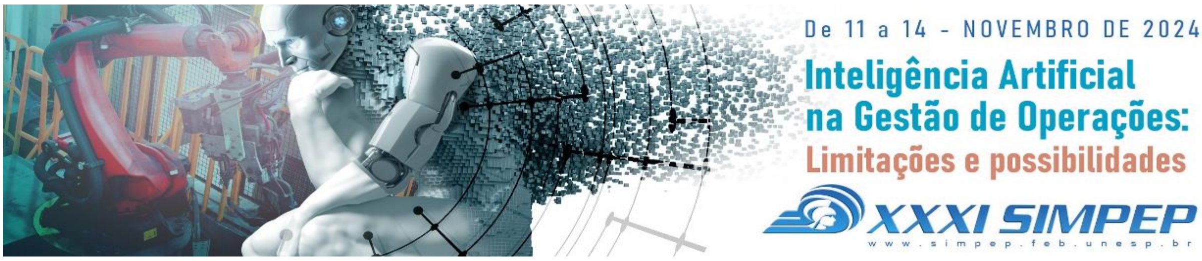

INNOVATIVE APPROACHES TO ECO-FRIENDLY PRECISION GRINDING OF VP50 STEEL

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ÁREA: *09.ENGENHARIA DA SUSTENTABILIDADE*
SUBÁREA: *9.7 - Desenvolvimento Sustentável*

RESUMO: *Climate actions have been gaining prominence in discussions about the industrial future due to the need to reduce the amounts of residual pollutants in manufacturing processes. Although the grinding process is widely applied in the industry for its finishing capabilities and dimensional and geometric precision, it is significantly polluting and detrimental to workers' health. This is attributed to the quantity of mineral oil used in conventional flood lubrication-cooling systems. With these demands in mind, this work proposes alternative methods by comparing the performance of the alumina grinding wheel with the conventional method of lubrication-cooling using MQL, with and without the WCJ auxiliary system, and distinguishing the direction angles of the air jet in the cylindrical grinding process. The workpieces are made of VP50 steel, and the analyzed output parameters include surface roughness (Ra), with confocal microscopy used on the workpiece surface, roundness error, diametrical wheel wear, and cost and pollution analysis.*

PALAVRAS-CHAVES: *Grinding wheel;. VP50IM. Al_2O_3; Mold steel; Grinding cost; Grinding Pollution.*

1. INTRODUCTION

Grinding is widely used due to its ability to produce components with high-quality surface finishes, excellent geometric precision, and low surface roughness (MALKIN; GUO, 2007). As the final production step, grinding adds high value, and its effectiveness is crucial to avoid significant economic losses (ROWE, 2014). Linke (2015) highlighted that 36% of the abrasives market stems from grinding wheels, generating 4 billion Euros annually.

Eco-efficiency in machining aims to achieve productivity with minimal environmental impact, balancing technological, environmental, and economic factors. Key elements in this process are grinding wheels, cutting fluids, and machining tools, each requiring optimization.

Grinding wheels, the costliest component, are made of abrasive grains like silicon carbide and aluminum oxide, held together by a binder and pores for chip removal. These wheels are undefined geometry tools due to the irregular shapes of the grains (LOPES et al., 2020a, 2020b; MALKIN; GUO, 2008). The development of advanced materials impacts the final quality of workpieces, with global plastic production reaching nearly 360 million tons in 2018 (PLASTICS EUROPE., 2019).

In mold manufacturing for thermoplastics, components must be ground for high machinability and resistance to high-pressure oxidation (OHMORI et al., 2008). Poor grinding quality affects fatigue resistance by inducing residual stress. VP50 steel, essential in precision industries, lacks comprehensive grinding studies, necessitating research into new lubrication-cooling techniques for clean production.

During grinding, abrasive grains remove material through contact, causing elastic and plastic deformations, increasing temperature at the part-tool interface, and leading to structural changes and wheel wear (LOPES et al., 2019b, 2020a; SATO et al., 2019). Effective lubrication-cooling techniques are crucial to maintaining process integrity.

However, cutting fluids contain chemicals that ensure stability and viscosity but are harmful to the environment and operator health (LAWAL; CHOUDHURY; NUKMAN, 2013). Disposal costs are significant, ranging from 28 to 56 US$/m³, and fluids require specific treatments before discarding .

New techniques like cryogenic fluids, nanofluids, and minimum quantity lubrication (MQL) aim to reduce cutting fluid usage. Cryogenic fluids use extremely low temperatures to minimize thermal damage and enhance productivity (JAWAHIR et al., 2016). Nanofluids improve thermal conductivity, and MQL reduces fluid consumption, lowering costs and CO2 emissions (MORETTI et al., 2020).

MQL uses a small volume of fluid mixed with compressed air, significantly reducing storage and application costs. It forms a lubricant film with minimal heat generation due to reduced friction. Despite MQL's efficiency, only 5-40% of cutting fluid reaches the cutting zone during flood methods, while MQL's atomized oil achieves better penetration.

MQL in grinding AISI 4340 steels with a CBN wheel performed worse than conventional methods due to insufficient heat removal, though it achieved acceptable surface roughness and roundness error. (MORETTI et al., 2021) noted that while MQL reduced costs in cylindrical grinding of VP50 steel, the conventional method performed better at high feed rates.

