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Temperature Control System for CNC Milling to Improve Dimensional Accuracy and Surface Finish

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Abstract

Thermal effects in CNC machining are a primary source of dimensional inaccuracies and surface wear, particularly under dry conditions or variable cutting parameters. This study presents an experimental evaluation of a thermal regulation strategy applied to the milling of 1020 steel and 6010 aluminum workpieces. To ensure thermal stability during machining, an active temperature regulation system was developed and employed. By integrating the external control system for thermal stabilization, groove width errors were reduced by up to 100 µm, while dimensional precision remained within the IT12–IT11 tolerance band, ensuring compliance with industrial quality standards. Surface roughness values remained reliably within the N8–N7 tolerance classes, demonstrating greater uniformity and consistency compared to dry machining trials. Additionally, a significant reduction in measurement dispersion was observed, indicating improved process stability and repeatability. From a resource-efficiency standpoint, the system achieved comparable thermal performance while reducing coolant usage to as low as 1%–25% of that required by conventional continuous cooling approaches. These results highlight the effectiveness of thermal regulation as a robust method for enhancing machining precision, repeatability, and sustainability in industrial applications.

Keywords: CNC, thermal error compensation, surface roughness, dimensional tolerance, PID control

1. Introduction

Precision in CNC machining is frequently compromised by temperature-induced deviations, particularly under dry or semi-dry conditions where thermal regulation is absent. These thermal fluctuations affect both surface roughness and dimensional accuracy, often resulting in inconsistencies that undermine the reliability of the manufacturing process [1]. As machining operations continue to evolve toward higher speeds and tighter tolerances, thermal effects have emerged as a dominant source of geometric and surface errors, especially in processes involving prolonged tool–workpiece interaction.

While several approaches have been explored to mitigate thermal deformation—including trajectory compensation [2], spindle-integrated feedback systems [3], and temperature control through chip-breaking dynamics [4]—many of these strategies are limited by their reliance on embedded architectures, complex integration requirements, or narrow applicability. In this context, the present study evaluates the effectiveness of an external, modular thermal regulation system designed to improve dimensional stability and surface quality during milling operations. The system's performance is assessed experimentally by comparing surface roughness and groove width tolerances under dry machining and thermally regulated conditions, with results discussed in terms of process repeatability, tolerance compliance, and coolant efficiency.

2. Methodology

The physical implementation of the thermal control system was carried out on the **EMCO Concept Mill 450** CNC machine (Figure 1). The system was designed based on principles of scalability, robustness, and non-invasiveness, allowing it to be installed without modifying the original mechanical structure of the machine or interfering with the functionality of the machining process. Experimental tests were conducted on **AISI 1020 steel** and **6010 aluminum** workpieces, two materials widely used in the industry due to their good machinability and broad range of structural applications.
To ensure consistent emissivity and reduce measurement error due to external heat sources, the reamer was coated with matte black paint, fixing its emissivity at 0.98. The primary objective of the thermal control system was to maintain the cutting temperature within a stable functional range, minimizing thermal variability and preserving machining quality.

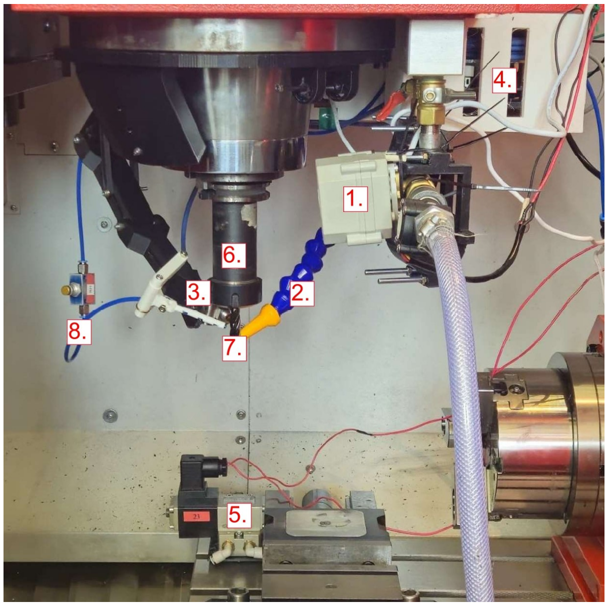

Figure 1: Experimental setup of the CNC thermal control system. 1. Coolant solenoid valve; 2. Coolant outlet nozzle; 3. Infrared temperature sensor; 4. Control unit / electronic systems; 5. Air solenoid valve; 6. Tool holder; 7. Cutting tool; 8. Air line.

