Experimental investigation of adaptive temperature control for energy efficient precision grinding machines

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Abstract

Thermal errors remain among the most critical challenges in precision manufacturing, especially in the grinding of high-accuracy workpieces such as cutting inserts. Even small temperature fluctuations within a machine tool can lead to thermal expansion, causing positioning errors and reduced dimensional accuracy. Addressing these issues requires either excellent compensation or highly stable thermal conditions throughout the machining process, or ideally a combination of both approaches.

This study investigates advanced temperature control strategies for a five-axis Agathon Evo Quinto grinding machine. The machine incorporates two independent cooling circuits: one for process cooling and another for internal structural components. Both cooling systems are independently monitored and controlled. The temperature setpoints of the systems can be adjusted in real-time, while coolant flow rates and power consumption are continuously recorded for each subsystem. A total of 34 temperature sensors, distributed across the machine, capture real-time thermal data, and a 3D touch probe enables measurement of thermally induced displacements during the operation of the machine in a fixed interval.

Initial findings demonstrate that even relatively simple control architecture adaptations in thermal management can yield significant energy savings while preserving or improving machining precision. Using dynamic, environment-adaptive cooling setpoints, rather than maintaining a constant nominal temperature (e.g., 22 °C), the cooling circuits are controlled based on low-pass filtered environmental temperature, allowing them to track daily fluctuations. This approach reduces unnecessary overcooling and aligns the machine's thermal state with its environment. Results show that such adaptive control can reduce average coolant requirements by almost 75%, from 12.8 L/min to 3.2 L/min for the investigated machine and environment. Although machine temperature fluctuated up to 5 °C within a day leading to larger nominal thermal displacements, thermal errors became smoother, due to the reduced cyclic variations caused by conventional chiller switching which allow for more robust subsequent software-based compensation of the thermal error.

Machine tools, Adaptive Cooling, Energy Efficiency, Temperature control, Thermal errors

1. Introduction

Thermal errors are among the dominant sources of inaccuracy in machine tools (MTs), responsible for up to 75% of the total geometric error of a machined workpiece [1]. In industrial practice they can contribute to as much as 50% of scrap production [2]. To minimise these effects, MTs are typically subject to extensive thermal stabilisation, most commonly through active cooling. Cooling systems, however, account for 15–30% of the total power consumption of a machine tool, sometimes exceeding the energy required for its feed drives and spindle systems [3], [4]. With increasing process speeds, higher accuracy requirements, and more widespread use of thermally sensitive components, the energy demand of cooling has continued to grow [5].

Conventional cooling strategies rely on fixed setpoints and simple on/off control. While effective in maintaining acceptable stability, they frequently cause overcooling, excessive switching of refrigeration equipment, and inefficient energy use [6]. This illustrates the need for control concepts that can balance and potentially improve both objectives.

Recent research has explored a range of approaches to improve cooling and energy efficiency in relation to thermal errors [7]. For example, Grama et al. [8] proposed a model-based Cooler Trigger Model for spindle cooling, where compressor operation is dynamically adjusted to match heat generation, resulting in significantly reduced spindle thermal errors compared to conventional ambient-tracing strategies. Wenkler et al. [9] applied conventional and demand-oriented cooling strategies on a machine tool frame, showing that flow-controlled, demand-oriented cooling can significantly reduce energy consumption without impairing thermal stability. Maurya et al. [10] developed an ANN–GA model to predict and minimise spindle thermal deformation, transferable to dual-spindle systems, improving precision while lowering cooling demand. Mori et al. [11] proposed an indoor condition offset strategy, dynamically adjusting factory air-conditioning setpoints to outdoor weather, achieving up to 40% cooling energy reduction while maintaining stable and compensable machine tool thermal displacements. Mori et al. [12] also developed an on–off control strategy for hot-gas-bypass spindle cooling, experimentally demonstrating up to 75% energy savings with minimal impact on thermal displacement compared to conventional continuous cooling.

