques indicate that the selection of linear, offset, or spiral toolpaths has a significant impact on surface roughness and geometric deviations. In certain instances, five-axis milling employing spiral and linear strategies can improve surface quality by minimizing negative deviations relative to three-axis milling [7]. Additionally, enhancements to NC code through specialized software have been shown to reduce geometric errors and machining time, while maintaining or improving surface quality across diverse experimental scenarios [8].

Online monitoring of drive parameters and tool conditions provides essential insights into the relationship between geometric deviations and dynamic phenomena. Different machining techniques produce unique load waveforms and peak loads, which directly affect tool service life and drive system reliability, as demonstrated by data acquisition systems integrated with the OPC UA protocol [9]. Research indicates that selecting an appropriate tilt angle, such as 15°, can optimize the effective cutting diameter, reduce vibration, and enhance surface finish [10]. Machine measurement technologies, including confocal microscopy, facilitate three-dimensional tool reconstruction and direct wear assessment during machining, thereby expanding monitoring capabilities and enabling real-time wear compensation [11].

Despite these significant advancements, a key research gap remains in managing the dynamic tribological interactions—specifically friction-induced thermal expansion and progressive tool wear—within a seamless, closed-loop machining framework. Specifically, for complex 3D freeform surfaces, a comprehensive validation of the system-level error budget that explicitly isolates wear-induced and thermo-kinematic deviations from structural and CAM-generation errors remains underexplored.

To address this gap, this study proposes an integrated framework for evaluating and optimizing friction control and active tool wear compensation during complex 3D surface machining. This is achieved by combining: (i) the structural rigidity of a high-speed machining center (Makino PS65) to stabilize dynamic cutting forces; (ii) advanced CAM toolpath algorithms (Hypermill 2025) to optimize tool-workpiece engagement and reduce frictional heat; and (iii) active, closed-loop compensation of progressive tool wear and thermal expansion using on-machine metrology (Blum systems) executed via Macro G-code.

Through meticulous experimental validation on ductile C45 steel test specimens—including 3D geometric acquisition, contact and non-contact surface profilometry, and dynamic machine tool wear assessment under controlled lubrication conditions, this paper systematically analyses the error budget. By correlating tribological phenomena with real-world geometric outcomes, this research provides explicit data on individual sources of error and offers practical recommendations to enhance surface integrity and dimensional precision, thereby advancing highly reliable precision manufacturing.

## 2. MATERIALS AND METHODS

This study used the Makino PS65 three-axis vertical machining center, designed for high-speed machining, to test closed-loop automation with advanced signal communication. Its heavy frame and large work area (X: 660 mm, Y: 510 mm, Z: 460 mm) help absorb vibrations during fast movements. The axes use Fanuc servo motors with high-resolution encoders, allowing feed rates up to 30,000 mm/min and rapid moves up to 48,000 mm/min on the X axis. Makino uses oil cooling within ball screws and bearings to

limit heat-induced expansion caused by friction, maintaining accuracy of  $\pm 0.0015$  mm even during long runs. The 14,000-rpm spindle (CAT40 taper) is controlled by the Fanuc-based Makino Professional P system, which maintains smooth, stable feed rates on complex surfaces through multi-threaded processing and advanced G-code handling. The C45 steel plate blank was prepared as a rectangular block measuring 200 mm  $\times$  200 mm  $\times$  35 mm. The fundamental design parameters of the workpiece to be machined are illustrated in Figure 1. The required machining surfaces include curved profiles, flat planes, cavities, and holes, each specified with tolerance and surface roughness criteria. Based on these requirements, an appropriate machining process plan was developed to ensure compliance with the specified technical standards.