2.1. Thermal Control System Overview

To enable thermal stabilization during milling, a dedicated external control system was integrated into the machining setup. Its purpose was to maintain the cutting tool temperature within operational thresholds by dynamically responding to thermal fluctuations during the machining cycle. The system operates through three functional modules: temperature acquisition, control logic, and dual-mode actuation.

- **Temperature Acquisition:** Tool temperature was monitored using a compact Raytek MI3 infrared sensor, mounted approximately one inch above the cutting zone to ensure an unobstructed line of sight. This positioning helped mitigate measurement interference from chip accumulation and coolant spray. To ensure accuracy, the sensor was experimentally calibrated through a cross-reference procedure using thermocouples certified under the ISO/IEC 17025:2017 standard.

- **Control Logic:** The control system selected one of three actuation modes based on predicted thermal stress, estimated through pre-process simulations using a one-dimensional finite difference model. These modes included: passive bypass for low loads, PID regulation for moderate fluctuations, and a precomputed model predictive control (MPC) strategy for high-demand conditions.

  To ensure adaptability during operation, a real-time PID loop applied corrective adjustments to the MPC output, maintaining thermal stability under transient disturbances. This hybrid strategy provided a practical balance between responsiveness and computational efficiency, adjusting dynamically to machining parameters such as material, toolpath, and cutting load.

- **Actuation:** Cooling was applied using a combination of airflow and liquid coolant, with each medium regulated independently via electro-pneumatic and motorized valves. Actuation intensity was adjusted dynamically based on both measured and predicted temperature states to ensure smooth and efficient thermal compensation.

2.1.1. Control Objectives

The system was configured to maintain the tool–workpiece interface temperature within a target range of 200°C to 400°C, based on material-specific considerations and heat dissipation behavior. To achieve this indirectly, the control loop operated on a setpoint range of 30°C to 45°C at the sensor location, which was determined through preliminary calibration and thermal modeling. The selected sensor setpoints were adjusted dynamically based on the anticipated heat load for each machining condition.

A full description of the complete system architecture development is available in a prior technical report [1].

2.2. Experimental Setup

To evaluate the performance of the thermal control system, an experimental test was conducted using a 10 mm high-speed steel (HSS) reamer for slotting operations on workpieces. Each test consisted of machining eight grooves per workpiece, with the spindle speed progressively increased from one groove to the next. Each material was tested under two conditions: one in dry machining and the other with the implementation of the automatic thermal control system. Consequently, a total of eight workpieces were machined, corresponding to four dry tests and four controlled tests. The complete set of machining parameters for each workpiece is summarized in the following table.

Table 1: Machining parameters per workpiece. A total of eight tests were performed: four under dry conditions and four with the thermal control system activated.

Workpiece	Material	Test Type	Depth of Cut (mm)	Feed Rate (mm/min)	Spindle Speeds (RPM)
1	Aluminum 6010	High	2	90	300, 450, 600, 750 900, 1050, 1200, 1350
2	Steel 1020	Low	2	70	400, 500, 600, 700 800, 900, 1000, 1100
3	Steel 1020	High	2	90	1200, 1300, 1400, 1500 1600, 1700, 2000, 2500

2.3. Measurement Tools and Procedures

To evaluate the performance of the thermal control system, two key quality indicators were measured: surface roughness and groove width. Both measurements were conducted on each machined groove at three different locations—entry, center, and exit—allowing for analysis of consistency along the toolpath. At each location, two consecutive measurements were taken, totaling six measurements per groove, to assess repeatability and the uniformity of the machining process, as well as to observe variations related to spindle speed and thermal control conditions.

Table 2: Measurement instruments and tolerance criteria.

