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Experimental Assessment of Cryogenic Surface Grinding of AISI 4140H Steel

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Abstract

Metalworking fluids play a crucial role in grinding by mitigating heat-related issues such as surface cracks, grinding burn and tensile residual stresses. An alternative approach involves cryogenic cooling, where cryogenic fluids like LN₂ or CO₂ are applied at extremely low temperatures. Different strategies exist for implementing cryogenic cooling in the grinding process, including full precooling of the workpiece prior to grinding, LN₂ partial precooling of the workpiece surface, or in-process cooling — where the cryogenic fluid is supplied directly into the cutting zone. In this study, the effects of these cooling strategies on the grinding process — including grinding forces and temperatures — and on the resulting workpiece surface integrity, evaluated by roughness, hardness, and residual stress measurements, were investigated for surface grinding of AISI 4140H. The cryogenic strategies were then compared with conventional oil-based cooling and dry grinding. It was found that all cryogenic strategies led to increased forces compared to conventional oil-based cooling, suggesting greater heat generation and reduced process stability which hindered the thermal advantages associated with cryogenic cooling. In contrast, conventional cooling produced more stable near-surface temperatures and tangential forces, indicating lower thermomechanical loads and ultimately leading to superior surface integrity. In-process cryogenic cooling using CO₂ showed the most promising results among the cryogenic strategies; therefore, further work focused on improvements to the experimental setup of this cooling strategy is recommended to enhance cooling efficiency and achieve more favorable outcomes.

Keywords: surface grinding, cooling, cryogeny, surface integrity

1 Introduction

Grinding, commonly employed as a finishing process, relies on metalworking fluids (MWF) to alleviate thermal issues such as surface cracks, grinding burn and tensile residual stresses and

to enhance the workpiece quality [1]. However, metalworking fluids (MWF) are classified as hazardous to health and pose numerous environmental hazards during their end-of-life treatment, which leads to significant cost challenges in terms

of filtration, recycling and disposal [2]. Potential sustainable alternatives include biodegradable MWF, minimum quantity lubrication (MQL) and cryogenic or dry machining [3]. In manufacturing technologies, the term cryogenic is often used to refer to supply temperatures of the coolant below 0 °C, also including CO₂ besides LN₂ applications, despite its original definition [2]. The inert nature and the immediate evaporation of the cryogenics offer economic advantages by eliminating recycling and disposal costs. Previous research mainly focused on the in-process cryogenic cooling, utilizing cold high-speed gas or fluid jets like CO₂ or LN₂.

The literature review by Jawahir et al. highlighted, that most investigations showed promising results when using LN₂ in-process cooling over dry grinding and using conventional cooling [2]: Reduced grinding forces/power [4–7] and temperatures [4–6, 8, 9] leading to reduced tensile residual stresses [4, 5, 9] and microcracking [4, 5], an improved surface quality [4–7] and a hardened surface layer [10] were found. For example, Fredj et al. observed an improvement of the surface roughness by 40% and reduced tensile residual stresses due to reduced temperatures for grinding austenitic stainless steel AISI 304 with cryogenic LN₂ in-process cooling in comparison to dry grinding and using a conventional oil cooling [9]. However, Reddy and Ghosh observed an increase of the spindle power accompanied with decreased surface quality for LN₂ in-process cooling [11].

Fewer works have been published on cryogenic grinding with CO₂. Breidenstein et al. observed an increased chip thickness by using CO₂ instead of a conventional oil-based cooling when grinding 20MnCrS5 steel with cBN grains in a bronze-bonded grinding wheel [12]. Spahni found that the cutting temperature increased due to the lack of lubrication and the increased friction for cryogenic CO₂ in-process cooling compared to conventional cooling with oil for creep feed grinding of carbide [13]. However, a lower surface roughness was achieved.

Furthermore, another cooling strategy was investigated: Oliveira et al. explored the cryogenic pre-cooling strategy, where heat is extracted from the workpiece before grinding takes place [14]. For instance, in external cylindrical plunge grinding of AISI 1045, the cryogenic pre-cooling strategy, which was performed by immersing the workpiece

in liquid LN₂ for 100 s resulted in superior surface finish and no thermal damage. The success of this cooling method depends on the extraction of the heat, which should be equivalent to the amount of heat that enters the workpiece during grinding.

The focus of this paper is then to investigate the effect of different cryogenic cooling strategies on the surface grinding process, evaluated through force and temperature measurements, and on the workpiece morphology by means of roughness, hardness and residual stress analysis. The results obtained were partly published in German [15].

2 Methods

2.1 Experiments

Surface up-grinding was carried out on workpieces made of hardened and tempered AISI 4140H steel (42CrMo4; 60 HRC) with dimensions 127 × 30 × 19.1 mm³ (coordinates $x \times y \times z$, volume-to-surface ratio $V/A = 5.3$ mm) on the ELB CAM-Master I/1 FR1. A vitrified bonded corundum grinding wheel with a diameter D of 400 mm (400×42×127 EKW 80/1 I 8 V5900M) was used. Three different workpiece velocities v_w (1000, 3000, 6000 mm/min), which resulted in different thermal loads, were investigated at a constant circumferential speed of the wheel v_s of 30 m/s for each cooling strategy.