Wheel cleaning jet systems (WCJ) can address wheel clogging by applying compressed air to the wheel surface, enhancing abrasive grain activation and reducing wheel wear (BIANCHI et al., 2018c). Studies show MQL+WCJ can provide results comparable to conventional methods, especially with optimized air jet angles (LOPES et al., 2019a; Oliveira et al., 2012).

This study compares alumina grinding wheels using conventional lubrication-cooling methods with MQL, with and without WCJ, focusing on VP50 steel. Parameters analyzed include surface roughness, roundness error, wheel wear, and cost and pollution analysis.

2. EXPERIMENTAL PROCEDURE

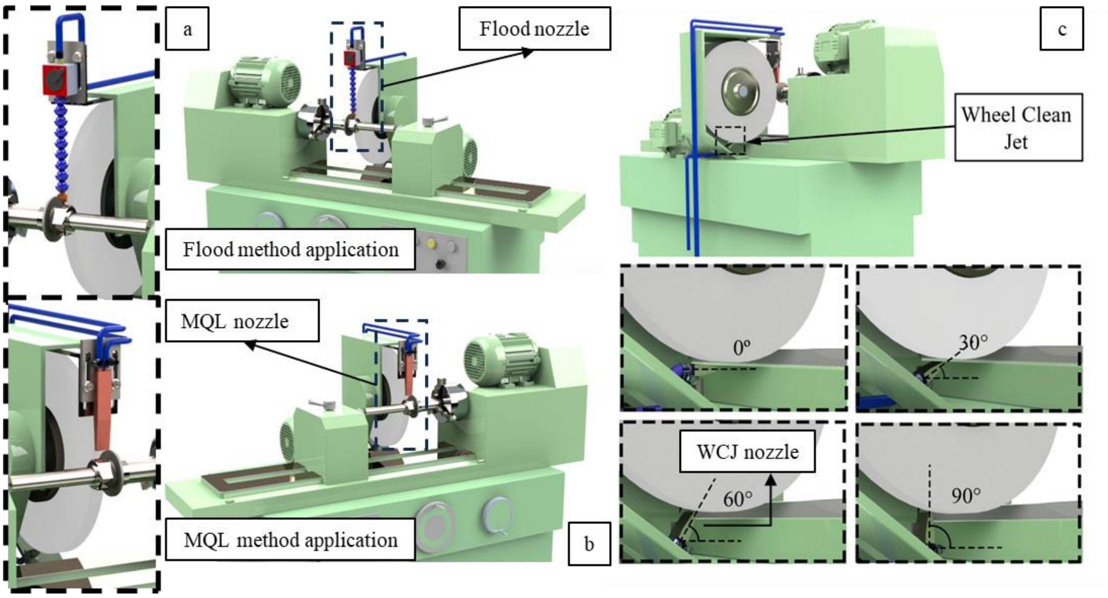
The execution of the experimental procedures took place on a plunge cylindrical grinder manufactured by Sulmecânica Company, model RUAP515H, assisted by Computer Numerical Control (CNC) Fagor. The grinding wheel used is composed of white aluminum oxide (Al_2O_3) grains and a vitrified bond of medium hardness, model AA 60L7V201, produced by ABRASIPA company. The tooling has an annular shape with an outer diameter of 350 mm, inner diameter of 127.45 mm, and thickness of 25 mm.

The workpieces were fabricated from VP50IM steel. The material was supplied by Villares Metals S.A. and machined in an annular shape with an outer diameter of 75 ± 0.1 mm, inner diameter of 30 ± 0.1 mm, and thickness of 4 ± 0.1 mm.

For the dressing operation, a cluster of multigrain diamonds produced by Master Diamond was used, with dimensions of 15 mm in length and 8 mm in width. The total superficial layer removed from the grinding wheel in the dressing process was 200 µm, divided equally into 50 passes of 4 µm depth each, all at a standardized dressing speed of 500 mm/min and a tool tangential speed of 31.5 m/s. The setup for the method can be observed in Figure 1(a).

The equipment used for applying the flood method consists of a fluid reservoir, a turbine-type flow meter, hoses, a centrifugal pump, ball valves, and an application nozzle. The Rocol 4847 Ultracut 370 semi-synthetic fluid applied in the method was emulsified in water at a concentration of 5% (1:20), with the addition of corrosion inhibitors, biocides, fungicides, alkalizing agents, and antifoaming agents. The mixture was dispensed at low pressure in the cutting region at a flow rate of 17 L/min, utilizing a circulatory reuse system, with continuous maintenance and control of the lubricating and cooling fluid properties.

FIGURE 1 - (a) Flood application system (b) MQL application system (C) WCJ application system.



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The MQL system includes an air compressor, pressure regulator, and ITW Accu-Lube 79053D atomizer using Biocut 9000 biodegradable oil. Air and oil are conveyed separately until atomization at the nozzle, then released at the grinding wheel's tangential speed with 8 bar pressure and 20 ml/h flow rate. Compressed air flow is measured with a turbine meter calibrated for 8 kgf/cm².

The Wheel Cleaning Jet system uses a compressor with 8 l/s flow rate and 8 bar pressure, directing air to the grinding wheel's surface. Nozzle angles of 0°, 30°, 60°, and 90° were tested. Setup details are shown in Figure 1(b) and 1(c).

