

Elevated ZnO Concentrations as a Trade-Off Strategy to Decrease Spindle Speeds in Face Milling

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ABSTRACT

Higher productivity, lower cost, environmental requirement and occupational health have become serious challenges for manufacturing industries nowadays. In this study, a mixture comprising canola oil, emulsifier and ZnO nanoparticles was applied as the cutting oil for face milling of stainless steel SS316L. Previous studies have demonstrated decreasing surface roughness with increasing spindle speed. Numerous previous studies have also revealed decreasing surface roughness with increasing ZnO concentrations. However, a relationship between elevated ZnO concentrations and reduced spindle speeds has barely been addressed. Building on this circumstance, a novel machining strategy was proposed in this study by employing elevated ZnO concentrations as a trade-off strategy to reduce the spindle speeds. The spindle speeds in this study were 1500, 1800 and 2100 rpm. The experiment demonstrated that elevating ZnO concentrations from 1.0 to 4.0 wt% could be used to decrease the spindle speeds from 2100 to 1800 rpm while maintaining acceptable surface roughness. Although future studies are warranted, reducing spindle speed is beneficial for manufacturing industries as it may contribute to lower electrical energy consumption. Furthermore, the proposed trade-off strategy can also be implemented for manufacturing industries located in regions with limited electrical grid capacity, for example, due to restricted capacity of electrical transformers.

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INTRODUCTION

A computer numerical control (CNC) based face milling operation has been widely used in modern manufacturing as it provides high precision, sound surface properties, and flexibility for producing products with high-complexity geometries. Challenges, however, remain for face milling. The use of mineral cutting oil (MCO) has been associated with adverse environmental effects [1]–[3]. Additionally, several studies reported adverse health effects to machine operators due to prolonged

exposure to the MCO [4]–[6]. The use of MCO for components intended for food and beverage, pharmaceutical and medical equipment may present additional challenges, as residual MCO used during the machining can remain adhered to the surface of machined components, thereby increasing the risk of product contamination. To address this issue, the machined components are cleaned which consequently add the manufacturing step and cost. Therefore, the use of bio cutting oil (BCO) can minimize the risk of product contamination by hazardous MCO, which can reduce the cleaning step.

This study focused on the surface roughness of face-milled products, as it is an important property of machined products. Surface roughness influences the energy lost due to friction, which shortens the service life of moving components [7]. In addition, surface roughness also influences light reflection and absorption [8], thermal conductivity particularly when a wide gap exists due to high surface roughness [9], coating quality [10], phase transformation [11], fatigue strength [12], creep strength [13], corrosion resistance [14], sensor accuracy [15], lubrication performance [16], friction and wear for moving parts [17], wettability [18], adhesion [19], erosion characteristic [20], emissivity [21], vibration [22], electrical resistance [23], turbulency in fluid flow [24] and aerodynamics performance [25],[26].

To address these challenges, BCO is offered. The BCO is relatively environmentally friendly and carbon-friendly as it is made of vegetable oils. Subsequently, its use also reduces adverse health effects to operators. Maneedaeng *et al.* [27] and Gasni *et al.* [28] demonstrated that fatty acids in vegetable oils enhanced the lubrication performance of BCO, which subsequently reduced friction at the cutting tool-workpiece-chips interface and reduced adhesive wear on the surface of the cutting tool. The reduced friction subsequently decreased the cutting force during machining, thereby minimizing vibration and surface roughness [29]. Tiwari and Amarnath [30] reported a 14–17% reduction in cutting tool wear after replacing the MCO with coconut-oil-based BCO. Elewaa *et al.* [31] demonstrated a 21% reduction in surface roughness when the MCO was replaced with olive oil. Lower surface roughness can reduce the effort required for subsequent finishing operations after the face milling process, e.g. polishing and honing. Gunjal and Sana [32] reported that the use of BCO generated thinner machining chips, which can be easily removed. As a result, enhanced cutting stability and reduced vibration could be achieved. Nevertheless, the tribological performance of pure vegetable oil requires further improvement as several products demand very low surface roughness under acceptable spindle speeds and feed rates.