Five different cooling strategies were investigated for surface grinding: LN₂ pre-cooling, LN₂ partial pre-cooling, CO₂ in-process cooling, conventional oil-based cooling, and dry grinding.

The LN₂ pre-cooling strategy is characterized by immersing the workpiece in liquid nitrogen for a duration of 10 min, achieving a workpiece temperature of −196 °C. Polyurethane (PUR) insulated clamping covers were also used to reduce heat exchange between the pre-cooled workpiece and clamping parts, see Figure 1a. Subsequently, the pre-cooled workpiece was ground dry. Despite the PUR covers, the workpiece heated up to −80, °C during the interval between pre-cooling and the first grinding spark. The influence of the pre-cooling strategy, particularly the effect of the clamping strategy on the cooling process, was investigated in a previous study [16].

The experimental configuration for LN₂ partial pre-cooling featured a tank with maximum pressure of 2 bar, vacuum-insulated hoses, a degasser

to maximize the discharge of liquid LN₂ and a 12 mm diameter nozzle. The workpiece surface was pre-cooled by the liquid LN₂ jet before the actual grinding and no supply during the process. The nozzle initially moved at a speed of 500 mm/min over the workpiece, while the dry grinding of the cooled workpiece happened in an extra step. The time between the cooling and the grinding was approximately 30 s. Approximately 2 bar supply pressure with a mass flow rate of 0.025 kg/s.

In the case of the CO₂ in-process cooling, the setup involved utilizing a CO₂-tank pressurized at 57 bar. The cooling was achieved through specially designed nozzles featuring five openings, each with a diameter of 0.5 mm, leading to a mass flow rate of 0.035 kg/s, see Figure 1b.

A volume flow rate of 50 l/min was chosen for the conventional oil-based cooling (Petrofer¹ Iso-cut R10H) to match the cutting velocity (exit area nozzle $A_{nozzle} = 28.6 \text{ mm}^2$). Additionally, a cleaning nozzle was used to prevent the wheel from clogging (50 l/min). The experimental set up for this cooling strategy is depicted in Figure 1c.

Two workpieces were ground for each cooling strategy and three grinding steps with a depth of cut a_e of 5 μm per workpiece were performed. Before and in between those steps, the surface of the workpieces was ground flat without cooling (dry) using a workpiece velocity $v_w = 3000 \text{ mm/min}$ and depth of cut $a_e = 10 \mu\text{m}$. The tests were randomized to minimize potential wear influences. Furthermore, the grinding wheel was dressed after three workpieces were ground, ensuring consistent conditions and microtopography of the wheel. The dressing parameters were: overlap ratio $U_d = 4.7$, dressing feed speed $v_d = 258 \text{ mm/min}$ and dressing depth of cut $a_{ed} = 15 \mu\text{m}$.

2.2 Measurement technology

Temperatures and forces were measured during the grinding tests. In addition, the surface morphology, consisting of the surface and near-surface region, was analyzed. In particular, the surface roughness, microstructure and microhardness, and the grinding induced residual stresses were measured after grinding.

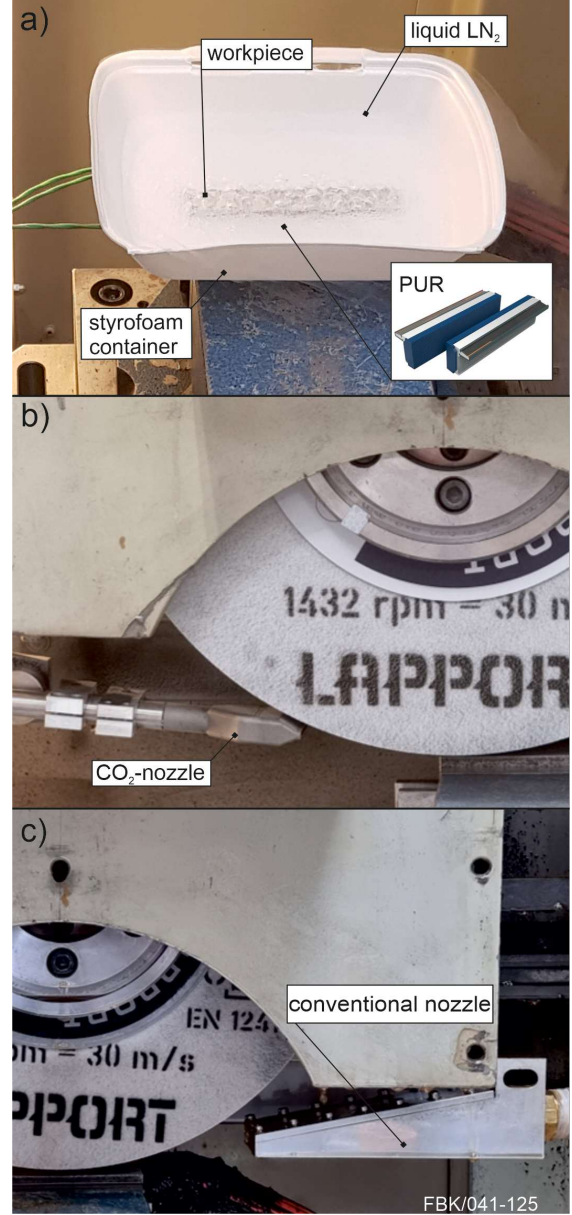


Fig. 1: Experimental set up for LN₂ pre-cooling (a), CO₂ in-process cooling (b) and conventional oil-based cooling (c)