Furthermore, with a primary focus on advancing scientific knowledge surrounding the grinding process of VP50IM steel using sustainable, safe, and alternative methods to flood application. In this regard, comparisons were conducted among Flood, MQL, and MQL+WCJ with various positions, considering the following procedures for measuring output parameters:

Surface roughness measurements were conducted using the arithmetic mean standard (Ra) with a surface roughness tester produced by Taylor Hobson, model Surtronic 3+, equipped with a Gaussian filter, cutoff length of 0.25mm, total length of 1.25mm, and a pen-type probe with a radius of 2µm. The result was obtained by averaging 15 measurements taken at equidistant intervals (24°) between each measurement.

The roundness error was assessed using a circularity measuring instrument manufactured by Taylor Hobson, model Talyrond 31C, employing the Least Square Circle (LSCI) filter. The measurement frequency was set at 3600 points around the circumference with a precision of 0.02 µm. Measurements were taken at three different points across the thickness of the workpiece, enabling the calculation of the mean values obtained.

Diametral wheel wear was measured indirectly. A Ø 35 mm x 120 mm AISI 1020 steel cylinder (90 HRB) was ground with the experimental wheel before each dressing. Two specimens were machined at intervals, creating grooves on the cylinder. Using a roughness tester and TalyMap ultra-Gold software, groove depth and width were measured to calculate the worn material volume based on the radius difference.

The cost estimation for the implementation of each technique was conducted based on the calculations provided by Equations (1)-(4) by (FIELD, KEGG AND BUESCHER, 1980), (PUSAVEC *et al.*, 2010) and adapted by (LOPES *et al.*, 2021).

$$C_{wheel} = \frac{C_s * V}{G} + \frac{\pi * b_s * C_s}{N_d} * \left(d_s * a_d - a_d^2\right) \quad (1)$$

$$C_{fluid} = \frac{v_{jet} * a_e}{N_c * v_w} * \left(C_f + C_w\right) \quad (2)$$

$$C_{energy} = \frac{(P_c + P_{bo} + P_{air}) * C_e}{60000} * \left(\frac{2 * R}{r} + \frac{a_e}{v_w} + t_{so}\right) \quad (3)$$

$$C_{method} = C_{time} + C_{wheel} + C_{fluid} + C_{energy} \quad (4)$$

The analysis of pollution as well as the estimation of carbon emissions during the grinding process were calculated based on the fluid used and the energy consumption (cutting, compressed air, and recirculating system) and equations (5)-(7).

$$CE_{energy} = \frac{(P_c + P_{bo} + P_{air}) * CE_e * 3,6}{60000} * \left(\frac{2R}{r} + \frac{a_e}{v_w} + t_{so}\right) \quad (5)$$

$$CE_{fluid} = \frac{V_{jet} * k_p * CE_{oil} \cdot}{N_c} * \left(\frac{2R}{r} + \frac{a_e}{v_w} + t_{so}\right) \quad (6)$$

$$CE_{method} = CE_{fluid} + CE_{energy} \quad (7)$$

Finally, scanning electron microscopy of the tool surface was conducted using a microscope model EVOLS15, manufactured by Carl Zeiss. The images were generated with a magnification of 50X.

3. RESULTS AND DISCUSSIONS

3.1 Surface roughness (Ra)

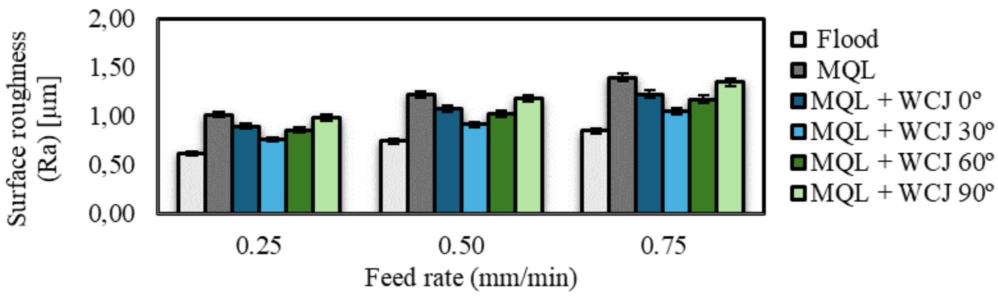
The grinding process is usually implemented towards the conclusion of product manufacturing, given its capacity to ensure dimensional, shape, and finishing tolerances. When considering finishing tolerance, surface roughness stands as the most pertinent parameter for assessment. Hence, comprehending the component's behavior concerning surface roughness becomes imperative in evaluating the grinding process comprehensively within a scientific context (LOPES et al., 2023b).

Some factors influencing roughness include the friction coefficient, abrasive type, lubrication, thermal conductivity, and the mechanical resistance of the workpiece. Thus, all input parameters that could influence final roughness values were kept constant, except for lubrication, as six different methods were compared in this study. Hence, the differing results are solely attributed to the lubrication methods applied in the process.

The Figure 2 displays the surface roughness results for each studied machining condition.

