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Study on High-Speed Machining of 2219 Aluminum Utilizing Nanoparticle-Enhanced Minimum Quantity Lubrication (MQL) Technique

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Abstract: High-speed machining processes are significantly affected by the accumulation of heat generated by friction in the cutting zone, leading to reduced tool life and poor quality of the machined product. The use of cutting fluids helps to draw the heat out of the area, owing to their cooling and lubricating properties. However, conventional cutting fluid usage leads to considerable damage to human health and the environment, in addition to increasing overall manufacturing costs. In recent years, minimum quantity lubrication (MQL) has been used as an alternative lubricating strategy, as it significantly reduces cutting fluid consumption and eliminates coolant treatment/disposal needs, thereby reducing operational costs. In this study, we investigated microstructural surface finishing and heat generation during the high-speed cutting process of 2219 aluminum alloy using an MQL nanofluid. 2219 aluminum alloy offers an enhanced strength-to-weight ratio and high fracture toughness and is commonly used in a wide range of aerospace and other high-temperature applications. However, there is no relevant literature on MQL-based high-speed machining of these materials. In this study, we examined flood coolant and five different MQL nanofluids made by synthesizing 0.2% to 2% concentrations of Al_2O_3 nanoparticles into ultra-food-grade mineral oil. The study results reveal the chemistry between the MQL of choice and the corresponding surface finishing, showing that the MQL nanofluid with a 0.5% concentration of nanoparticles achieved the most optimal machining result. Furthermore, increasing the nanoparticle concentration does result in any further improvement in the machining result. We also found that adding a 0.5% concentration of nanoparticles to the coolant helped to reduce the temperature at the workpiece–tool interface, obtaining a good surface finish.

Keywords: aluminum alloy; minimum quantity lubrication (MQL); nanofluids

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1. Introduction

In high-temperature applications, 2219 aluminum alloy is one of the most sought-after alloys [1]. Its high strength, low ductility, good machinability, light weight, and excellent fracture toughness [2] are the characteristics that make 2219 aluminum alloy the alloy of choice for liquid oxygen (LOX) feedline launch vehicle systems for most known aerospace and space transportation companies, such as SpaceX, ULA (United Launch Alliance), and the Boeing.

While this alloy offers superior benefits for use in space applications, previous studies indicate that the surface finish is severely scratched and becomes rougher with increased total cutting depth [3]. Furthermore, models that are not entirely acceptable were developed by several regression analyses for the surface roughness measurements [4]. This improper surface roughness challenge can generally be resolved by additional sanding, polishing, and chemical etching processes to obtain a smooth surface finish. However, chips are torn rather than sheared from the workpiece during cutting processes [5]. Therefore, one of the critical aspects to achieving a good surface finishing while avoiding the above additional non-value-added operations is the utilization of appropriate coolants and highly effective cooling/lubrication methods to transport chips, waste, and removed workpiece material [6].

Flooding the workpiece and tooling with cooling fluid (mostly coolant mixed with water) is a standard cooling method in conventional machining [7]. The use of flood coolant in conventional machining harms the environment and impacts the health of operators, technicians, and other personnel [8]. Transportation, maintenance, appropriate disposal, storage, and real estate costs are some major factors in conventional cooling that significantly negatively impact manufacturing businesses [9]. The other downside of using coolant is thermal shock. During the cutting process, the friction generated between the workpiece and the cutting tool raises the cutting area's temperature and makes the workpiece material extremely hot. Meanwhile, coolant is poured on the surface and instantly cools it down. Then, the workpiece is immediately returned to the cutting operation and heats up again. This constant back-and-forth in heating up and cooling down leads to thermal shock in the material [10].