Several studies have been dedicated to investigating the effect of nanoparticles addition on the surface roughness of machined products. Various types of nanoparticles have been added to the BCO, e.g. carbon nanotube (CNT), alumina (Al_2O_3), molybdenum disulfide (MoS_2), copper oxide (CuO), and zinc oxide (ZnO). Among wide range of those additives, this study employed ZnO as it exhibited high chemical stability and low flammability [33]. ZnO is widely used as a supplement in cosmetic products, beverages, milk products and foods attributed to its non-toxicity to humans. Accordingly, the addition of ZnO to the BCO is considered to present any adverse health effects for the operators. Oerbandono *et al.* [34] demonstrated an 18.8% reduction of the mean surface roughness (Ra) value after ZnO additions up to 1.0 wt%. They also suggested increasing the ZnO concentration to achieve a more significant decrease in surface roughness. According to Nassef *et al.* [35], the addition of 0.05 wt% ZnO to rapeseed oil significantly decreased the average surface (Ra) value by 42%. A 35% reduction in tool wear was achieved following the addition of 0.05 wt% ZnO to *Carapa guianensis* oil [36]. Unlike those previous studies which used low ZnO concentrations (≤ 1.5 wt%), the novelty in this study lies in the use of elevated ZnO concentrations up to 4.0 wt%. Accordingly, a novel process optimization strategy is outlined in this study by demonstrating the positive effect of elevated ZnO concentrations on reduced spindle speeds. The relationship between elevated ZnO concentrations and reduced spindle speeds could only be observed when the ZnO concentrations significantly exceeded the low ranges investigated in previous studies.

MATERIALS AND METHODS

The HAAS VF2 vertical milling machine (country of origin: USA) was used in this study (Figure 1). Zinc oxide (ZnO) nanoparticles were added to the canola oil at 0.0 to 4.0 wt% employed increments of 1.0 wt%. ZnO has a significantly higher thermal conductivity at 23.4 W/m.K (Table 1) [37]–[39], which is approximately 140 times greater than that of canola oil (0.167 W/m.K) (Table 2) [40], thereby providing increased thermal conductivity to the BCO. The specific heat of ZnO is 494 J/kg.K which is in a similar range to the specific heat of steel. Owing to its high specific heat capacity (C_p), ZnO is capable of absorbing a significant amount of heat with only a slight increase in temperature. The ZnO exhibits low hardness, which does not cause any third-body friction on the surface of SS316L workpiece used in this study. The ZnO nanoparticles used in this study had a purity of 99.0% and a size between 15 and 25 nm.

In this study, the ZnO concentrations were varied from 0.0 to 4.0 wt% employed increments of 1.0 wt%. The spindle speeds were varied at 1500, 1800 and 2100 rpm. The feed rate in this study was 350 mm/min and the depth of cut was 0.5 mm. The cutting tool used in this study was manufactured by LG Tools (country of origin: China) with a hardness of 70 HRC and a diameter of 6 mm. To maintain the experiment quality, the cutting tool was replaced after three face milling operations. Further independent and controlled variables in this study are outlined in Table 3. The minimum quantity lubrication (MQL) technique was adopted using a BCO flow rate of 400 mL/h. A magnetic stirrer was performed for 15 minutes to ensure homogeneous dispersion of ZnO nanoparticles within the canola oil as the base fluid. The BCO was sprayed directly onto the workpiece immediately after the magnetic stirring to prevent sedimentation and re-agglomeration. The specimens used were austenitic stainless steel SS316L with dimensions of 150 x 30 x 4 mm. The 4 mm specimen thickness was implemented to prevent deflection/ bending during the face milling. The specimen's composition is outlined in Table 4. According to its chemical composition, the SS316L used in this study was categorized as austenite stainless steel [41],[42].