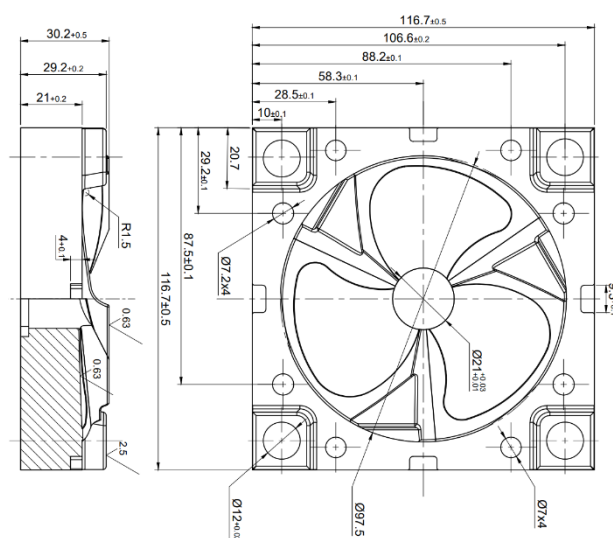


Fig. 1. Workpiece drawing

To remove setup errors caused by human judgment, measurement devices were built directly into the machining area. This study used a wireless Blum TC50 3D touch probe (infrared) with 0.3  $\mu$ m repeatability. The probe scans the workpiece and sets reference points without harming the surface, thanks to its low probing force (2 N in XY, 7 N in Z). At the same time, the Blum LC50 DIGILOG laser system measured tools without contact, with 0.3  $\mu$ m repeatability, avoiding the risk of chipping associated with mechanical probes. DIGILOG technology collects and analyzes thousands of data points per second, enabling accurate assessment of tool wear and runout at real spindle speeds. Laser scanning also keeps the Z-axis stable during long jobs by accounting for thermal expansion and updating coordinate offsets as needed.

Hypermill 2025 CAM software was used to optimize toolpaths. The 3D Optimized Roughing algorithm separates CAD radii from toolpath radii, helping prevent tool overload during wide cuts, avoiding jamming in tight spots, and keeping chip load steady. For finishing, the High Precision Surface Mode calculates NC points directly from the CAD model, using a dense point layout rather than triangular meshes. The Smooth Overlap algorithm was also used to reduce machining errors and blend transitions smoothly.

A post-process verification system was set up to objectively verify machining results. Using ISO 10360 standards for measurement error ( $MPE = 3.0 + L/100 \mu\text{m}$ , where L is the measured length in mm), a 3D coordinate measuring machine (ACCRETECH XYZAX AXCEL PH) was used to measure actual spatial deviations. A MITUTOYO SURFTEST SJ 301 contact profilometer, with a 5  $\mu\text{m}$  diamond tip and 4 mN scanning force, measured surface roughness (Ra, Rz). This provided reliable data for comparing with cutting models.

### 3. EXPERIMENTAL SETUP

Medium-carbon steel C45 was selected for the experiments. C45 is a widely used structural steel that possesses greater ductility than mold steels, which are specifically designed for ease

of polishing. Consequently, C45 is more susceptible to built-up edge formation and surface scratching during cutting. Previous studies indicate that optimal surface roughness for C45 under practical machining conditions typically ranges from  $Rz = 3$  to  $8 \mu\text{m}$ . Employing C45 as the test material established a stringent benchmark for objectively assessing the system's capability to generate accurate toolpaths and perform dynamic optimization.

Given the high ductility of C45 steel and its tendency to form built-up edges (BUE) under high-speed milling conditions (up to 10,000 rpm), the cutting environment was carefully controlled. A continuous flood cooling system using a water-soluble emulsion was applied to minimize friction at the tool-chip interface, evacuate chips efficiently from deep cavities, and stabilize the thermal state of the cutting zone, thereby isolating the kinematic and CAM-generated toolpath variables for objective evaluation.

The test workpiece was a mold core shaped like a turbine blade, with complex 3D curves, guiding islands, and deep cavities (see Figure 1). This design tested the machine's movement and error correction because it required continuous three-axis control. The process included eight steps, from raw material to a high-quality surface finish. Table 1 lists the full process plan.