The dry machining process can solve this issue to some extent. This method utilizes no lubrication to machine parts, resulting in the total elimination of cutting fluids [11]. Dry machining helps to reduce the cost of the life cycle of the cutting fluid, thereby reducing the overall manufacturing cost [12]. Additionally, it eliminates the environmental concerns associated with conventional cutting fluids [13]. However, dry machining can negatively affect machining characteristics and material properties such as precision, and material failure becomes a concern for the operator when machining dry [12].

Minimum quantity lubrication (MQL), also known as "near-dry machining" or "NDM" and "micro lubrication" or "micro-lubrification", is a firm method in machining processes that has been shown to resolve the issue with the disposal and/or recycling of the used cutting fluid [14]. The concept of MQL is fundamentally different than that of traditional flood coolants. After the high-pressure gas is mixed with a small amount of cutting fluid, microdroplets are formed and sprayed into the machining area. The high-pressure airflow plays the role of cooling and chip removal [15]. The lubricant fluid coheres on the machined surface of the workpiece, becomes a protective film, and acts as a lubricant [16]. The MQL concept was invented years ago to address the concern of environmental and occupational hazards caused by conventional cutting fluids. By reducing the consumption of cutting fluid, lubricant costs decline, leading to economic benefits, in addition to saving cleaning time [17].

In the nanoparticle-enhanced MQL technique, a minimum amount of oil is mixed with nanoparticles and compressed air, then sprayed onto the surface of the workpiece [18]. An element of matter between 1 to 100 nanometers (nm) in diameter is denominated as a nanoparticle or ultrafine particle. Nanoparticles can provide different physical and chemical properties than their macro-sized counterparts. Material properties change once particles become smaller and gets closer to the atomic size. Although the choice of MQL depends on numerous characteristics, such as workpiece material, hardness, restraint stress, and required cooling ratio, previous research indicates that nanoparticles have a superior scatter property and transfer heat better between surfaces and subsurfaces [19].

Dongkun et al. analyzed different volume concentrations of molybdenum disulfide (MoS_2) nanoparticles in their experiments on MQL lubrication and studied their pertinent surface roughness. They studied 1%, 2%, and 3% MoS_2 concentrations during the grinding process. With increased MoS2 nanoparticle concentration, the surface roughness of the workpiece initially increased, but the surface quality decreased beyond a certain nanoparticle concentration. The optimum surface roughness was observed when 2% MoS2 nanoparticle concentration was used [20]. Therefore, the fluid type, nanoparticles, and their concentration strongly affect cutting performance.

O. Pereira et al. analyzed the use of natural biodegradable oils as an alternative to traditional canola oils for use in MQL, comparing five options (i.e., sunflower oil, high oleic sunflower oil, castor oil, and ECO-350 recycled oil). They found that oil viscosity changes rapidly at low temperatures and that oil penetration due to low viscosity has more relevance than friction properties during machining [21].

Molaie et al. showed that MQL with water-based nanofluids can provide a critical value-added quality to ultrasonic vibration-assisted surface grinding. Their research also emphasizes that the type and concentration of nanoparticles in the base fluid, the shape of the nanoparticles, and their molecular structures are critical factors impacting the result in the nanolubricant grinding process utilizing ultrasonic vibration [22]. In their research about micro/nanofluids in sustainable machining Duc et al. reported that the performance of nanofluids is better than that of microfluids in reducing cutting temperatures, cutting forces, tool flank wear, and surface roughness of the machined surface [23].

It has been proven in the literature that when nanoparticles are used as additives to lubricants, various properties, such as surface finish roughness, thermal stability, antifriction, antiwear, and extreme pressure, can be improved. High-speed machining (HSM) has received increasing attention in recent years, as it offers several benefits, including a high material removal rate, superior surface quality, and reduced operational costs [24]. HSM benefits MQL-based machining to achieve high energy efficiency and environmental benefits [8]. However, to the best of our knowledge, no comprehensive studies have been conducted in an effort to understand the effects of nanoparticle-enhanced MQL on the HSM of Al2219 alloys.