Together these contributions highlight promising directions, yet most studies focus either on energy efficiency or on thermal error reduction alone. Only few have examined their combined impact under realistic production conditions, especially considering multiple temperature-controlled fluid systems active at the same time. This study therefore examines adaptive cooling strategies on a fully instrumented grinding machine, evaluating both energy demand and implications for thermal behaviour. While the broader goal is to identify cooling strategies that are both energy-efficient and facilitate robust

thermal error compensation, the scope of this paper is limited to showing how two representative strategies affect energy consumption and thermal behaviour. Section 2 describes the experimental setup, Section 3 presents representative energy, cooling, and error behaviour results, and Section 4 concludes the findings and offers an outlook on future work.

2. Methodology

2. 1. Overview

The experimental platform is a five-axis Agathon Evo Quinto grinding machine equipped with two independent cooling systems:

1. Component cooling circuit for internal machine structures (spindles, axes, support frames).
2. Process cooling circuit for metalworking fluid delivery to the grinding zone.

Both systems are supplied by a dedicated chiller and operate independently. A network of 34 temperature sensors, complemented by a touch trigger probe, enables comprehensive monitoring of the machine's thermal behaviour [13]. Flow, pressure, and power monitoring devices provide additional tracking for each subsystem. All measurement data is continuously recorded in a centralized time-series database, ensuring synchronized analysis across all subsystems. All experiments were performed under a constant, repeatable load case to ensure comparability.
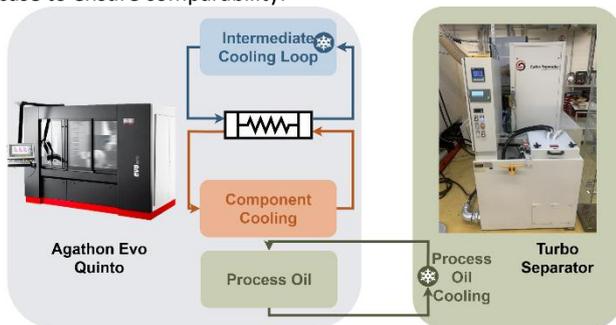

Figure 1 Overview of cooling fluid system on the investigated MT.

2.2. Component Cooling

The component cooling system stabilizes the thermal state of the machine's frame, axes, auxiliary systems and spindle housings.

It is structured into three interconnected circuits:

1. Component cooling loop: circulates coolant through embedded channels in machine elements. A temperature sensor in this loop measures the coolant temperature directly at the machine. A setpoint for this temperature can be defined, and the machine's PLC controls a valve in the intermediate cooling loop accordingly. By adjusting this valve, the system regulates the heat transfer between the component cooling loop and the intermediate loop.
2. Intermediate cooling loop: transfers heat from the component cooling loop to the refrigerant circuit via a heat exchanger. This loop contains temperature and flow sensors both before and after the heat exchanger section, allowing the estimation of transferred thermal energy.
3. Refrigerant circuit: part of the chiller system, responsible for cooling the intermediate loop. It is controlled via a hysteresis controller to keep the refrigerant within a defined temperature range.

The temperatures in the component cooling circuit, before and after the heat exchanger in the intermediate circuit, and in the refrigerant circuit are monitored. In addition, the flow rate and valve status in the intermediate circuit are recorded, while the total power consumption of the Agathon Evo Quinto, including the component cooling system, is measured (basic accuracy 0.25%). Taken together, these measurements enable a detailed evaluation of the various cooling strategies.