**Table 1.** Technological Parameters and Machining Procedures

Step	Experimental Procedure	Cutting Tool	Spindle Speed S (rpm)	Feed Rate F (mm/min)	Interpolation Strategy & Technical Notes
1	Facing the reference surface	Facemill $\varnothing 80$	1,200	1,000	Zigzag direction. Establish Z-reference plane.
2	Roughing and semi-finishing the outer cavity	Endmill $\varnothing 4$	4,000	2,000	Preparation of external profile for subsequent 3D interpolation.
3	Roughing of the 3D surface profile	Endmill $\varnothing 12$	4,500	2,500	High-volume material removal using an optimized roughing algorithm. Stock allowance: 0.2 mm.
4	Roughing of deep concave regions	Endmill $\varnothing 6$	5,000	2,000	Local load relief in turbine blade cavities.
5	Finishing of complex 3D surfaces	Ballmill $\varnothing 2$	10,000	800	"High Precision Surface" mode applied; $a_e = 0.05 \text{ mm}$ .
6	Finishing of planar reference surfaces	Ballmill $\varnothing 4$	8,000	700	Precision finishing of static reference planes.
7	Machining of four boundary islands	Endmill $\varnothing 6$	5,500	1,800	Multi-step vertical profiles with tight tolerances.
8	Machining of the hole system	Endmill $\varnothing 6/12$	Variable	Variable	Deep-drilling cycles G81-G89; spiral-milling strategy.

At Step 3, the feed rate was set to  $F = 2,500$  mm/min, resulting in a very high Material Removal Rate (MRR). The standard equation was used to calculate MRR:

$$MRR = a_p \cdot a_e \cdot F \quad (1)$$

Where,  $a_p$ : axial depth of cut (mm);  $a_e$ : radial depth of cut (mm);  $F$ : feed rate (mm/min)

In high-speed roughing, this formula is a key way to measure machining efficiency and tool load, showing how much material is removed over time. The "3D Optimized Roughing" algorithm in Hypermill managed the large amount of material removed. It smooths toolpaths in corners to reduce mechanical shocks, making material removal efficient and protecting the tool.

Steps 5 and 6 used ball end mills with diameters of 2 mm and 4 mm, running at 10,000 rpm and 8,000 rpm. The high cutting speeds increased the temperature at the contact points, temporarily making the C45 steel chips softer. Using a very fine radial step ( $a_e=0.05$  mm) generated a large amount of NC command data. The Makino Professional P controller's advanced processing and memory management kept toolpaths smooth and prevented tool stalls from overloading data.

#### 4. RESULTS AND DISCUSSION

The integration of Macro programming with advanced CAM interpolation enables comprehensive control and error isolation during complex 3D machining. In this study, Fanuc Custom Macro B was employed to establish a digital workflow that mitigates issues associated with manual operations and tool offsets, which are common sources of error. The G65 P9700 S... X... Y... Z... W... command facilitated automatic workpiece coordinate setting by initiating the Blum TC50 infrared probe. This probe scans the C45 steel workpiece, determines the 3D reference, and establishes the X/Y center and Z datum. The system subsequently calculates tilt and directly updates the G54 work offset. This approach eliminates operator bias and reduces setup error from 0.01–0.03 mm to 0.002–0.003 mm.

The G612 D... R... command was used to monitor both tool wear and thermal changes

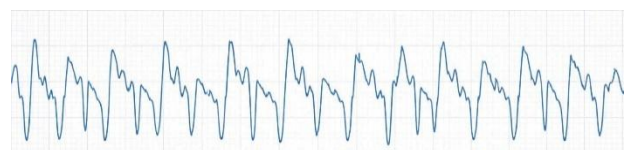
simultaneously. This command instructs the Blum LC50 DIGILOG laser to scan the tool while the spindle runs at full speed. The G612 cycle was added to the NC program because the spindle length increases as it heats up during long cuts on C45 steel (according to the formula  $\Delta L = \alpha \cdot L \cdot \Delta T$ ). This setup enabled automatic tool scans after each finishing pass, accurate tool-length measurement, and direct compensation in the offset database.