Measured Parameter	Instrument	Resolution	Tolerance Range Evaluated
Groove Width (Dimensional Accuracy)	MITUTOYO Digital Caliper	0.01 mm	IT11 – IT12 (ISO 286-1)
Surface Roughness	MITUTOYO SJ-210 Roughness Tester	0.001 µm	N7 – N8 (ISO 1302)

3. Results

The analysis aimed to determine not only whether the system could maintain or improve the standards, but also to identify any clear trends associated with the application of the control strategy.

3.1. Surface roughness

Under uncontrolled thermal conditions, both for Aluminum 6010 and AISI 1020 steel (Figures 2 and 3), high dispersion was observed in the surface roughness measurements. In particular, as spindle speed increased, a downward trend in roughness values was noted; however, several measurements exceeded the minimum N8 tolerance threshold. This variability indicates insufficient thermal stability during machining, which compromises the uniformity of the surface finish.

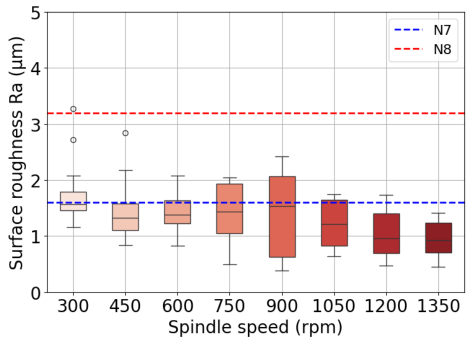

Figure 2: Surface roughness without control – Aluminum 6010.

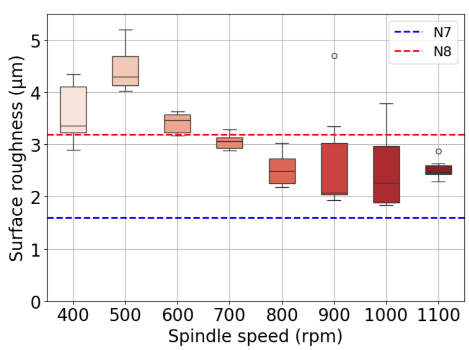

Figure 3: Surface roughness without control – Steel 1020.

The implementation of the thermal control system led to significant improvements for both materials(Figures 4 and 5). A marked reduction in data dispersion was observed, resulting in greater uniformity of the machined surface along the grooves. Furthermore, roughness values remained consistently within the N8 tolerance class, and in several cases reached the more stringent N7 threshold, representing a level of surface quality that surpasses the minimum required standard.

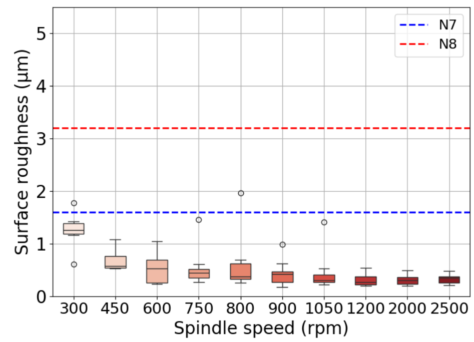

Figure 4: Surface roughness with control – Aluminum 6010.

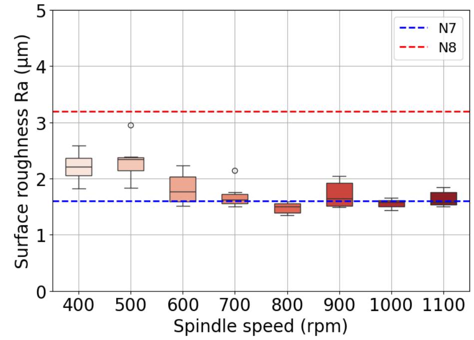

Figure 5: Surface roughness with control – Steel 1020.

In the most demanding scenario, corresponding to AISI 1020 steel at high spindle speeds (Figure 6 and Figure 7), thermal loads were considerably more severe. While dry machining yielded lower average roughness values with less dispersion, the thermal control system, despite exhibiting slightly higher variability in this specific case, maintained all measurements within the N8 classification. This demonstrates the system's capability to preserve acceptable surface roughness even under elevated thermal loads.