2.3 Process Cooling

The process cooling system supplies oil-based metalworking fluid to the grinding zone, namely Blasogrind GTM 4. After application in the grinding area, the process oil flows to a Turbo Separator, where it is first cleaned in a centrifuge to remove fine particles.
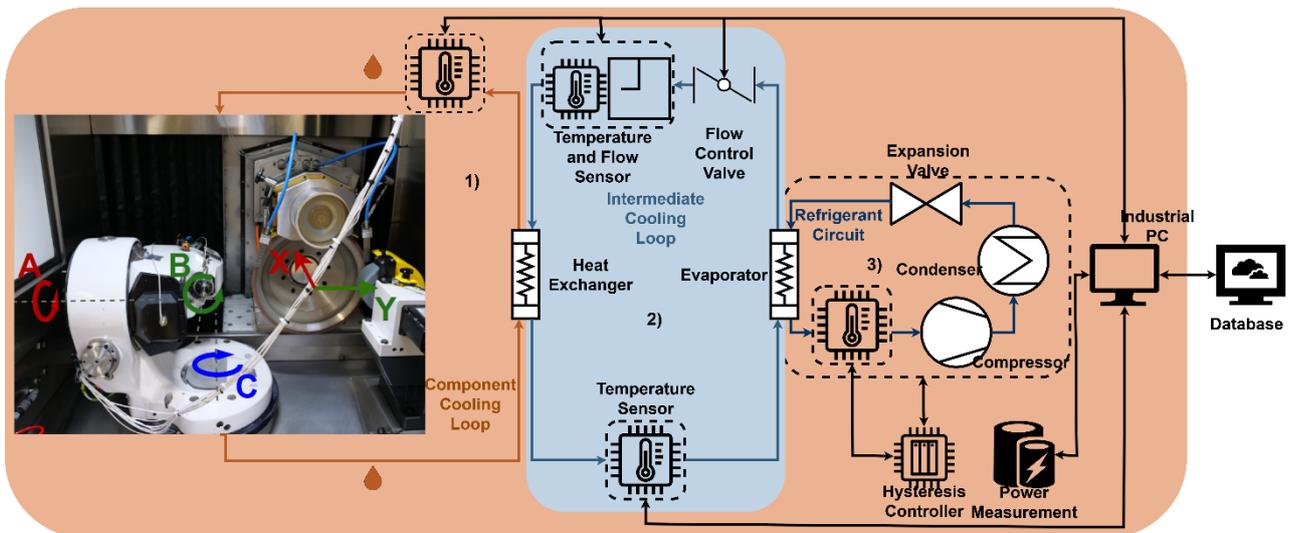

Figure 2 Component cooling overview based on three separated closed cooling loops.

The cleaned oil then enters the actively stirred and temperature-controlled process oil tank, from which it is pumped into the process zone. Cooling in the tank is provided by an immersion cooler, which operates under a simple on/off control scheme. The controller can be managed directly by the machine's

computer, allowing automated switching based on temperature setpoint. The temperature of the process oil, power consumption (0.2, IEC 61557-12), and status of the controller are continuously measured to evaluate the performance of the component cooling system for different cooling strategies.
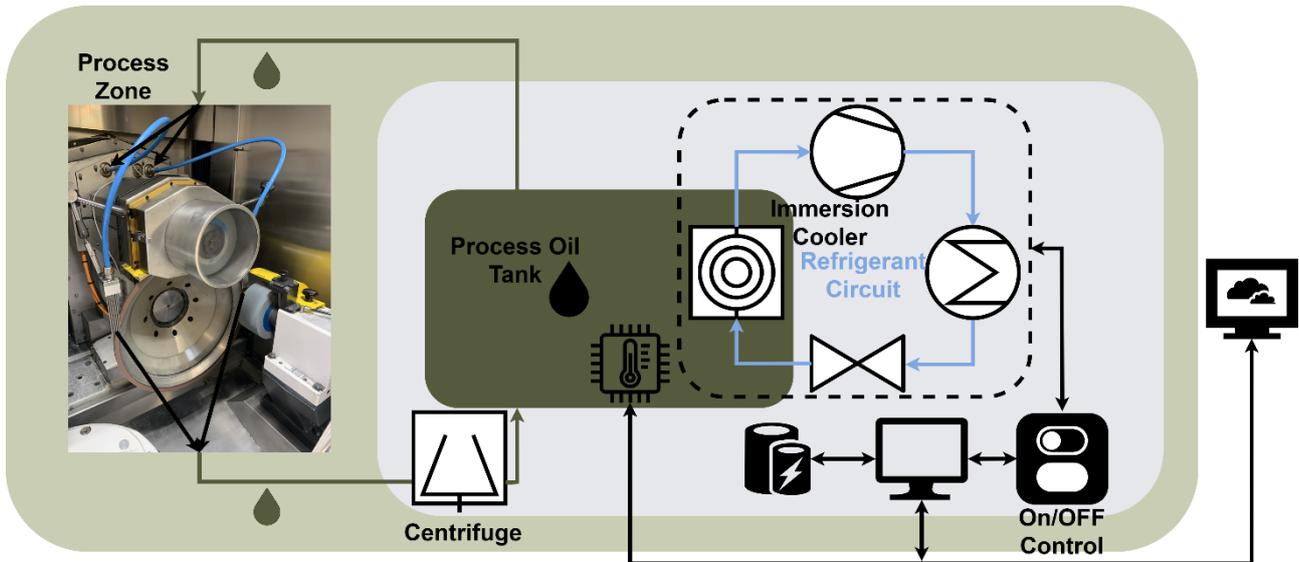
Figure 3 Process cooling overview, consisting of the open loop into the machine 's grinding zone and the closed loop refrigerant.