The coordinated use of G65 probing cycles and G612 laser compensation yielded a robust system that reduced the total input error from 0.03 mm to 0.005 mm. These findings demonstrate that closed-loop kinematic control maintains high accuracy when machining complex freeform surfaces at high speeds. For high-speed milling of C45 steel, the typical range for high-quality machining processes is  $R_z = 3\text{--}8 \mu\text{m}$ .

Evaluation of the flat-surface benchmark: The feed per tooth was determined to be  $f_z = 0.0438$  mm/tooth under high-intensity cutting conditions (spindle speed  $S = 8,000$  rpm, feed rate  $F = 700$  mm/min, end mill diameter 4mm). This value significantly exceeds typical ultra-fine finishing thresholds. Using the cantilever beam model, the tool's elastic deflection was determined to be  $1.49 \mu\text{m}$ . The theoretical maximum micro-roughness was approximately  $4.5 \mu\text{m}$ , comprising the kinematic scallop height ( $2.99 \mu\text{m}$ ), the tool deflection ( $1.49 \mu\text{m}$ ), and the measurement error ( $0.02 \mu\text{m}$ ).



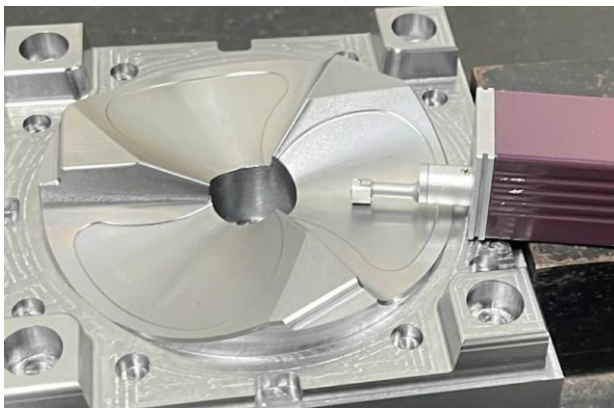
**Fig. 2.** Contact measurement method using a planar-touch stylus probe



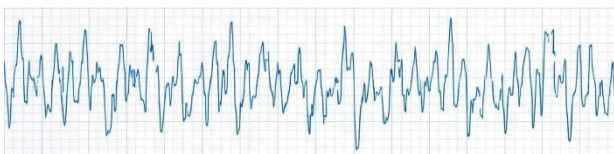
**Fig. 3.** Surface roughness in the contact measurement method using a planar-touch stylus probe

Tests with the Mitutoyo SJ 301 contact profilometer (Figures 2–3) showed that surface roughness remained very stable, ranging from 4.37  $\mu\text{m}$  to 4.40  $\mu\text{m}$ . These values fall within the best range for C45 steel, indicating that the spindle controls vibrations effectively and confirming the Makino system's reliability.

Freeform 3D curved surface evaluation: A  $\varnothing 2$  ball end mill was used on complex curved areas with a radial step of  $a_e = 0.05$  mm, a spindle speed of  $S=10,000$ rpm, and a feed rate of  $F=800$ mm/min, which is equal to  $f_z = 0.04$  mm/tooth. Theoretical extrapolation of scallop height and cumulative error sources indicated a maximum roughness nearing 5  $\mu\text{m}$ .