In this study, we investigated the effects of critical process parameters on the surface finishing and produced heat using nanoparticle-enhanced minimum quantity lubrication (MQL) instead of conventional cooling and/or dry machining for high-speed machining of 2219 aluminum alloy. The aim of this study is to understand the chemistry between the MQL of choice and the corresponding surface roughness under high-speed machining conditions. The remainder of this paper is organized as follows. In Section 2, we presents the experimental setup, material, and methods used. In Section 3, we presents the results of high-speed machining trials. Finally, concluding remarks are presented in Section 4.

2. Materials and Methods

The nanoparticle lubricant developed for this research was a mixture of nanopowder aluminum oxide (Al_2O_3, gamma) and ultra-pro-food-grade mineral oil. The nanopowder aluminum oxide (Al_2O_3, gamma) was mixed with ultra-pro-food-grade mineral oil for a minimum of six hours using an electric laboratory centrifuge. It has to be noted that the use of metal oxide nanoparticles could result in toxicity at various levels in living beings, with effects on the ecosystem. However, studies have found that the toxicity of Al_2O_3 nanoparticles is relatively reduced when compared to other metal oxides such as zinc oxide (ZnO), tin (IV) oxide (SnO_2), tungsten trioxide (WO_3), etc. [25–27]. Typically, the lubricant flow rate of 50 to 500 mL/h is misting or atomizing on the cutting zone in the MQL technique to minimize the quantity of lubricant [14]. In this experiment, an aerosol atomizer system was utilized to apply a minimum amount of developed lubricant on the cutting surface. The aluminum specimens were cut by a high-speed saw-cutting machine using conventional cutting (coolant) lubricant and indigenously developed MQL lubricant at different nanoparticle concentrations. Then, the cut samples were studied to compare their microstructural surface finishes and heating temperatures during the process.

2.1. Materials Used

In the present investigation, 2219-T8 high-strength aluminum alloy material was used. To achieve this temper (T8), the metal solution was heat-treated, strain-hardened, artificially aged at 325 °F for 18 h, and air-cooled. The size of the specimen was 6 × 6 (L × W) inches with a thickness of 0.250 inches. The chemical composition and mechanical properties of the workpiece materials are shown in Tables 1 and 2.

Table 1. Chemical composition of workpiece material.

Al	Mn	Mg	V	Si	Cr	Ni	Ti	Cu	Zr	Fe	Zn
92.3	0.31	0.01	0.088	0.06	0.003	0.00	0.062	6.35	0.12	0.12	0.02

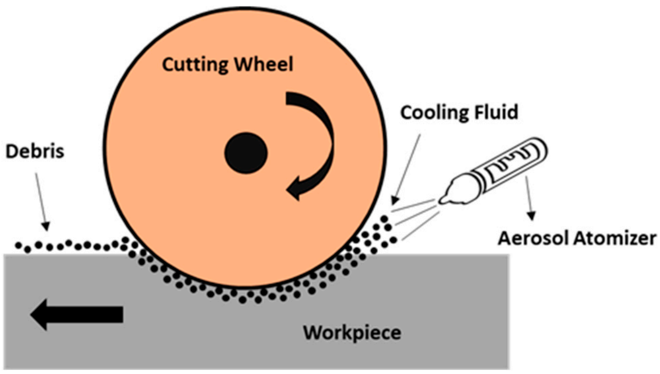
Table 2. Mechanical properties of workpiece material.