Figure 1. The vertical milling machine HAAS VF2 used in this study

Table 1. Properties of ZnO [37]–[39]

Property	Value
Density [kg/m ³]	5600
Hardness [Mohs]	4.0 to 4.5
Melting point [°C]	1975
Specific heat [J/kg.K]	494
Thermal conductivity [W/m.K]	23.4

Table 2. Properties of canola oil at 20 °C [40]

Property	Value
Density [kg/m ³]	920.2
Viscosity [mPa.s]	93.99
Specific heat [J/kg.K]	1837
Thermal conductivity [W/m.K]	0.166

Table 3. Independent and controlled variables in this study

Variable	Value
Independent variables	
ZnO concentration	0.0 to 4.0 wt% employed 1.0 wt% increments
Spindle speed	1500, 1800 and 2100 rpm
Controlled variables	
Feed rate	325 mm/minute
Depth of cut	0.5 mm
BCO flow rate	400 mL/h
Air pressure	2.0 bar
Cutting tool	LG tools (6 mm diameter, 70 HRC hardness, 4 flutes)

Table 4. Composition of SS316L used in this study

Element	C	Mn	P	S	Si	Mo	N	Cr	Ni	Fe
	[wt%]									
Value	0.03	2.00	0.045	0.03	0.75	2.20	0.10	16.70	12.38	Bal.

The analysis of thermal conductivity of BCO was performed using the KD2 Pro Analyser (country of origin: USA) (Figure 2). The KS-1 sensor (1.3 mm diameter and 60 mm long) was employed. For each MoS₂ concentration, three repetitions of analysis were performed. For the analysis of thermal conductivity, the specimens were immersed in a controlled water bath maintained at a constant temperature of 50 °C. The viscosity test followed the ASTM D445 standard [43], which is widely employed to analyse the kinematic viscosity of bio-based oils, liquid petroleum products and lubricants. The viscosity test was performed at 80 °C. According to this standard, the kinematic viscosity was determined by measuring the duration (T) [s] required by the BCO to flow from an upper reservoir to a bottom reservoir through a glass capillary hose (Figure 3). The duration was subsequently converted into the kinematic viscosity (eq. 1) [43].

$$V = 0.0025 \times (T - 1.75/T) \quad (1)$$



Figure 2. The KD2 Pro Analyser to measure the thermal conductivity of BCO



Figure 3. Viscometer used in this study: a) Upper reservoir, b) Lower reservoir

For every combination of ZnO concentration and spindle speed, three values of Ra for each sub-specimen were obtained. Since each combination of MoS₂ concentrations and spindles speed had 3 sub-specimens, the mean value of the nine Ra measurements (3 Ra for each sub-specimen x 3 sub-specimens) was determined. For each spindle speed, there were 18 sub-specimens (3 sub-specimens for each MoS₂ concentration x 6 MoS₂ concentrations). To enhance the accuracy of surface roughness measurement, a dedicated equipment setup was adopted (Figure 4). The equipment deployed for surface roughness measurement in this study is listed in Table 5. To enhance measurement accuracy, the roughness stylus was carefully calibrated prior to the commencement of measurements.



Figure 4. Equipment setup for surface roughness measurement: 1 – Wanzel Präzision measuring stand; 2 – Waterpass; 3 – Dial height gauge; 4 – Surface roughness sensor; 5 – Visual and communication device for surface roughness sensor; 6 – Workpiece; 7 – Calibrator

Table 5. List of equipment used for surface roughness measurement in this study

Equipment	Purpose	Manufacturer
Measuring stand	Ensured proper alignment and minimized the effect of external vibration	Wanzel Präzision (country of origin: Germany)
Waterpass	Ensured a flat and parallel position between the surface roughness sensor and workpiece.	JLD tools (country of origin: China)
Dial height gauge	Maintained a perpendicular and correct distance between the sensor and the workpiece.	Mitutoyo 192 – 130 (country of origin: Japan)
Surface roughness tester	Measured the surface roughness	Mitutoyo SJ-201 (country of origin: Japan)
Surface roughness calibrator	Calibrated the surface roughness stylus sensor	Mitutoyo 178 – 602 (country of origin: Japan)