Primarily, it is noticeable that an increase in the feed rate leads to a degradation in surface roughness results. This is attributed to the heightened severity of the process. With an augmented feed rate, there is an increase in the equivalent chip thickness, resulting in elevated forces and temperatures during the process. The impact of this change manifests in the surface roughness. The same trend was observed in the work of (TALON et al., 2020), where the authors found that an increase in feed rate led to higher surface roughness during the machining of AISI 4340 steel. Similarly, (RIBEIRO et al., 2020) reported a similar trend in interrupted cutting studies using resinoid and vitrified bonded grinding wheels. Furthermore, (TALON et al., 2021) obtained similar results while grinding steel with CBN wheels of varying friabilities.

FIGURE 2 - Surface roughness for each machining condition.



Source: Author himself

On the other hand, when comparing flood method with MQL, it is evident that MQL exhibited, on average, values 65% higher than the conventional technique. This can be attributed to the cooling capacity of the flood method and its excellent chip removal capability. (LOPES et al., 2023b) obtained similar results when studying the influence of water dilution in MQL. Regardless of the dilution, the authors concluded that MQL is not capable of cooling as effectively as the conventional method, and the temperature increase in the process is responsible for higher values of surface roughness.

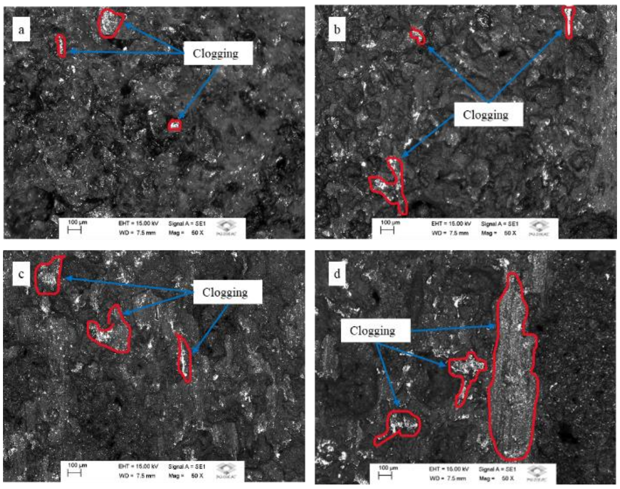
Complementary to this, (TALON et al., 2022) observed that MQL showed higher roughness values across four different feed rates compared to the flood method. However, the authors reinforced that MQL should still be considered in processes due to its lower costs and reduced CO_2 emissions. (ÁVILA et al., 2023) attributed this behavior of MQL compared to the traditional method to the low cooling power of MQL, which can lead to temperature increases, deformations, and clogging.

On the other hand, the Wheel Cleaning Jet (WCJ) ensured better results than MQL across all cleaning angles. It is evident that wheel cleanliness is a crucial factor in ensuring an increase in MQL efficiency. This is attributed to the chip removal capability of the WCJ, which prevents the clogging phenomenon. (JAVARONI et al., 2020) observed that the WCJ, by reducing clogging, ensured the maintenance of a higher number of active grains on the wheel. Consequently, the wheel's cutting ability was preserved, preventing an increase in plastic deformations on the workpiece.

Comparing WCJ angles, Figure 4 shows that a 30° angle is the most efficient, achieving 24.6% better surface roughness than the conventional technique and 60% better than the flood coolant technique. The 30° angle effectively breaks the aerodynamic barrier around the wheel, while normal angles (60° and 90°) fail to remove significant amounts of chips. According to (LOPES et al., 2023a), depending on the angle, the combination of the aerodynamic barrier and overall turbulence caused by the WCJ can detrimentally impact surface roughness. Therefore, the MQL + WCJ at a 30° angle was the technique that came closest to the conventional method.

Figure 3 displays electron microscopy images of the grinding wheel surface for each tested WCJ angle. The images confirm that the clogging phenomenon is less prevalent at a 30º angle. At 0º and 90º angles, a higher accumulation of material on the tool surface is observed.

FIGURE 3 - Electron Microscopy: (a) MQL + WCJ 30º (b) MQL + WCJ 60º (c) MQL + WCJ 90º (d) MQL + WCJ 0º.



Source: Author himself

Correlating this effect with surface quality reveals that heightened clogging results in the normalization of the grinding wheel surface, increasing the contact area and consequently, friction. This leads to a loss in the tool's cutting efficiency, temperature elevation, and a decrease in the surface quality of machined parts.

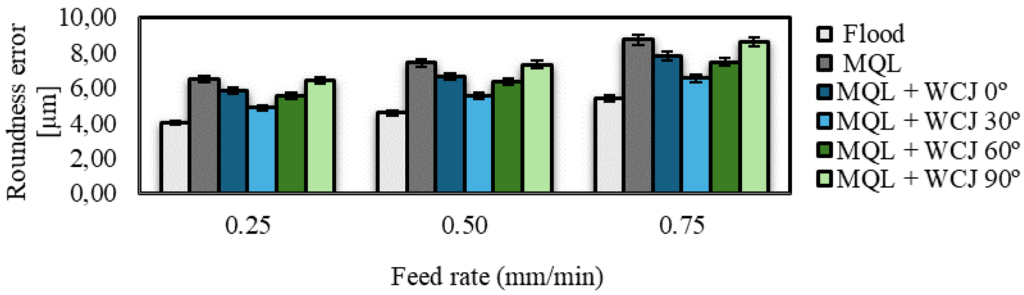
3.2 Roundness error

Figure 4 shows the average roundness error for each tested condition. Grinding generates significant heat, making temperature management crucial for maintaining geometric and dimensional precision by controlling workpiece thermal expansion (MALKIN; GUO, 2008; SILVA et al., 2020). Cutting fluids are essential for heat removal to prevent distortions.