Yield Str. (Ksi) *	Ultimate. Str. (Ksi)	% Elongation	Hardness (HRBW)	% Conductivity (IACS) **
53.8	68.0	9.5	74–76	35.5–36.0

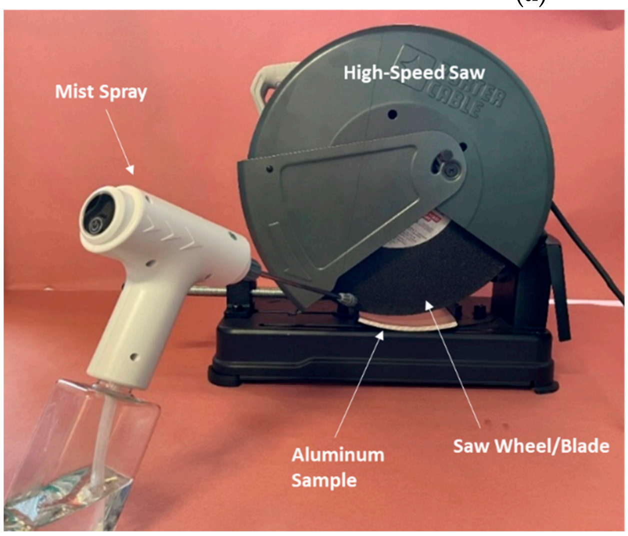
* Modulus of elasticity (yield strength); ** IACS (International Annealed Copper Standard).

2.2. Experimental Setup

All steps of the experimental assay were performed at room temperature (68 to 77 °F). A circular high-speed saw (15-Amp, 14-Inch, 3800 RPM) with a 1.8 KW motor and a conventional high-speed aluminum oxide type 1 metal cutting blade was used to cut 2219-T8 aluminum specimens with a thickness of 0.250 inches. The tool edge was prepared by the drag grinding process. The cooling fluid was supplied as a mixture of mineral oil and nanoparticles and delivered onto the surface of the workpiece undergoing the cutting, as well as the saw blade, utilizing an aerosol atomizer mechanism. A schematic representation ([20,28]) and the actual equipment/instrumentation used in this study are shown in Figure 1, and the corresponding information is provided in Table 3.



(**a**)



(**b**)

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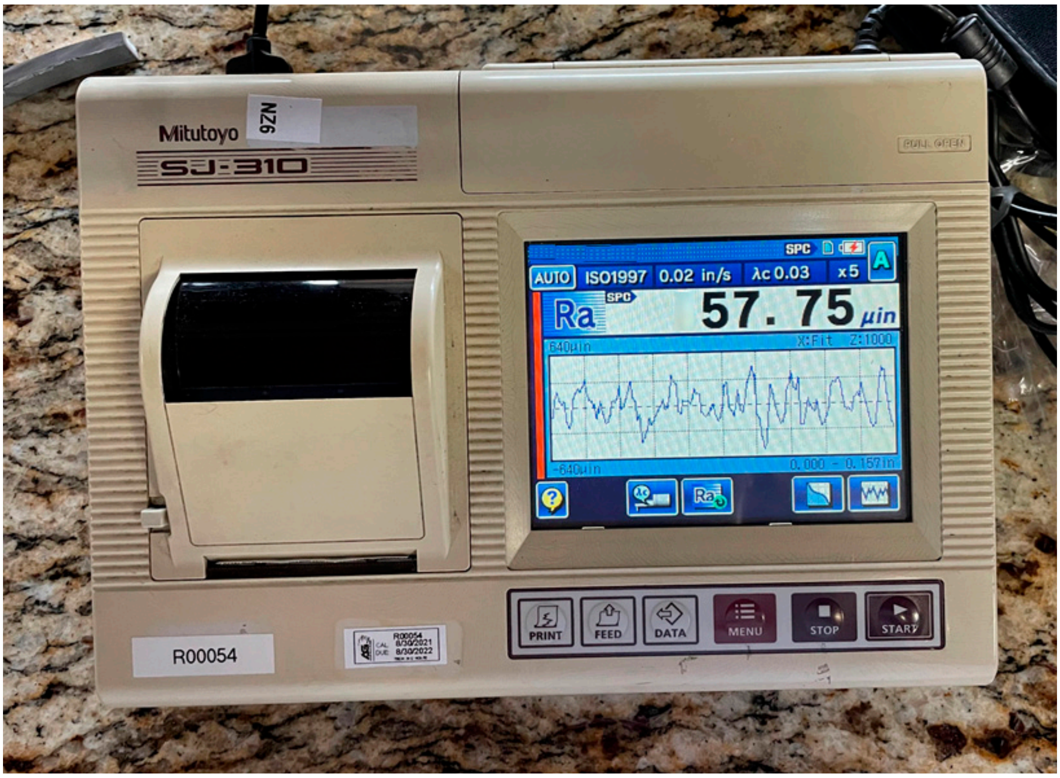
Figure 1. *Cont.*