RESULT AND DISCUSSION

Result of Thermal Conductivity and Viscosity Analysis

In the beginning, the analysis of thermal conductivity was performed at 80 °C. However, the standard of deviation was high at this temperature. This circumstance could be due to the presence of convection inside the BCO which interfered the analysis of thermal conductivity. Thus, the thermal conductivity was performed at 50 °C. At this temperature, the standard of deviation was considerably low. The thermal conductivity of BCO increased with increasing ZnO concentration (Table 6). The thermal conductivity at 0.0 wt% in this study (0.174 ± 0.001 W/m.K) showed a relatively small discrepancy with the study by Rojas *et al.* (0.172 W/m.K) [40]. The thermal conductivity increased significantly when ZnO increased from 0.0 to 1.0 %wt. Thereafter, the thermal conductivity continually increased at a lower rate as the ZnO concentrations increased from 1.0 to 4.0 %wt. Li *et al.* [44] demonstrated a 10.86% increase in thermal conductivity from 0.258 to 0.283 W/m.K after the ZnO concentrations in ethylene glycol increased from 1.75 to 10.5 wt%. Nevertheless, the thermal conductivity of the mixture only slightly changed with increasing temperatures. At the temperature approximately 39 °C, Erdogan *et al.* [45] demonstrated an increase of thermal conductivity of BCO from 0.131 to 0.164 W/m.K after the addition of 0.5 vol% of ZnO nanoparticles in sunflower oil. The thermal conductivity of the mixture also increased with temperature increase. At 50 °C, the addition of ZnO nanoparticles by 0.04 mg/L increased the thermal conductivity of palm oil based BCO by 23.6% [46]. Nwoguh *et al.* [47] reported that increasing thermal conductivity after nanoparticles addition was due to increasing Brownian motion and increasing collisions of nanoparticles.

Due to the addition of the emulsifier, increasing viscosities with increasing ZnO concentrations could be prevented (Figure 5). Higher viscosity of the BCO exerts both beneficial and adverse effects on the machining process. Higher viscosity increased the load of cooling system, i.e. higher power and electrical energy consumption for the pump in the flood cooling system or the compressor in the MQL system. Meanwhile, highly viscous BCO also caused ineffective lubrication performance. The BCO barely flows when the vegetable oil exhibits excessively high viscosity, which causes ineffective chips removal and cooling. Highly viscous BCO stays longer in the milling

Table 6. Result of thermal conductivity analysis for varied ZnO concentrations at 50 °C

MoS ₂ concentration [wt%]	Value [W/m.K]
0.0	0.174 ± 0.001
1.0	0.181 ± 0.002
2.0	0.187 ± 0.001
3.0	0.192 ± 0.003
4.0	0.200 ± 0.002