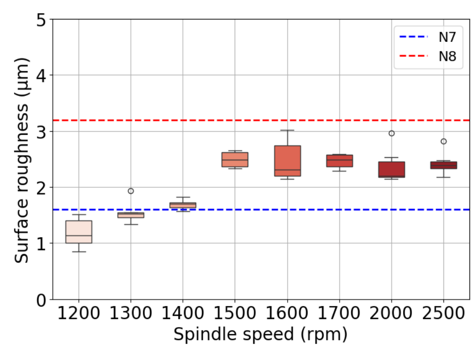

Figure 6: Surface roughness without control – Steel 1020 (High speed test).

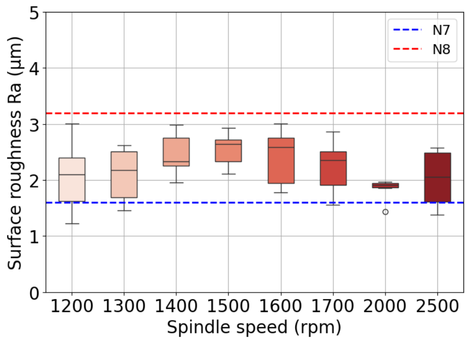

Figure 7: Surface roughness with control – Steel 1020 (High speed test).

3.2. Groove width dimensional accuracy

Under uncontrolled thermal conditions (Figures 8 and 9), a high degree of data dispersion and significant dimensional error were observed, with deviations exceeding 200 µm. The groove width emerged as the most affected variable due to its sensitivity to heat generation and thermal expansion. Under these conditions, the IT12 dimensional tolerance was not met throughout the entire workpiece, and for AISI 1020 steel, none of the measurements fell within the minimum required tolerance range.

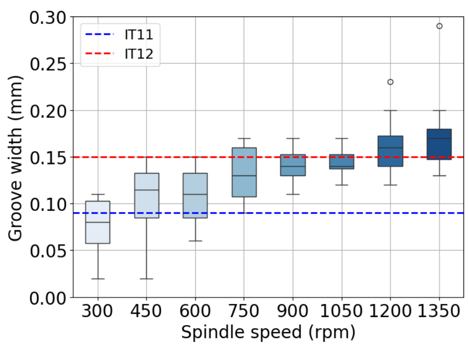

Figure 8: Groove width deviation without control – Aluminum 6010.

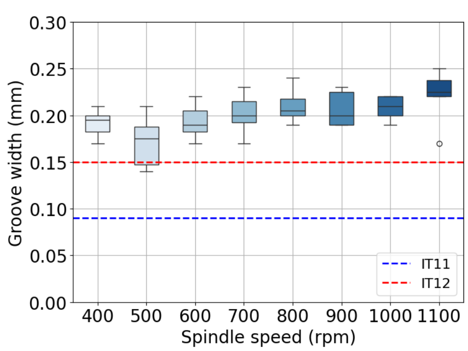

Figure 9: Groove width deviation without control – AISI 1020.

In contrast, the implementation of the thermal control system (Figures 10 and 11) resulted in a noticeable reduction in data dispersion, indicating improved repeatability and uniformity in groove width, as well as enhanced dimensional quality. Furthermore, the groove width values became less dependent on spindle speed, as the system maintained the cutting temperature within a range that limited thermal expansion.

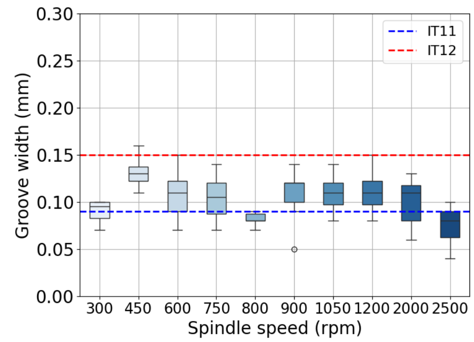

Figure 10: Groove width deviation with control – Aluminum 6010.