2.2.1 Temperature

Temperature measurements were conducted continuously using two thermocouples with a diameter $D_T = 1 \text{ mm}$ and sampling rate of 100 Hz. One thermocouple T_s was positioned in the near-surface area of the workpiece at: $z = 0.5 \text{ mm}$, $x = 56 \text{ mm}$, $y = 15 \text{ mm}$; according to Figure 2a,

while the other thermocouple T_b was positioned at a greater distance from the surface, measuring the temperature in the bulk at: $z = 14.1$ mm, $x = 100$ mm, $y = 15$ mm; as shown in Figure 2. The thermocouples were inserted into eroded holes of diameter $D_{edm} = 1.3$ mm on the workpiece bottom to measure the near-surface temperature T_s and on the right side to measure the bulk temperature T_b , as illustrated by the orange lines and T_s and T_b symbols on the 3D illustrative view of the workpiece in Fig. 2b. The maximum temperature values near-surface $T_{s,max}$ and at the bulk $T_{b,max}$ was determined for each single cut to allow further comparison of the different cooling strategies.

2.2.2 Force

The normal (F_n) and tangential (F_t) forces were recorded using a piezoelectric Kistler Type 9255¹ dynamometer at a sampling rate of 1 kHz. The steady-state forces were determined by arithmetic averaging over 70 % of the recorded signal, excluding cut-in and cut-out effects. These regions are delimited by the boundaries of the analyzed range shown in Figure 2a. Forces generated by the MWF were measured at zero depth of cut and subtracted from the grinding forces prior to averaging.

2.2.3 Surface roughness

The surface roughness was measured three times after each grinding step using the Marsurf RD 18¹ tactile roughness device. The roughness was measured transverse to the feed direction. The parameters arithmetic mean roughness R_a and the maximum roughness depth R_{max} were determined according to DIN EN ISO 4287.

2.2.4 Microstructure and hardness

The microhardness and -structure were analyzed for one workpiece at $v_w = 1000$ mm/min for each cooling strategy. The microhardness measurements were carried out using a microhardness device DuraScan 70 G5¹. Specimens were taken from the workpieces using a band saw and a precision cutting machine at a distance of 50 mm to the left edge, see the cross-section plane position at Figure 2b. Their surfaces were ground and polished. The microhardness was measured in 10 μ m steps from a depth of 20 μ m up to 1600 μ m using a test load of 10 gf (HV 0.01) according to DIN

EN ISO 6507-1. Three measurements per sample were performed, evenly distributed in y-direction in the center of the sample, as shown in Figure 2b. To compare the increase in microhardness, the mean bulk hardness was measured by conducting ten measurements in the bulk of two samples. To analyze the microstructure, the specimens were etched with Nital (alcoholic nitric acid HNO₃, 3%) for 15 seconds.

3 Results

3.1 Force

The mean maximum normal and tangential forces under various cooling strategies and for different workpiece velocities v_w are shown in Figure 3. An increase of v_w led to higher forces, independent of the cooling strategy, due to a higher specific material removal rate Q'_w . The lowest forces were achieved by using conventional cooling, followed by LN₂ partial pre-cooling, dry grinding, pre-cooling and lastly CO₂ in-process cooling. For pre-cooling, however, deviations in workpiece dimensions may have affected the effective depth of cut of 25 μ m. Due to the workpiece's whole extent being subjected to cryogenic temperature, contraction and expansion during heating up of the cooled workpiece happened. The dimensional changes were, in comparison to the low depth of cut a_e , as reported in [17]. Figure 3 also highlights the average tangential force (F_t) values and variability for the $v_w = 1000$ mm/min experiments in a bar chart. Further phenomena are discussed in the temperature analysis section.

3.2 Temperature

The CO₂ in-process cooling resulted in higher temperatures compared to conventional cooling and showed no significant difference to dry grinding for all investigated workpiece speeds. The pre-cooling and LN₂ partial pre-cooling led to reduced temperatures compared to dry grinding. The success of the pre-cooling strategy depends on the time passed between the cooling of the workpiece and the grinding process, which results in heating of the workpiece as reported in previous works by the authors [16], while also depending on the workpiece speed. In general, conventional