Reduced fluid flow decreases heat transfer efficiency, impairing heat dissipation. Additionally, surface variations on the grinding wheel due to clogging, exacerbated by high temperatures, significantly impact roundness error results.

With a lower conventional heat transfer coefficient, the cooling ability of the MQL method is not enough for the grinding process, and 46% of the heat partition stays in the workpiece. This provides high values of roundness error, increasing by 62% when compared with the conventional method with 0,75 mm/min of feed rate.

FIGURE 4 - Roundness error for each machining condition.



Source: Author himself

The WCJ system improved the process, reducing roundness error by 25% at a feed rate with a 30° nozzle angle, the most effective angle tested. A 0° angle only marginally affects the abrasive layer, while 60° and 90° angles push against the pores and grains, increasing adhesion. The 30° angle allows the jet to penetrate efficiently between the abrasive layer and adhered chips, clearing the pores.

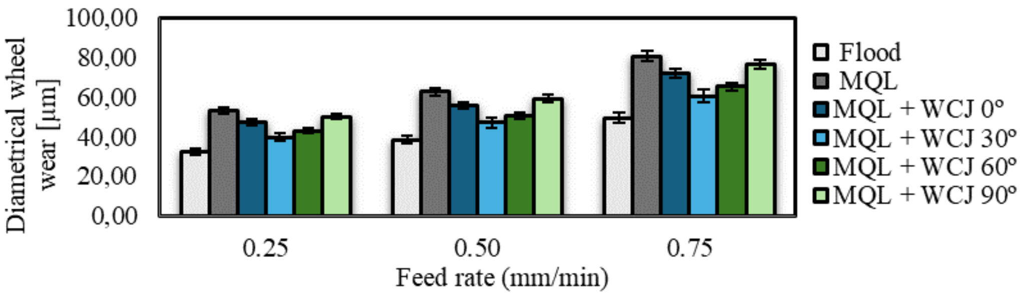
As a result, a reduction of the clogging phenomenon contributes to keep the grinding wheel sharp, which reduces the energy necessary to shear the material. Following this way, the heat generation during the process gets lower, and, therefore, the distortions of the workpiece, that increase of roundness error, are minimized.

According to (BIANCHI et al., 2018), The variation in oil flow in the MQL technique can positively influence the machining of AISI 4340 steel. In his study, the author analyzes three different flow rates for MQL+WCJ techniques, finding similar results where the MQL+WCJ technique can produce surfaces with quality and shapes within acceptable tolerances. This demonstrates the potential for substituting conventional methods.

3.3 Diametral wheel wear

According to (LOPES et al., 2023a), the cost of the grinding wheel can represent 10% of the total production cost. Therefore, evaluating tool wear is necessary to reduce process costs. Figure 5 presents the data on the diametrical wheel wear for each studied condition.

FIGURE 5 - Diametrical wheel wear for each machining condition.



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Lubrication has a strong influence on grinding wheel wear. Increasing lubrication reduces friction between the wheel, workpiece, and chips. Consequently, there is a decrease in grain wear, preserving cutting edges for a longer period. Preserving the grinding wheel's cutting capacity facilitates the smoother cutting of the workpiece material, leading to a reduction in cutting forces and subsequently minimizing the occurrence of grain pull-out. Employing an efficient lubrication-cooling method for the cutting area ensures the integrity of the grinding wheel's bonding, thereby securing the firm attachment of abrasive grains to the wheel for an extended duration. This sustained bond strength significantly enhances the wheel's resilience and efficacy in removing material during grinding operations (LOPES et al., 2023a); The main wear mechanisms of the grinding wheel include the loss of abrasive grains, which can occur due to partial grain breakage (macrofracture) or complete detachment caused by bond fracture, alongside the wear of the cutting edge due to friction with the workpiece during machining (microfracture) (LOPES et al., 2023b).

Therefore, cooling and lubrication influence the grinding wheel's wear rate, as temperature and friction are detrimental to the tool. In this regard, observing Figure 5 makes it evident that an increase in the feed rate leads to higher wear due to the increased severity of the process. Moreover, it's noticeable that the flood coolant technique exhibited the lowest grinding wheel wear rates. This outcome is a result of the smaller volume of cutting fluid used in MQL (LOPES et al., 2023b).