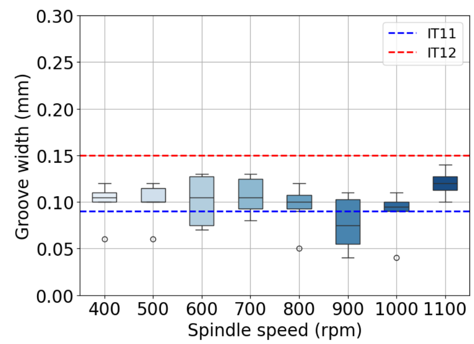

Figure 11: Groove width deviation with control – AISI 1020.

Specifically, under the most demanding conditions—AISI 1020 steel machined at high spindle speeds (Figure 12 and 13)—none of the groove width measurements under dry conditions fell within the IT12 tolerance range. In contrast, the implementation of thermal control enabled all measurements to comply with IT12, with several even achieving the tighter IT11 classification. This reflects a maximum dimensional error reduction of up to 150 µm. These results highlight the system's capability to actively regulate temperature, effectively mitigating thermal expansion and ensuring a consistent balance between surface finish quality and dimensional accuracy under severe thermal loads.

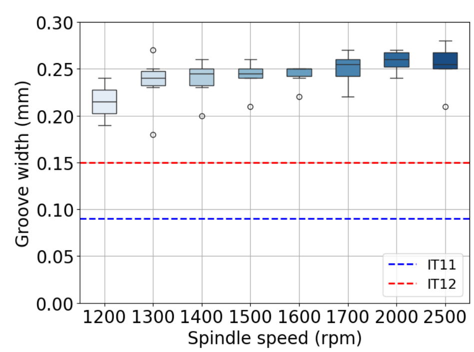

Figure 12: Groove width deviation without control – AISI 1020 (High speed test).

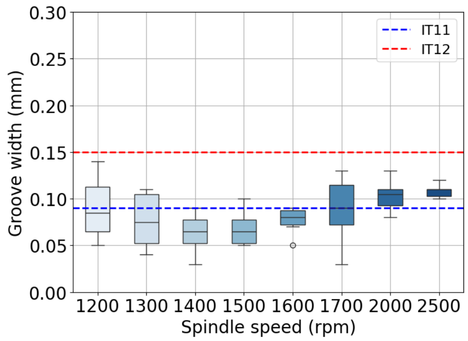

Figure 13: Groove width deviation with control – AISI 1020 (High speed test).

3.3. Coolant Consumption Efficiency

The thermal regulation system significantly reduced coolant usage by applying demand-based actuation, supplying fluid only when necessary. Experimental results showed a reduction of **75% to 99%** compared to continuous cooling strategies, especially under low- and medium-power conditions. This reduction contributes to cost savings and supports more sustainable manufacturing practices.

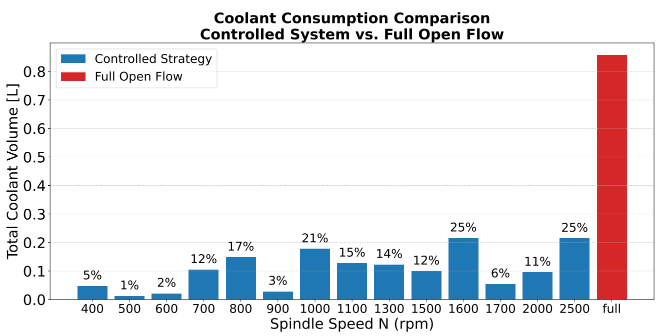

Figure 14: Comparison of coolant usage between controlled and full open flow strategies across spindle speeds.

4. Conclusion

This study experimentally validated the effectiveness of the developed thermal regulation strategy for improving dimensional and surface quality in CNC milling of 1020 steel and 6010 aluminum. By maintaining cutting zone temperatures within target ranges, the system achieved consistent confinement of surface roughness within the N8–N7 tolerance classes and dimensional accuracy within the IT12–IT11 standards, with groove width errors reduced by up to 100 μm.

The system also enhanced repeatability and process stability, while reducing coolant consumption by 75–99% compared to conventional continuous cooling. These results confirm the practical applicability of real-time thermal control in improving machining precision under variable load conditions, especially in medium- to low-intensity regimes.

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