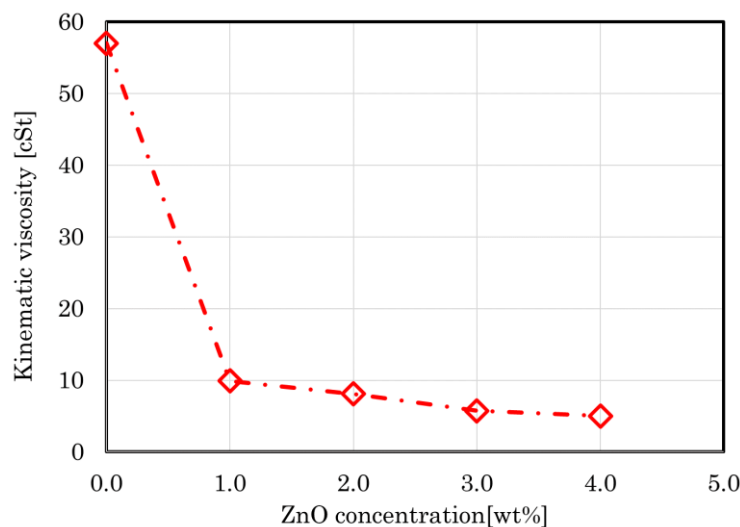


Figure 5. Kinematic viscosity of bio cutting oil used in this study

zone, which consequently enhances friction reduction and prolongs the lifetime of the cutting tool. Conversely, increasing emulsifier concentration decreased the viscosity and the fatty acid concentration in the BCO. Huang *et al.* [48] reported that fatty acids in the vegetable oil contributed to increasing anti-friction and anti-wear performance of BCO. Additionally, Bai *et al.* [49] demonstrated that higher saturated fatty acid concentrations in vegetable oil increased the lubrication performance. Vegetable oils exhibit very low viscosity, e.g. the soybean oil, had the lowest lubrication performance. Conversely, cotton oil, which exhibits very high viscosity, could not generate lower surface roughness than cottonseed oil and palm oil. Building on these findings, an appropriate emulsifier concentration should be determined to obtain a balance between an acceptable viscosity of BCO and the solubility of ZnO particles in the canola oil.

Influence of Spindle Speed and ZnO Concentration on the Surface Roughness

Overall, the Ra values decreased with increasing ZnO concentrations and spindle speeds (Table 7). This finding was in agreement with the results of previous studies. The highest Ra value of 0.401 μm occurred for 0.0 wt% ZnO concentration and 1500 rpm spindle speed. Concurrently, the lowest Ra value of 0.167 μm was observed for 4.0 wt% ZnO concentration and 2100 rpm spindle speed. In general, the surface roughness decreased with increasing MoS₂ concentration. Furthermore, higher spindle speeds also decreased surface roughness.

In this study, increasing the spindle speed by 40% from 1500 to 2100 rpm decreased the average Ra value by 39.39% from 0.339 to 0.206 μm . The decreasing surface roughness with increasing ZnO concentration in BCO in this study is in agreement with other previous studies. For the 3780 rpm spindle speed, Oerbandono *et al.* [34] reported 18.75% decrease in Ra value after an increased ZnO concentration from 0.0 to 1.0 vol%. During face milling of AA6061, Mahmood *et al.* [50] demonstrated that spindle speed became the only machining parameter which statistically significant in governing the Ra value. For the dry face milling of AISI 420, spindle speed exhibited the second greatest influence on surface roughness, after the feed rate [51]. Similarly, Basar *et al.* [52] also demonstrated that feed rate and spindle speed had the most significant influence on the surface roughness during face milling of AA5083. Akiyama *et al.* [53] also demonstrated that feed rate and spindle speed became the most influential face milling parameters on the surface roughness.

The spindle speed significantly influenced the surface roughness due to several reasons. The mass of the cutting tool (m) [kg], the diameter of the cutting tool (d_{CT}) [m] and the angular speed (ω) [rad/s] governed the centrifugal force (eq. 2). Thus, higher spindle speed linearly increased the angular speed which consequently increased the centrifugal force. If the centrifugal force exceeded the shearing force of the workpiece, thereby facilitating the cutting process.

$$F_c = m \omega^2 (d_{CT}/2) \quad (2)$$

Secondly, higher spindle speed provided better stability and reduced chatter at the cutting edge. However, excessively high spindle speed can significantly increase the surface roughness. Thirdly, higher spindle speed reduced flank wear and breakage of the cutting edge, as the built-up edge (BUE) was minimized [54]. This circumstance consequently reduced the surface roughness.