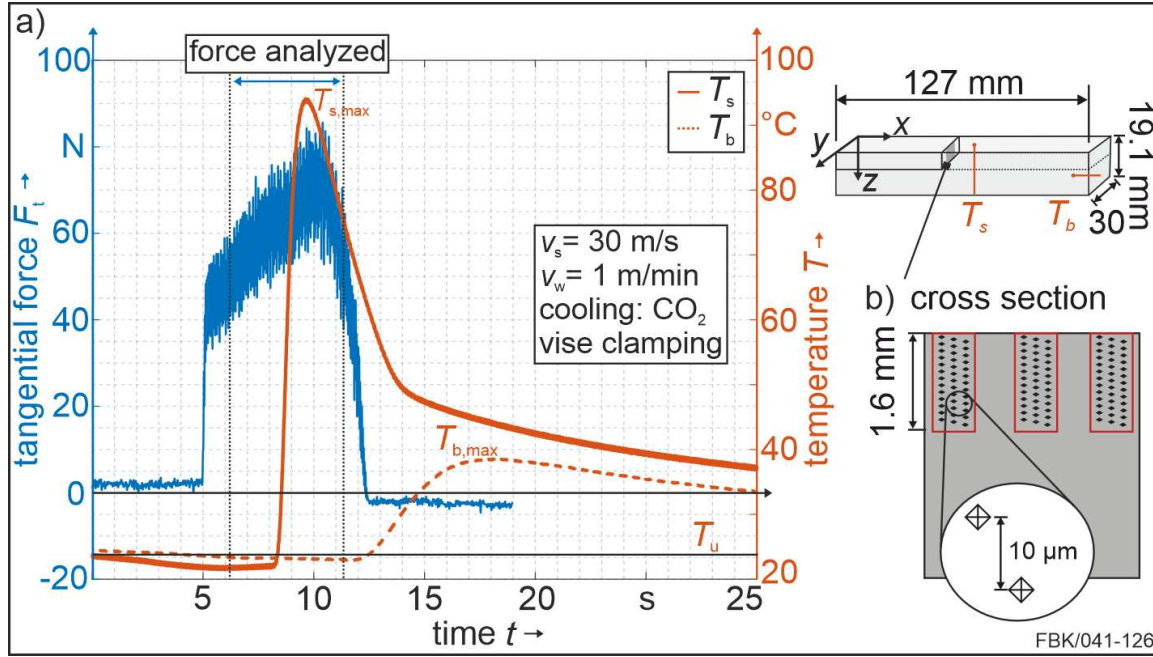


Fig. 2: Force and temperature analysis (a), and 3D illustration of workpiece's dimensions with the thermocouple's location and detailed cross section view of hardness measurements (b)

cooling led to the lowest temperatures in the near-surface area and grinding forces, as observed in Figure 3.

3.3 Roughness

Using a conventional cooling strategy in most cases led to the best surface finish due to the decreased mechanical and thermal load, see Figure 5. Furthermore, microscopic images revealed increased clogging for the other cooling methods. In contrast, clogging was reduced under conventional cooling by enhanced chip removal from the contact zone and the use of an additional cleaning nozzle, resulting in improved surface quality. The CO_2 in-process cooling strategy resulted in surface quality comparable to conventional cooling in terms of average roughness, although higher forces and temperatures were measured. The roughness values of the pre-cooled and partial pre-cooled workpieces showed no significant differences compared to dry ground parts. Furthermore, chatter marks of unknown cause were detected independent of the used cooling strategy for all workpieces.

3.4 Microstructure and hardness

The least effects in terms of a change in microhardness and microstructure were observed on the workpiece ground with MWF, see Figure 6. Hardly any change in hardness or microstructure are visible due to the low thermomechanical load. The pre-cooling surprisingly led to a significant reduction of the hardness in the near-surface layer and in regions, although lower temperatures were measured compared to dry grinding. The cross-section also shows a change of the microstructure in those regions. The CO_2 in-process, the LN_2 partial pre-cooling and the dry grinding led to a reduced hardness limited to the near-surface layer up to a depth below 200 μm .

3.5 Residual stress

Figure 7 depicts the grinding induced residual stress measurements in both feed σ_f and orthogonal-feed σ_{fn} directions. Tensile residual stresses were observed for all cooling strategies. The lowest tensile residual stress maximum of $\sigma_f = 206 \pm 50$ MPa and $\sigma_{fn} = 242 \pm 50$ MPa were found for the conventional cooling strategy. In