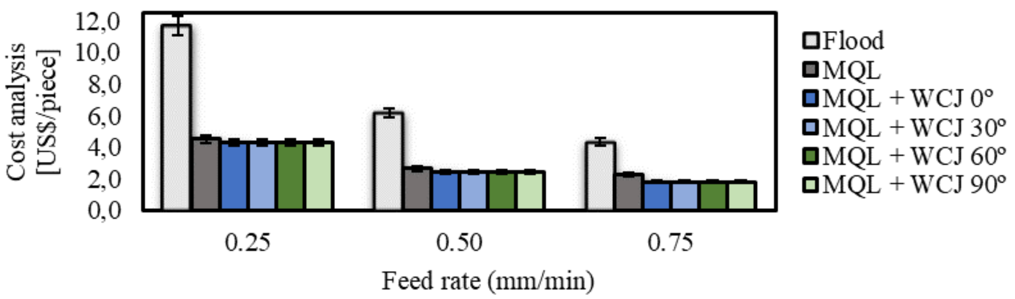
However, when applying the WCJ to MQL, the results became closer to those of the conventional method. Excluding the conventional technique, the MQL + WCJ at a 30° angle was the best-performing technique, achieving results approximately 22% higher than the flood coolant technique. In your research (LOPES et al., 2023a) obtained similar results in the machining of AISI 4340 steel. The authors reported that the WCJ assisted MQL in reducing grinding wheel wear by minimizing clogging and, consequently, reducing machining forces and temperature. The authors further concluded that the 30° angle proved to be the most effective for WCJ application, allowing for the highest level of debris removal from the grinding wheel. Additionally, (JAVARONI et al., 2020) stated that clogging blocks the pores of the grinding wheel, leading to reduced cutting ability. Consequently, temperature rises, increasing plastic deformations in the workpiece, which further contributes to clogging. Hence, it becomes a challenging cycle to break. In this context, WCJ aids in maintaining the grinding wheel's cutting ability and regulating temperature during the process, thereby reducing tool wear.

3.4 Cost and Pollution analysis

Global warming concerns are evident in industry, with rising surface temperatures. High initial costs for sustainable technologies hinder their adoption. Studies are crucial to compare costs, benefits, and environmental impacts of alternative versus conventional methods. Accurate analyses regarding implementation costs for lubrirecooling methods are still scarce. Therefore, Figure 6 presents cost estimates based on equations (2)-(5). Each displayed value comprises three components: fluid cost, grinding wheel cost, and energy cost.

According to Figure 6, costs decrease as feed rates increase. At a feed rate of 0.75, costs are 50% lower than at 0.25. Time costs for MQL and MQL+WCJ methods represent 77%, 68%, and 61% of total costs at feed rates of 0.25, 0.50, and 0.75, respectively.

FIGURE 6 - Cost analysis for each machining condition.



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Furthermore, the consistency of costs across variations in the angle of incidence for the auxiliary cleaning system is noteworthy. The cost behavior differs from that observed for other parameters, such as surface roughness and roundness error, where the advantages of deploying the cleaning system at a 30º angle relative to the grinding wheel surface are evident.

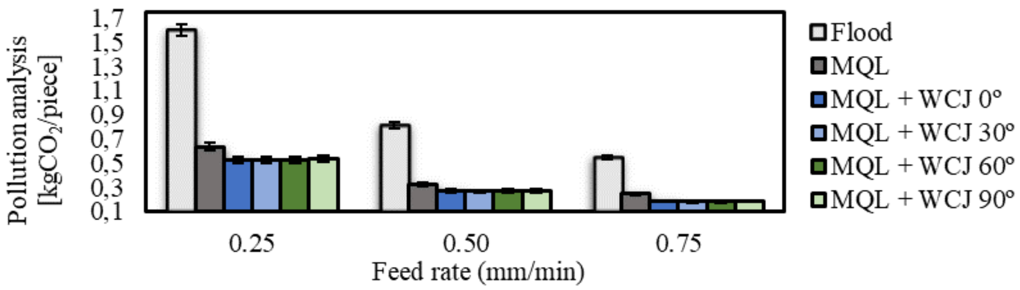
While there is no significant variation among the different angles of the WCJ system, the cost reduction of MQL methods compared to conventional ones averages 60 percentage points. This reduction is significant due to the decrease in the amount of oil used. In conventional methods, fluids account for 61% of total costs, whereas in alternative methods, this proportion drops to 5.5%.

On the other hand, the behavior also differs from the results obtained by (LOPES et al., 2023a). In this study, the authors compared implementation costs for alternative methods such as MQL+WCJ, also varying the angle of incidence. However, the researchers investigated the grinding of advanced ceramics with a diamond wheel, concluding that, among the possible angle variations, the 30º option showed greater efficiency due to its increased ability to remove chips lodged on the grinding wheel surface.

According to (BIANCHI et al., 2018) improved chip removal efficiency delays the Clogging phenomenon, which is directly related to the level of the achieved G ratio in the process and consequently to the implementation cost of the method.

Concerning the assessment of environmental impacts, Figure 7 illustrates the amount of carbon in kilograms emitted for each tested machining condition. The values are calculated based on equations (6)-(8).

FIGURE 7 - Pollution Analysis for each machining condition



Source: Author himself

The behavior is like the found costs; the amount of emitted carbon is inversely proportional to the feed rate used, due to the reduction in machining time. The MQL+WCJ techniques show little variation among themselves; however, they reduce the emitted carbon by 67% when compared to the conventional method. This reduction is a result of the low amount of fluid needed in the process and the chemicals used for quality control in the Flood method, such as fungicides and bactericides.