2.4. Cooling Strategies

Two control strategies were evaluated:

- Initial strategy: process oil temperature set to 22.5 °C; cooling switched on when the tank temperature exceeded the setpoint and off when it dropped below. Component cooling loop set to 23 °C. In this mode, the valve in the intermediate cooling loop and the hysteresis controller in the refrigerant circuit of the component cooling operated without additional control intervention.
- Ambient setpoint: cooling circuit setpoints adjusted according to ambient temperature. For component cooling, the setpoint of the component cooling loop was set to a low-pass-filtered ambient temperature. For the process oil loop, the same approach was applied but with a ±2 °C range to prevent frequent on/off switching of the immersion cooler.

3. Results

First, the behaviour of the component cooling system is evaluated in terms of power consumption and coolant flow under the ambient setpoint strategy and compared to a static baseline. Next, the process cooling system is analysed, also using ambient setpoints, but a longer period is presented due to its less frequent switching behaviour. Finally, the total energy consumption of both systems is compared across the two strategies and the influence of process cooling on the thermal behaviour of the machine is demonstrated.

Figure 4 shows the power consumption, the temperature of the component cooling loop and the coolant flow of the intermediate loop. It becomes clear that the machine consumes the power, around 1.68 kW, when the compressor of the refrigerant loop is active, which is shown in the temperature drop of the intermediate loop. Table 1 compares the average coolant flow and the average power consumption for both strategies. The coolant flow can be reduced by up to 75% and power consumption by 5.85% when applying the ambient setpoints strategy to the component cooling.

Figure 5 shows that the process cooling system consumes the around 1.62kW more power during active cooling periods, which is also reflected in the corresponding drop in process oil temperature. A comparison of the average power consumption for both cooling systems for both strategies is shown in Figure 6.
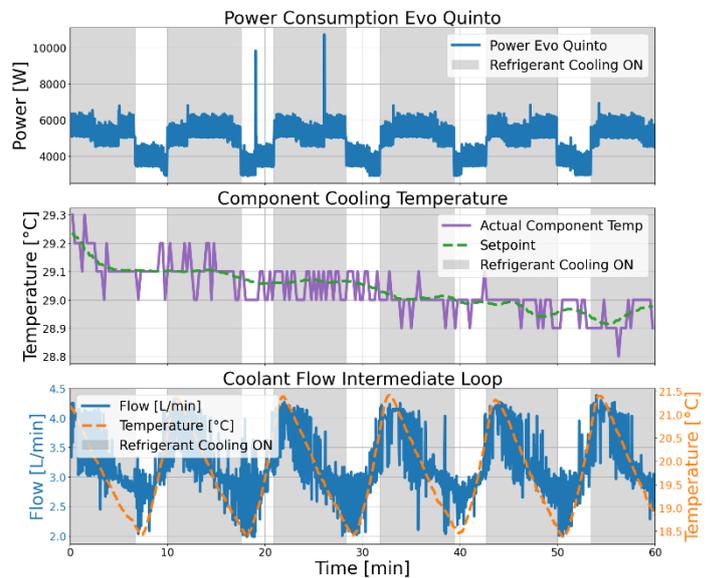

Figure 4 60 minutes of component cooling with ambient setpoint

Table 1 Average coolant flow and power consumption of component cooling under two control strategies over 48h respectively.