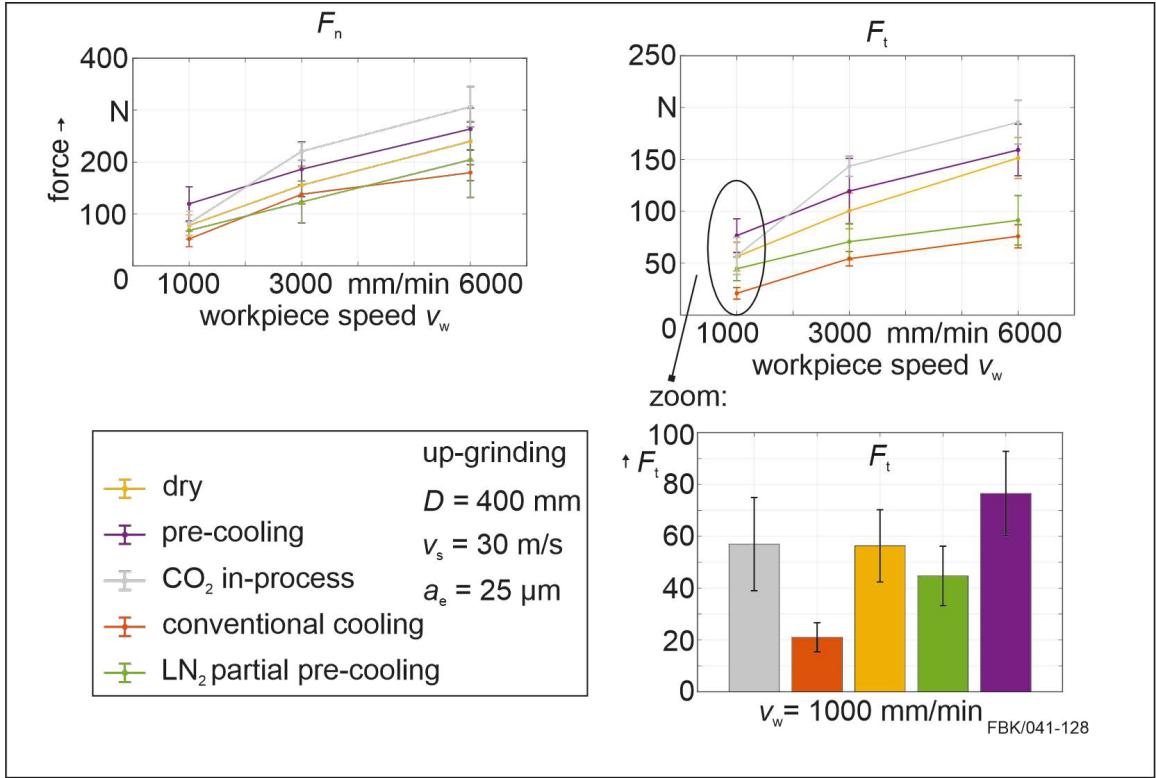


Fig. 3: X-Y charts depicting the average normal force (F_n) and tangential force (F_t) as a function of workpiece speed (v_w). Below, a bar plot zooms in on the average tangential force values for tests conducted at $v_w = 1000$ mm/min

contrast, dry grinding exhibited pronounced tensile residual stresses, with peak values consistently occurring at depths of approximately 100 μm due to the absence of heat removal, which leads to higher thermal gradients. The cryogenic cooling strategies exhibited residual stress profiles that fell between those of dry grinding and conventional cooling yet still showed consistently higher tensile residual stresses than the conventional lubricant-based approach. The residual stress curves for the pre-cooling and LN_2 partial pre-cooling strategies converged with those of the conventional cooling strategy at depths between 300 and 400 μm .

4 Discussion

Regarding the pre-cooling strategy, since both the surface and bulk temperatures of the workpiece are considerably below room temperature, an increase in material hardness and a reduction in ductility (i.e., material embrittlement) are

expected. Unlike cooling strategies that primarily affect the near-surface region, pre-cooling lowers the temperature of the entire workpiece. The resulting reduction in bulk compliance means that deeper material layers might conform less to surface deformation, leading to increased resistance to abrasive grain penetration, as well as higher normal and tangential grinding forces.

Despite the lower measured temperatures, the pre-cooling strategy caused both a reduction in near-surface hardness and visible microstructural alterations. The combination of elevated grinding forces and thermal contraction, altering the effective depth of cut, as well as the resulting thermomechanical loading may have contributed to this response. In contrast, the LN_2 partial pre-cooling strategy preserved a hardness profile much closer to the MWF cooling strategy, pointing that localized surface pre-cooling limits bulk material effects while still reducing the measured temperatures.