Table 7. Influence of ZnO concentration of spindle speed on surface roughness

ZnO concentration [wt%]	Surface roughness (Ra) [μm]		
	1500 rpm	1800 rpm	2100 rpm
0.0	0.401 $\pm$ 0.012	0.324 $\pm$ 0.008	0.278 $\pm$ 0.010
1.0	0.346 $\pm$ 0.007	0.283 $\pm$ 0.011	0.218 $\pm$ 0.009
2.0	0.335 $\pm$ 0.010	0.267 $\pm$ 0.008	0.192 $\pm$ 0.009
3.0	0.305 $\pm$ 0.012	0.243 $\pm$ 0.009	0.173 $\pm$ 0.011
4.0	0.309 $\pm$ 0.009	0.224 $\pm$ 0.007	0.167 $\pm$ 0.006
Average	0.339	0.268	0.206

Finally, higher spindle speed increased the friction at the workpiece-cutting tool interface which subsequently increased the local temperature at that interface. Higher local temperature decreased the local fracture and shear strength. This facilitated the cutting process.

As can be observed, this study also demonstrated reduced surface roughness for higher ZnO concentrations. This finding is in agreement with those reported in numerous previous studies. Depending on the spindle speed, Oerbandono *et al.* [34] reported an 18–31% decrease in surface roughness when the ZnO concentrations increased from 0.0 to 1.0 vol%. For the electrical discharge machining (EDM) process, Pour *et al.* [55] demonstrated that the use of 4 g/L ZnO nanoparticles sized 400 nm decreased the surface roughness of AISI1045, AISI4140, and AISI D3 by 16.66%, 29.41% and 56.25%, respectively. The material removal rate (MRR) also increased by 10.71 to 45.5% for these three distinct steels. They reported that these findings were attributed to the enhanced thermal conductivity of the cutting fluid following the ZnO addition. As reported in the previous sub-section, ZnO addition increased the thermal conductivity of BCO. Nanofluid containing 35% ZnO nanoparticles reduced the surface roughness of a single pass grinding by 37.18% from 0.710 to 0.446 μm [56]. Concurrently, the surface roughness was reduced by 41.9% from 0.541 to 0.225 μm for the multi-passes grinding

Trade-Off Strategy to Decrease Spindle Speed

The previous subsection discussed the reduced surface roughness at higher spindle speeds. Concurrently, increasing MoS₂ concentrations, which led to lower surface roughness, was also elaborated in this study. A novelty of this study lies in the discovery of a trade-off strategy applied in the face milling. Higher MoS₂ concentrations can be used as a trade-off strategy to decrease the spindle speeds (Figure 6). For example, increasing MoS₂ concentrations from 1.0 to 4.0 wt% in this study decreased the spindle speed by 14.3% from 2100 to 1800 rpm.

The reduced spindle speed was expected to reduce the electrical energy consumption. For a particular CNC-based face milling machine and for a particular machining load, Wang *et al.* [57] demonstrated that the electrical power consumption at spindle speeds of 1800 and 2100 rpm was approximately 40 and 64% higher than that at 1500 rpm. This can significantly reduce the electrical energy consumption. Furthermore, this cost implication of the electrical energy consumption is considered more significant when evaluated on an annual production basis. As each CNC face milling machine exhibits its specific electrical power consumption, quantitative analysis to measure the electrical energy consumption of the HAAS VF2 milling machine used in this study should be an important area for future study.

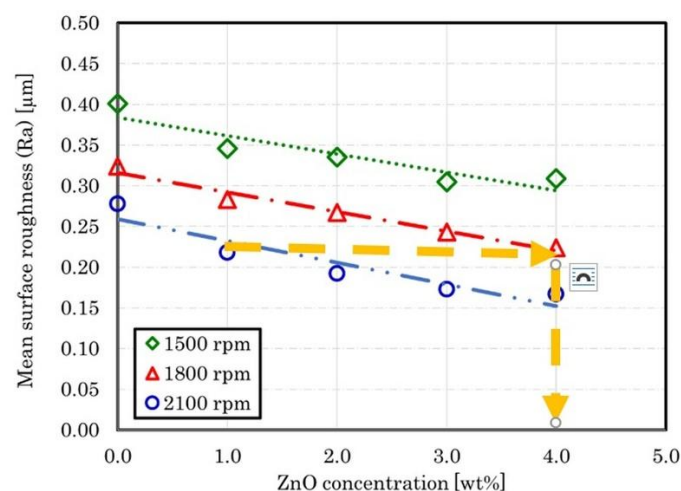


Figure 6. Influence of ZnO concentration and spindle speed on mean surface roughness (Ra)