**Fig. 4.** Contact measurement method using a curved-surface stylus probe



**Fig. 5.** Surface roughness in the contact measurement method using a curved-surface stylus probe

Experiments using contact stylus scanning (Figures 4–5) showed that roughness values were very stable, with  $R_z$  ranging from 5.09  $\mu\text{m}$  to 5.14  $\mu\text{m}$ . This indicates that  $R_a$  is approximately 0.35–0.45  $\mu\text{m}$ , giving the surface an almost optical matte finish. The "High Precision Surface" algorithm in Hypermill improved performance beyond expectations, with actual surface quality exceeding expectations. By applying dense interpolation points at the junctions of multiple axes and using the "Smooth Overlap" blending strategy, experiments using contact stylus scanning

(Figures 4–5) yielded stable roughness values, with  $R_z$  ranging from 5.09  $\mu\text{m}$  to 5.14  $\mu\text{m}$ . This means  $R_a$  was about 0.35–0.45  $\mu\text{m}$ , giving the surface a nearly matte finish. The 'High Precision Surface' algorithm in Hypermill improved results, with actual surface quality exceeding expectations. Dense interpolation points and the 'Smooth Overlap' strategy removed mesh artifacts and smoothed tool paths. This success with C45 steel shows the system can achieve excellent surface quality and reduce manual polishing by up to 70%. The results demonstrate that the integrated machining and measurement system consistently achieved high geometric accuracy while maintaining stable surface quality throughout the machining process.



**Fig. 6.** Probing process on a CNC machine

The on-machine probing procedure, as illustrated in Figure 6, facilitated the collection of geometric reference data directly under actual machining conditions, thereby reducing setup-induced uncertainty and ensuring reliable alignment prior to finishing operations. The measured probing data were subsequently utilized to support the three-dimensional surface profile evaluation depicted schematically in Figure 7, which provided a comprehensive geometric representation of the machined freeform surface. Based on this dataset, the average profile deviation across the evaluated area was 17  $\mu\text{m}$ . The positional error distribution along the Y axis, as shown in Figure 8, demonstrated a narrow and stable spread, with measured deviations ranging from 12  $\mu\text{m}$  to 20  $\mu\text{m}$ .