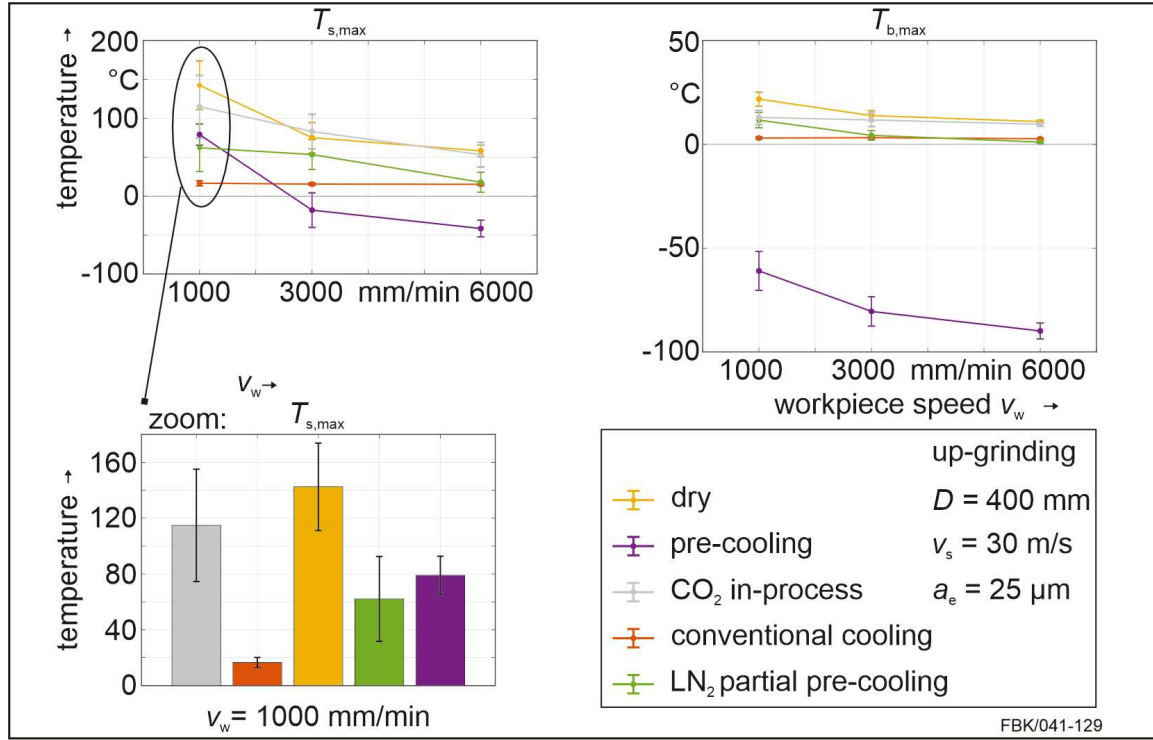


Fig. 4: X-Y charts depicting the maximum temperature values measured near-surface ($T_{s,max}$) and at the bulk $T_{b,max}$ as a function of workpiece speed v_w . Below, a bar plot zooms in on the maximum temperature measured near-surface for tests conducted at $v_w = 1000$ mm/min, with each cooling condition shown separately

Concerning CO_2 in-process cooling, the measured grinding forces were comparable to dry grinding at the lowest workpiece speed of $v_w = 1000$ mm/min, while consistently higher normal and tangential forces were observed at 3000 and 6000 mm/min. This suggests that at higher workpiece speeds, the shorter contact time limits heat accumulation, which might result in the CO_2 jet effectively suppressing thermal softening and increase the resistance to material removal. At lower workpiece speeds v_w , the longer contact time might allow heat to build up, counteracting the cryogenic cooling effect and leading to forces similar to those observed in dry grinding.

Given that higher grinding forces are associated with increased heat generation in the contact zone, corresponding changes in near-surface temperatures are to be expected. However, despite the application of the CO_2 jet directly toward the grinding zone, the measured near-surface maximum temperatures remained comparable to those obtained in dry grinding across all investigated

workpiece speeds. As such, under the investigated conditions, the CO_2 jet was not able to reduce the measured peak temperatures despite increasing the grinding forces, suggesting that its cooling action mainly affects the surrounding material rather than the grain-workpiece interface.

Given that higher grinding forces are associated with increased heat generation in the contact zone, corresponding changes in near-surface temperatures are to be expected. In the case of CO_2 in-process cooling, however, the measured near-surface maximum temperatures remained comparable to those obtained in dry grinding across all investigated workpiece speeds. This indicates that the cooling effect of the CO_2 jet was offset by the additional heat generated due to the higher forces, preventing any net reduction in peak temperatures.

However, the higher grinding forces observed under CO_2 in-process cooling were not accompanied by a proportional deterioration in surface finish. While the arithmetic average roughness

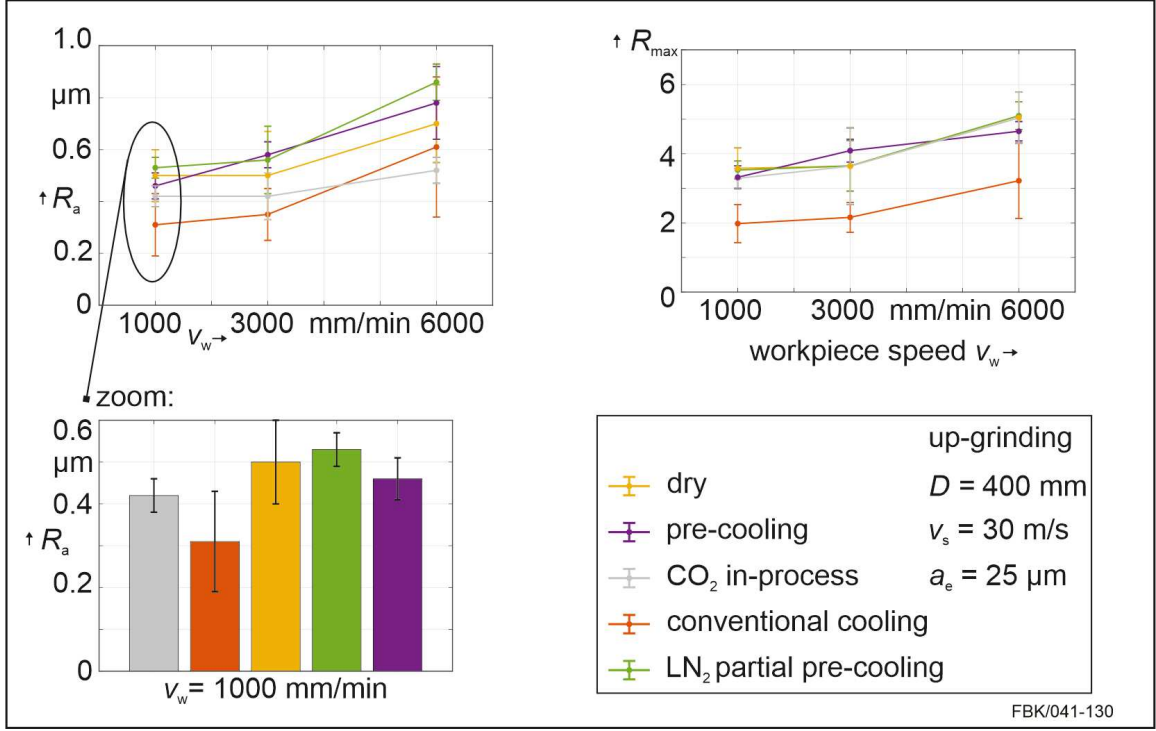


Fig. 5: X-Y charts depicting the average R_a and maximum R_{max} measured roughness values as a function of workpiece speed v_w . Below, a bar plot zooms in on the R_a values for tests conducted at $v_w = 1000$ mm/min