Thus, it can be concluded that the use of the MQL+WCJ method makes the field of industrial production more sustainable. This aligns with results found by (SATO et al., 2022) who compared different grinding wheel compositions in steel grinding. They concluded that the use of MQL+WCJ presents a possibility for industrial transformation, envisioning an eco-friendly industry. Moreover, it generates a more profitable process due to the cost reductions presented.

4. CONCLUSION

The results and analysis of the experiments allow the following conclusions:

- In conclusion, the analysis reveals that a 30° angle for the Wheel Cleaning Jet (WCJ) is the most efficient, resulting in 24.6% lower surface roughness than the conventional technique. The 90° angle, in contrast, showed a 60% increase compared to the flood coolant method. The 30° angle's efficiency is attributed to its superior ability to break the aerodynamic barrier around the wheel during rotation.

- The WCJ system positively influenced the process, achieving a 25% reduction in roundness error at the specified feed rate and with a nozzle angle of 30° identified as the optimal angle among those tested.

- WCJ contributes to preserving the grinding wheel's cutting effectiveness and controlling temperature during the process, ultimately minimizing tool wear.

- Although there is little variation among the different angles of the WCJ system, the MQL methods demonstrate a notable cost reduction averaging 60% compared to conventional ones.

- The MQL+WCJ techniques show little variation among themselves; however, they reduce the emitted carbon by 67% when compared to the conventional method.

REFERÊNCIAS

ÁVILA, B. N. et al. Grinding effect of thermoplastic mold steel using green manufacturing concepts combined with various conventional wheels. **International Journal of Advanced Manufacturing Technology**, v. 129, n. 5, p. 2443–2456, 1 nov. 2023.

BIANCHI, E. C. et al. Plunge cylindrical grinding with the minimum quantity lubrication coolant technique assisted with wheel cleaning system. **The International Journal of Advanced Manufacturing Technology**, v. 95, n. 5–8, p. 2907–2916, 1 mar. 2018a.

BIANCHI, E. C. et al. Plunge cylindrical grinding with the minimum quantity lubrication coolant technique assisted with wheel cleaning system. **The International Journal of Advanced Manufacturing Technology**, v. 95, n. 5–8, p. 2907–2916, 1 mar. 2018b.

BIANCHI, E. C. et al. Evaluating the effect of the compressed air wheel cleaning in grinding the AISI 4340 steel with CBN and MQL with water. **The International Journal of Advanced Manufacturing Technology**, v. 95, n. 5–8, p. 2855–2864, 30 mar. 2018c.

DA SILVA, A. E. et al. Behavior of austempered ductile iron (ADI) grinding using different MQL dilutions and CBN wheels with low and high friability. **The International Journal of Advanced Manufacturing Technology**, v. 107, n. 11–12, p. 4373–4387, 27 abr. 2020.

DANISH, M. et al. Machinability investigations on CFRP composites: a comparison between sustainable cooling conditions. **The International Journal of Advanced Manufacturing Technology**, v. 114, n. 11, p. 3201–3216, 2021.

DAVIM, J. P. **Machining: Fundamentals and Recent Advances**. [s.l.] Springer Science & Business Media, 2008.

DEBNATH, S.; REDDY, M. M.; YI, Q. S. Influence of cutting fluid conditions and cutting parameters on surface roughness and tool wear in turning process using Taguchi method. **Measurement**, v. 78, p. 111–119, jan. 2016.

FIELD, M.; KEGG, R.; BUESCHER, S. Computerized Cost Analysis of Grinding Operations. **CIRP Annals**, v. 29, n. 1, p. 233–237, 1 jan. 1980.

HADAD, M. J. et al. **An investigation on surface grinding of AISI 4140 hardened steel using minimum quantity lubrication-MQL technique**. **International Journal of Material Forming**, 2010.

JAVARONI, R. L. et al. Improvement in the grinding process using the MQL technique with cooled wheel cleaning jet. **Tribology International**, v. 152, p. 106512, 4 dez. 2020.

JAWAHIR, I. S. et al. Cryogenic manufacturing processes. **CIRP Annals - Manufacturing Technology**, v. 65, n. 2, p. 713–736, 2016.

LAWAL, S. A.; CHOUDHURY, I. A.; NUKMAN, Y. **A critical assessment of lubrication techniques in machining processes: A case for minimum quantity lubrication using vegetable oil-based lubricant**. **Journal of Cleaner Production**, 2013.

LINKE, B. S. Review on Grinding Tool Wear With Regard to Sustainability. **Journal of Manufacturing Science and Engineering**, v. 137, n. 6, 1 dez. 2015.

LOPES, J. C. et al. Application of a wheel cleaning system during grinding of alumina with minimum quantity lubrication. **The International Journal of Advanced Manufacturing Technology**, v. 102, n. 1–4, p. 333–341, 3 maio 2019a.

LOPES, J. C. et al. Effect of CBN grain friability in hardened steel plunge grinding. **The International Journal of Advanced Manufacturing Technology**, v. 103, n. 1–4, p. 1567–1577, 7 jul. 2019b.

LOPES, J. C. et al. Behavior of hardened steel grinding using MQL under cold air and MQL CBN wheel cleaning. **The International Journal of Advanced Manufacturing Technology**, v. 105, n. 10, p. 4373–4387, 14 dez. 2019c.