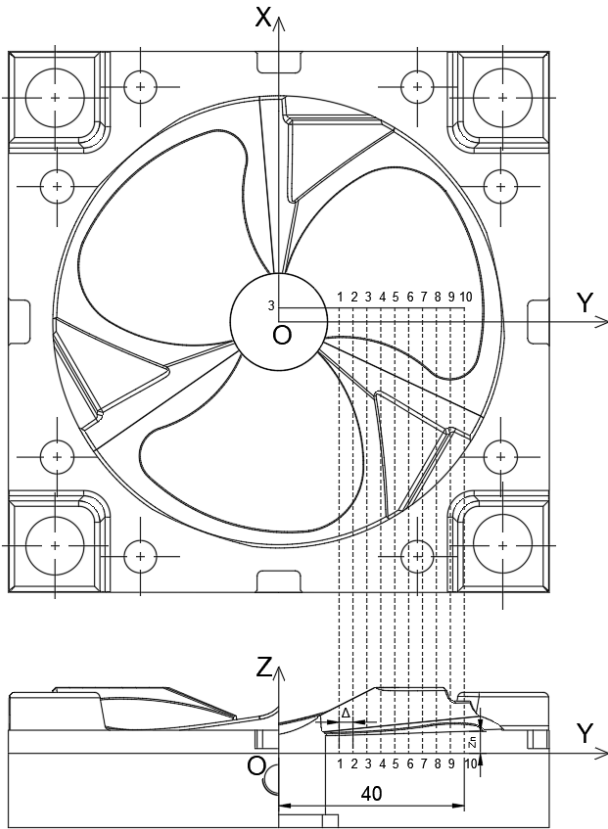


Fig. 7. 3D surface profile measurement diagram

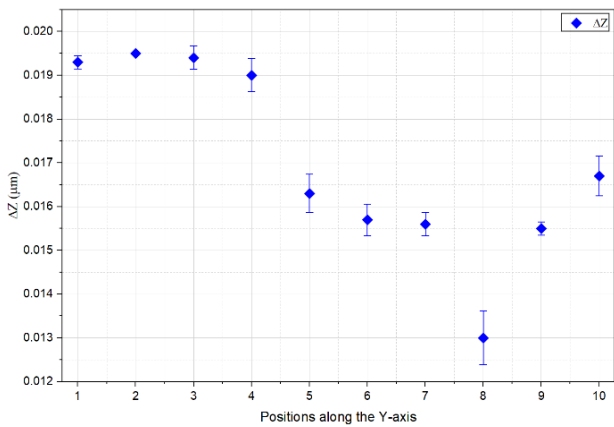


Fig. 8. Positional error evaluation

Based on the measured profile deviations and positional error data, a generalized volumetric error model was developed to quantitatively assess the contributions of kinematic, thermal,

measurement, tool wear, and fixture-related error components. In this formulation, thermal-kinematic interactions are explicitly included in the error budget.

$$E_{total} = E_{kinematic} + E_{thermal} + E_{wear} + E_{fixture} + E_{measure} \quad (2)$$

Where  $E_{kinematic}$  represents the inherent positioning errors of the machine tool, and  $E_{thermal}$  is the thermal deformation error (predominantly along the Z-axis due to spindle heat generation, quantified as  $\Delta L = \alpha \cdot L \cdot \Delta T$ ).  $E_{measure}$  signifies measurement error,  $E_{wear}$  represents tool wear deviation, and  $E_{fixture}$  indicates fixture-induced error. Through the implementation of the closed-loop macro routine (G612), the dynamic variable  $E_{thermal}$  and the progressive  $E_{wear}$  are actively measured by the Blum DIGILOG system and compensated through the tool offset database, thereby effectively neutralizing their influence on  $E_{total}$ . The investigation into probe resonance and microscale compensation errors in CNC ball screws revealed measurement inaccuracies, quantified as  $E_{measure}$ , that contributed to a noise band of 10-20 µm. During extensive machining of large-volume C45 steel components, continuous cutting friction induced tool wear errors, designated as  $E_{wear}$ . The tool geometries, both before and after machining, are summarized in Table 2. The  $\Phi 2$  ball end mill experienced diameter wear of  $\Delta D = 0.0272$  mm and axial tip loss of  $\Delta L = 0.0035$  mm (35 µm). This wear resulted in a spatial depth deviation of approximately 3.5 µm post-algebraic compensation. Additionally, micro-tilting moments induced by clamping forces were linked to fixture errors. A minor angular misalignment along the Oy axis was identified through tilt evaluation at four quadrant points (Figure 9) and Z-axis deviation data (Table 3). Such misalignment propagated into a measurable geometric error through the application of trigonometric analysis amplification.

Table 2. Cutting Tool Parameters: Pre- and Post-Machining.

Deviation parameters of cutting tool wear						
Cutting tool	Pre-machining		Post-machining		Deviation	
	L	R	L	D	ΔL	ΔD
Ballmill Φ2	113.4380	1.0274	113.4345	1.0138	0.0035	0.0272
Ballmill Φ4	120.4796	2.0445	120.4779	2.0200	0.0017	0.0490
Endmill Φ4	114.1616	2.0188	114.1553	2.0091	0.0063	0.0194