(R_a) remained comparable to conventional cooling, particularly at higher workpiece speeds, the maximum roughness depth (R_{max}) remained similar to the other cryogenic strategies and dry grinding. This behavior may be attributed to the high-pressure CO_2 jet, which likely improves chip evacuation from the grinding zone, maintaining the average surface quality. Nevertheless, the absence of lubrication might promote occasional severe grain-workpiece interactions, resulting in isolated surface defects, reflected by the higher R_{max} values which were observed for all strategies except MWF cooling.

The microhardness measurements further support these observations. Conventional cooling produced less hardness and microstructural variation. Dry grinding, CO_2 in-process cooling and LN_2 partial pre-cooling caused hardness reductions, primarily within the first 200 μm below the surface, with LN_2 partial pre-cooling presenting the closest behavior to the MWF strategy, followed by CO_2 in-process cooling. Full pre-cooling, on the other hand, resulted in a substantially deeper

and more pronounced softened layer coupled with observable microstructural changes. These findings suggest that reducing the measured workpiece temperature alone does not fully translate into improved surface integrity, with mechanical loading and workpiece contraction during grinding playing a significant role.

Overall, the conventional cooling strategy produced the most favorable combination of grinding forces, temperatures, surface roughness, hardness profile, microstructure and residual stresses. Besides providing lubrication, the additional cleaning nozzle likely improved chip removal and reduced wheel clogging, contributing to a more stable grinding process and the best overall surface integrity among the investigated cooling strategies.

5 Conclusion

Different cryogenic cooling strategies were investigated for surface grinding of AISI 4140H workpieces. In comparison with cryogenic approaches,

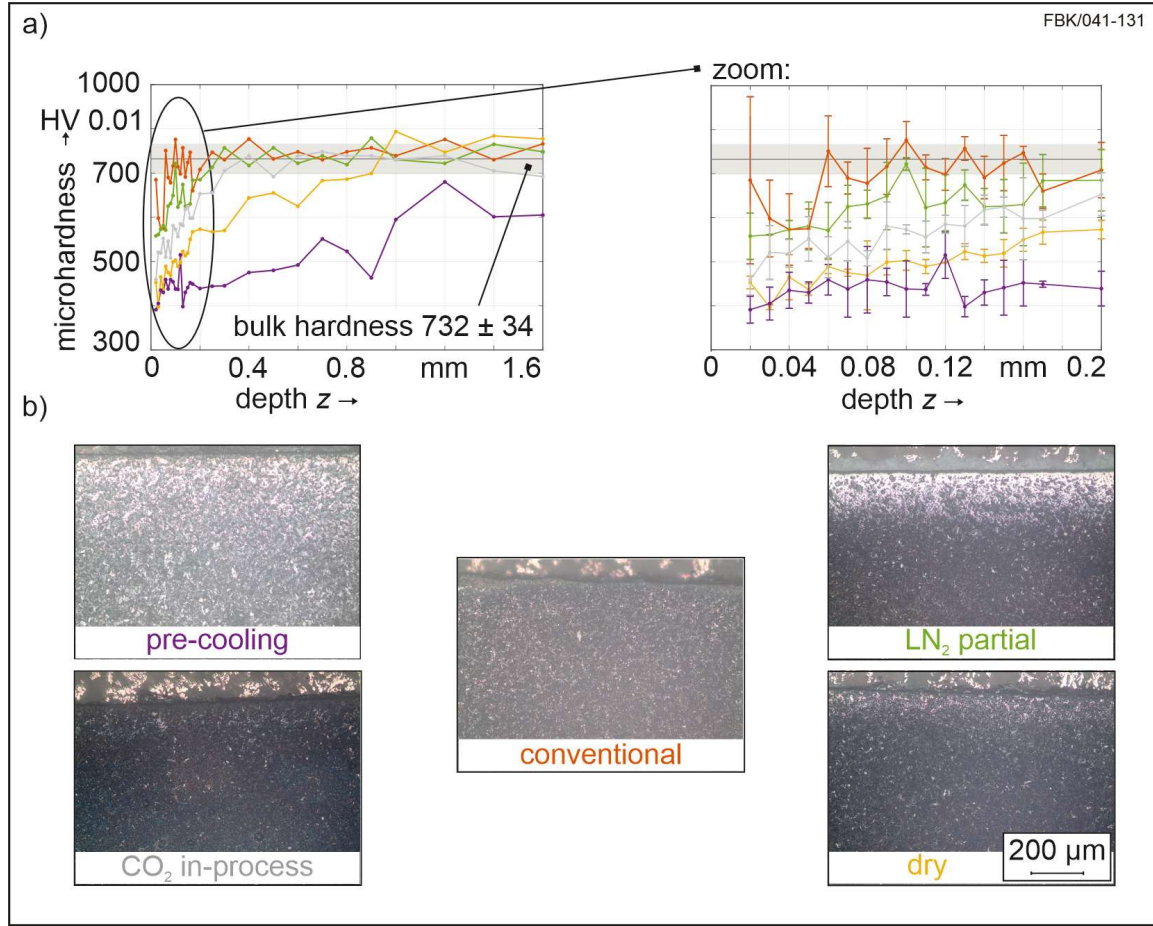


Fig. 6: Microhardness as a function depth for different cooling strategies (a), along with corresponding microstructure images (b). The analysis was conducted on specimens ground with a workpiece velocity of $v_w = 1000$ mm/min

the conventional oil-based metalworking fluid resulted in superior overall surface integrity, as evidenced by lower grinding forces, reduced near-surface temperatures, more favorable surface roughness, as well as smaller changes in hardness and residual stress profiles.