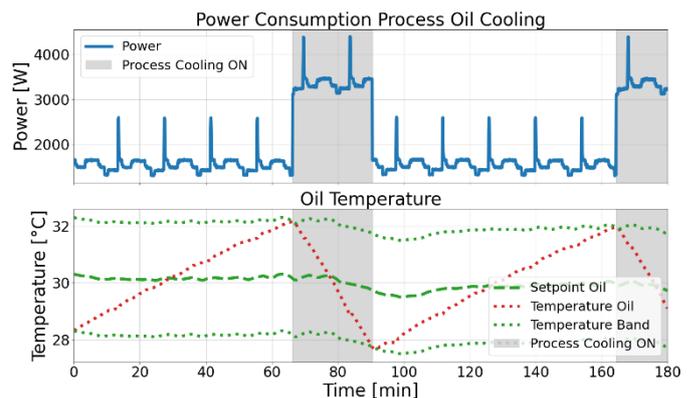| Strategy	Average coolant flow [L/min]	Average power [kW]
Initial	12.84	4.96
Ambient	3.23	4.67

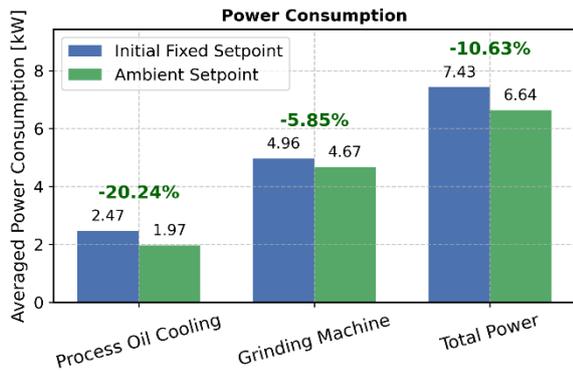Figure 5 180 minutes of process cooling with ambient setpoint.

Figure 6 Average power consumption under initial and ambient setpoint strategies.

For the process oil cooling a reduction of 20.24% in average power consumption has been achieved by adjusting the setpoint strategy. Together, this results in a reduction in power consumption reduction of 10.63%. To illustrate the influence of the cooling system on thermal behaviour, Figure 7 shows the thermal error along the X-axis together with selected machine temperatures in relation to the process cooling status. Both the temperatures and the thermal error are significantly influenced by the cooling behaviour.
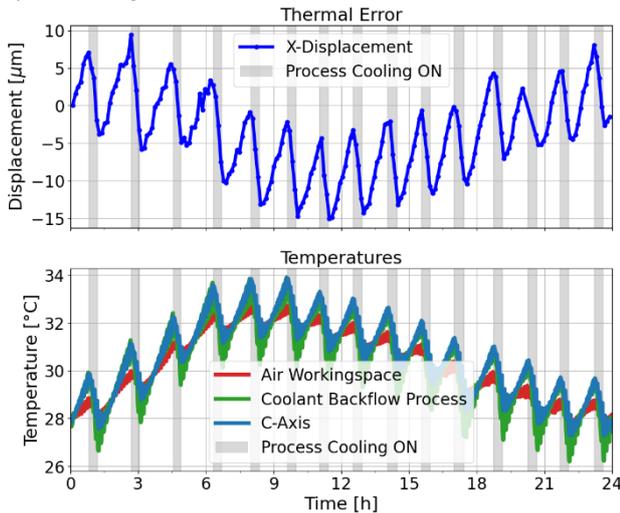

Figure 7 X-direction displacement and selected machine temperatures under influence of process cooling with an ambient setpoint.

4. Conclusion and Outlook

This study experimentally compared two cooling strategies on a five-axis Agathon Evo Quinto grinding machine. Adaptive ambient setpoints reduced component coolant flow by 75% and lowered overall power consumption by nearly 11% compared to fixed setpoints. The results further show that process cooling exerts a strong influence on both machine temperatures and thermal error behaviour, underlining the close coupling between cooling strategy and precision. Future work will therefore focus on identifying strategies that not only minimize energy consumption but also improve the reliability of thermal error compensation models. This will be supported by long-term studies under various production conditions and advanced data-driven control approaches to achieve sustainable thermal management in precision grinding.

Acknowledgements

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