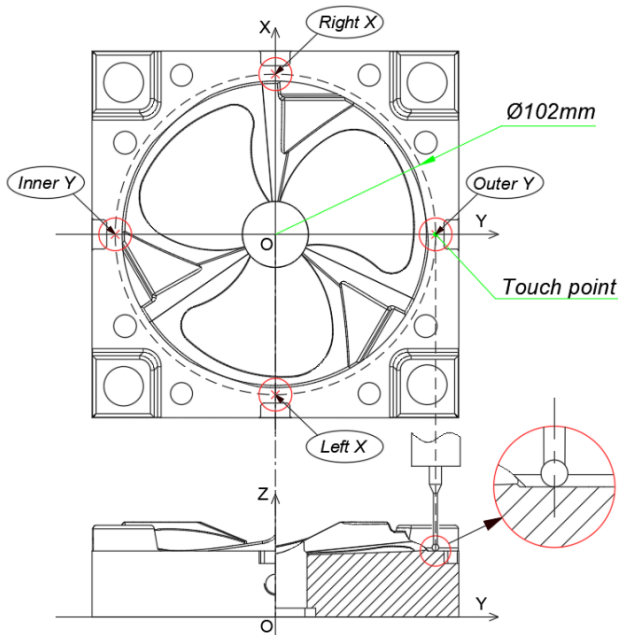


Fig. 9. Tilt evaluation diagram at four-quadrant points

Table 3. Tilt Evaluation Results

Position	Z value	Z Deviation ( $\Delta Z$ )
Right X	-459.2653	0.1030
Left X	-459.3683	0.1030
Outer Y	-459.2971	0.0407
Inner Y	-459.3378	0.0407

The calculated maximum error for 3D surfaces ranged from 22.76 to 32.76  $\mu\text{m}$ . However, actual measurements on curved surfaces averaged 17  $\mu\text{m}$ , with deviations from 12 to 20  $\mu\text{m}$ . This shows that Makino's spindle cooling and the Blum Macro G612 compensation cycle effectively reduced errors from heat and tool wear before they affected the workpiece.

The established procedure consistently maintained contour precision within a narrow tolerance band of 10–20  $\mu\text{m}$  (0.01–0.02 mm). This represents a significant technological achievement in precision manufacturing, enabling the machining of complex three-dimensional surfaces with exceptional geometric accuracy during continuous operations. Achieving such stability over prolonged machining cycles on ductile C45 steel highlights the process's ability to neutralize wear-induced errors and deliver high-precision results in demanding applications.

## 5. CONCLUSION

This study established an integrated, closed-loop machining framework designed to effectively manage essential tribological interactions, particularly progressive tool wear and friction-induced thermo-kinematic deviations, during high-speed milling of complex three-dimensional freeform surfaces. By advancing from traditional passive inspection methods to active on-machine metrology coupled with dynamic numerical control (NC) compensation, the study achieved significant outcomes on ductile C45 steel.

1. The deployment of customized macro programming effectively automated the compensation process for both physical tool wear and spindle thermal expansion. Automated probing cycles diminished initial setup uncertainties from 0.03 mm to a highly precise range of 0.002–0.003 mm. Moreover, active laser scanning during the machining cycle dynamically counteracted combined wear and thermal errors, limiting the total input deviation to approximately 0.005 mm.
2. Although theoretical models of the error budget predicted a maximum uncompensated volumetric error of 32.76  $\mu\text{m}$ , the active feedback system efficiently mitigated these tribological and kinematic deviations from resulting in dimensional inaccuracies. Post-processing validation using Coordinate Measuring Machine (CMM) confirmed an exceptionally stable three-dimensional profile, with an average spatial deviation of merely 17  $\mu\text{m}$  and the maintenance of a stringent tolerance band of 12–20  $\mu\text{m}$ .
3. Optimized toolpath interpolation, coupled with the dynamic rigidity of the machining center, effectively controlled tool-chip friction and mitigated built-up edge formation. Consequently, even under rigorous high-speed conditions (10,000 rpm), the system achieved superior surface integrity, with measured roughness ( $R_z$ ) values ranging from 4.37 to 5.14  $\mu\text{m}$ . This enhanced topographical quality nearly eliminates mechanical mesh artifacts, providing a significant manufacturing advantage by reducing manual post-polishing time by up to 70%.

In summary, embedding automated metrology and active wear compensation directly into the NC workflow offers a comprehensive, data-driven solution for mitigating tribological errors in precision machining. The experimental findings confirm that this integrated approach fundamentally addresses the ongoing challenges related to geometric accuracy and surface integrity within advanced manufacturing environments.

## Acknowledgement

This research is funded by Vietnam Ministry of Education and Training under project number B2026-BKA-07.

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