LOPES, J. C. et al. Performance of austempered ductile iron (ADI) grinding using diluted oil in MQL combined with wheel cleaning jet and different CBN grains friability. **International Journal of Advanced Manufacturing Technology**, v. 107, n. 3–4, p. 1805 – 1818, 2020a.

LOPES, J. C. et al. Application of MQL technique using TiO2 nanoparticles compared to MQL simultaneous to the grinding wheel cleaning jet. **The International Journal of Advanced Manufacturing Technology**, v. 106, n. 5–6, p. 2205–2218, 17 jan. 2020b.

LOPES, J. C. et al. Grinding comparative analysis between different proportions of water-oil applied to MQL technique and industrial production cost towards a green manufacturing. **The International Journal of Advanced Manufacturing Technology**, 2021.

LOPES, J. C. et al. Sustainable thinking toward to industry's future combined with new knowledge on greenhouse effect mitigation generated by the grinding process. **Journal of Cleaner Production**, v. 386, 2023a.

LOPES, J. C. et al. An experimental evaluation between pure and diluted MQL versus flood lubri-cooling focused on cost and environmental impact. **International Journal of Advanced Manufacturing Technology**, 1 nov. 2023b.

MALKIN, S.; GUO, C. Thermal Analysis of Grinding. **CIRP Annals - Manufacturing Technology**, v. 56, n. 2, p. 760–782, 2007.

MALKIN, S.; GUO, C. **Grinding Technology: Theory and Applications of Machining with Abrasives**. 2ªed ed. New York: Industrial Press Inc, 2008.

MORETTI, G. B. et al. Grinding behavior of austempered ductile iron: a study about the effect of pure and diluted MQL technique applying different friability wheels. **The International Journal of Advanced Manufacturing Technology**, v. 108, n. 11–12, p. 3661–3673, 23 jun. 2020.

MORETTI, G. B. et al. Industrial manufacturing linked to the mechanical and economic viewpoint of the mold steel grinding process using aluminum oxide wheel. **International Journal of Advanced Manufacturing Technology**, v. 117, n. 9–10, p. 2655–2666, 2021.

NOVOSELOV, YU.; BRATAN, S.; BOGUTSKY, V. Analysis of Relation between Grinding Wheel Wear and Abrasive Grains Wear. **Procedia Engineering**, v. 150, p. 809–814, 2016.

OHMORI, H. et al. Functionalization of stainless steel surface through mirror-quality finish grinding. **CIRP Annals**, v. 57, n. 1, p. 545–549, 2008.

OLIVEIRA, D. DE J. et al. Improving minimum quantity lubrication in CBN grinding using compressed air wheel cleaning. **Journal of Materials Processing Technology**, v. 212, n. 12, p. 2559–2568, 2012.

PLASTICS EUROPE. **PLASTICS-THE FACTS. An analysis of European plastics production, demand and waste data.** [s.l: s.n.].

PUSAVEC, F. et al. Transitioning to sustainable production – part II: evaluation of sustainable machining technologies. **Journal of Cleaner Production**, v. 18, n. 12, p. 1211–1221, 1 ago. 2010.

RIBEIRO, F. S. F. et al. Comparative analysis between resinoid and vitrified bond grinding wheel under interrupted cutting. **The International Journal of Advanced Manufacturing Technology**, v. 109, n. 1–2, p. 75–85, 30 jul. 2020.

RODRIGUEZ, R. L. et al. Application of hybrid eco-friendly MQL+WCJ technique in AISI 4340 steel grinding for cleaner and greener production. **Journal of Cleaner Production**, p. 124670, out. 2020.

ROWE, W. B. **Principles of Modern Grinding Technology**. [s.l.] Elsevier, 2014.

SATO, B. K. et al. Grinding performance of AISI D6 steel using CBN wheel vitrified and resinoid bonded. **The International Journal of Advanced Manufacturing Technology**, v. 105, n. 5–6, p. 2167–2182, 21 dez. 2019.

SATO, B. K. et al. Novel comparison concept between CBN and Al2O3 grinding process for eco-friendly production. **Journal of Cleaner Production**, v. 330, n. September 2021, p. 129673, jan. 2022.

SILVA, L. R. et al. Environmentally friendly manufacturing: Behavior analysis of minimum quantity of lubricant - MQL in grinding process. **Journal of Cleaner Production**, v. 256, p. 103287, maio 2020.

TALON, A. G. et al. Grinding performance of hardened steel: a study about the application of different cutting fluids with corrosion inhibitor. **The International Journal of Advanced Manufacturing Technology**, v. 108, n. 9–10, p. 2741–2754, 13 jun. 2020.

TALON, A. G. et al. Comparative evaluation of CBN wheels with abrasive grains of different friability applied to steel and ductile iron grinding process. **The International Journal of Advanced Manufacturing Technology**, 7 jan. 2021.

TALON, A. G. et al. Green manufacturing concept applied to the grinding process of advanced ceramics using an alternative lubri-refrigeration technique. **The International Journal of Advanced Manufacturing Technology**, v. 123, n. 7, p. 2771–2782, 2022.

TAWAKOLI, T. et al. An experimental investigation of the effects of workpiece and grinding parameters on minimum quantity lubrication-MQL grinding. **International Journal of Machine Tools and Manufacture**, v. 49, n. 12–13, p. 924–932, out. 2009.