This trade-off strategy has been insufficiently addressed in previous studies, as most previous studies used only low ZnO concentrations (≤ 1.5 wt%). At low ZnO concentrations, the intercorrelation between the spindle speeds and ZnO concentrations on surface roughness cannot be clearly observed. This novel strategy can be particularly advantageous for manufacturing industries operating in a region with high electrical energy prices. The electrical energy costs are also subject to dynamic fluctuations for a particular period. During periods of high electrical energy prices, the ZnO concentrations are increased to achieve lower spindle speeds and subsequently lower electrical energy costs. Conversely, in a region with low electrical energy costs, e.g. in a region with a significant electrical supply from nuclear or hydro-electricity power, the trade-off strategy involving higher MoS₂ concentrations and lower energy speeds may yield less efficient economic benefits. At a particular factory location, the electrical energy supply is weak attributed to a restricted output of electrical transformer. Thus, increasing spindle speed, which leads to higher electrical energy consumption, is not feasible. In this particular circumstance, the ZnO concentration can be increased to achieve an acceptable surface roughness under a lower spindle speed.

Limitation of This Study and Future Research Direction

The relationship among spindle speed, ZnO concentration and surface roughness has been discussed. This study proposes a novel process optimization based on the use of elevated ZnO concentrations to reduce the spindle speeds while maintaining an acceptable surface roughness. Nevertheless, this study is subjected to several limitations. The roughness of face-milled surface may vary when the cutting tools of distinct manufacturers or materials are used. Cutting tools fabricated by distinct manufacturers or distinct materials exhibit distinct mechanical properties, e.g. roughness of the cutting tool surface, hardness or modulus of elasticity. For example, the modulus of elasticity governs elastic deflection of the cutting tool during the face milling process, which subsequently influences the machining stability and the generated surface roughness.

To prove the consistent relationship between spindle speeds, MoS₂ concentrations and surface roughness, the face milling experiment can be performed for metals with varied mechanical properties. For example, aluminium with varied chemical compositions which influence the hardness and shear strength [58]–[60]. Face milling of ultra-strong steels, e.g. maraging steel [61], should be an interesting research topic. A quantitative evaluation of electrical energy consumption under varying spindle speeds, feed rates, and depths of cut should be an important topic for future research. This investigation would facilitate an in-depth cost evaluation of the trade-off between the additional cost incurred by employing higher ZnO concentrations and the cost savings achieved through optimized machining parameters.

CONCLUSION

Among several optimization goals in the face milling process, higher productivity and reduced electrical energy consumption were important aims for the manufacturing industry to elevate its competitiveness. Whereas previous studies focused on low ZnO concentrations (≤ 1.5 wt%), this study proposed a novel process optimization based on high ZnO concentrations. Elevated ZnO concentrations up to 4.0 wt% were offered as a trade-off strategy to decrease the spindle speed. For example, increased ZnO concentrations from 1.0 to 4.0 wt% corresponded to a decrease of spindle speed from 2100 to 1800 rpm while maintaining an acceptable surface roughness. Although further study is required to validate the quantitative relationship between decreasing spindle speed and decreasing electrical energy consumption, the 14.3% decrease in spindle speed from 2100 to 1800 rpm might correspond to a significant decrease in electrical energy consumption.

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AI DECLARATION

The authors declare that no generative artificial intelligence (AI) has been used during the experimental work and in the preparation of this manuscript. Grammarly was used to enhance the clarity, readability and linguistic quality of this manuscript.

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