All cryogenic cooling strategies led to increased tangential grinding forces, which negatively impacted surface integrity due to higher thermomechanical loads. Partial pre-cooling reduced near-surface temperatures and limited hardness alterations, but resulted in higher tensile residual stresses and increased surface roughness. Full pre-cooling also achieved lower near-surface temperatures but caused significant softening in the near-surface region.

For CO_2 in-process cooling, similar near-surface temperatures to dry grinding were measured across all workpiece speeds, while grinding forces were generally higher at elevated speeds. The resulting surface roughness (R_a) was partly comparable to conventional cooling depending on the workpiece speed, while the maximum roughness depth (R_{max}) was consistently higher than under conventional cooling conditions.

Future work should focus on optimizing the CO_2 in-process cooling configuration, particularly nozzle design and process parameters in order to improve cooling effectiveness in the cutting zone, reduce grinding forces and surface integrity alterations.

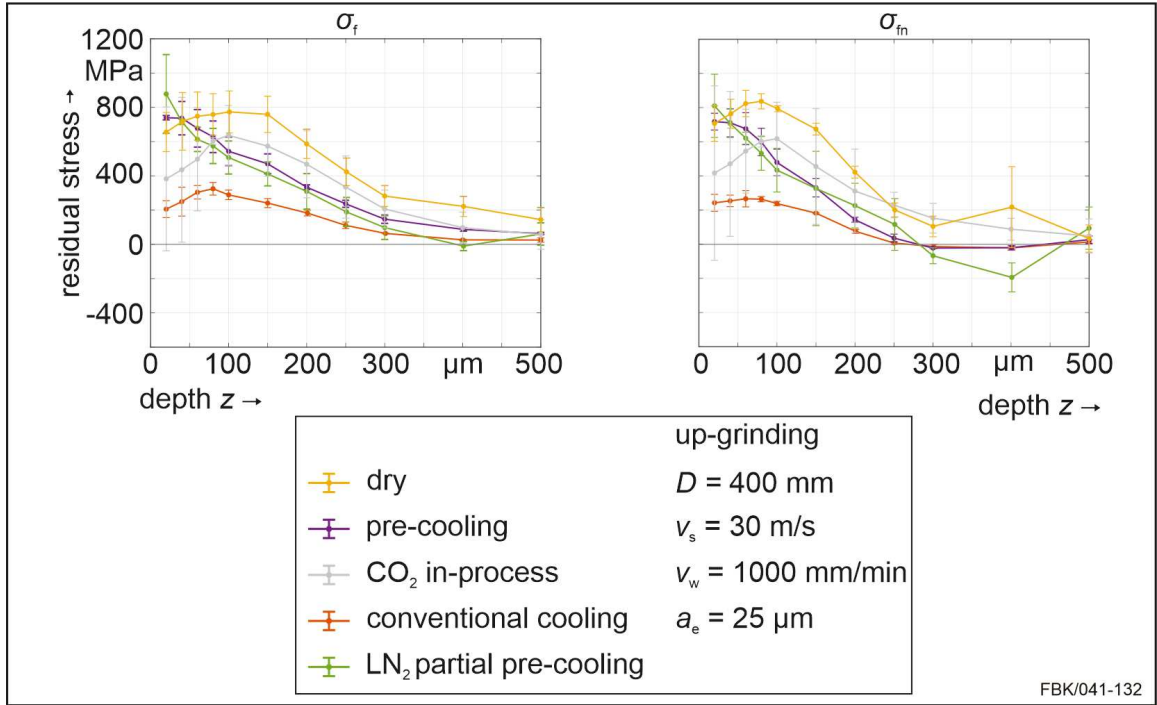


Fig. 7: X-Y charts depicting the measured residual stresses in the feed σ_f and orthogonal-feed σ_{fn} directions, as a function of depth from the external ground surface. The analysis was conducted on specimens ground with a workpiece velocity of $v_w = 1000$ mm/minn

- Author contributions: Ezio C. de Santana: Writing - original draft, Investigation, Methodology, Formal analysis. Daniel Weber: Writing - original draft, Investigation, Methodology, Visualization. Benjamin Kirsch: Writing - review & editing, Supervision, Conceptualization. Eraldo J. da Silva: Writing - review & editing, Project administration, Supervision, Conceptualization, Funding acquisition. Jan C. Aurich: Project administration, Conceptualization, Funding acquisition.
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Declarations

The authors have no competing interests to declare that are relevant to the content of this article.

¹Naming of specific manufacturers is done solely for the sake of completeness and does not necessarily imply an endorsement of the named companies nor that the products are necessarily the best for the purpose.

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