(d)

Figure 1. (**a**) Schematic of the nanoparticle-enhanced MQL experimental setup. (**b**) Actual experimental setup. (**c**) Laser thermometer used in this study. (**d**) Surface profilometer used in this study.

Table 3. Technical instruments used in this study.

Tool Name	Manufacturer	Model	Major Specifications
Circular High-Speed Saw	PORTER-CABLE	PCE700	Speed: 3800 RPM Power: 1.8 KW Size: 14-Inch
Saw Wheel/Blade	PORTER-CABLE	A24-R	Size: 14″ × 3/32″ × 1″ Max RPM: 4300 Permashield coating
* Laser Thermometer	Extech	42510A	Temperature Range: −58 to 1200 °F Resolution: 0.1 °F degree
* Profilometer/Surface Roughness Tester	Mitutoyo	SJ-310	Resolution: 0.002 µm (0.078 µin)
Automatic Electric Mist Spray	Reditbone	E-01	Bottle size: 350 mL Flow Rate Range: 4200–460 mL/h
Electric Lab Centrifuge	DOC.ROYAL	GH-44	Speed: 0–4000 RPM Timer Range: 0–60 min or always on Power: 25 W
* Digital Scale	Fuzion	PT500	Weighing Range: 0.03–500 g Resolution: 0.01 g

* Equipment was calibrated to NIST and ISO 17025 standards.

2.3. MQL Dispersion Preparation

The MQL base oil of choice, ultra-pro-food-grade mineral oil, was mixed with different concentrations of aluminum oxide (Al_2O_3) nanoparticles. The oil mixture was enhanced using the following five nanoparticle concentrations:

- Pure mineral oil;
- 0.2% Al_2O_3 nanoparticles;

- 0.5% Al_2O_3 nanoparticles;
- 1% Al_2O_3 nanoparticles; and
- 2% Al_2O_3 nanoparticles.

The selection and the range of nanoparticle concentration in the nanofluid were decided based on previous studies conducted by our research group on high-speed machining assisted by nanofluid MQL [8,29]. The properties of the aluminum oxide nanoparticles (Al_2O_3, gamma) used in this study are described in Table 4.

Table 4. Aluminum oxide nanoparticle (Al_2O_3, gamma) properties.

Material	Color	Chemical Composition (in ppm)							Size	Purity
Nano Alumina (Brand: XF-NANO)	White	Al_2O_3 99.99%	Ca ≤1	Fe ≤18	K ≤29	Na ≤35	Mn ≤1.2	Si ≤16	10–15 nm	99.9%

In this experiment, MicroSol 585XT Coolant (Table 5), followed by pure mineral oil (mixed with 0% nanoparticles), were used in the form of flood-cutting fluid on the surface of the aluminum workpiece and saw blade undergoing the cutting process.

Table 5. Physical properties of MicroSol 585XT.

Color (concentrate)	Straw
Odor (concentrate)	Mild amine
Form (concentrate)	Liquid
Flash point (concentrate)	>160 °C (320 °F)
pH (concentrate as range)	9.2–10.2
pH (typical operating range)	8.8–9.8
Coolant refractometer factor	1.2

Furthermore, an electric lab centrifuge was utilized at 4000 RPM for a minimum of six hours to synthesize aluminum oxide nanoparticles with mineral oil to achieve the desired concentrations. The prepared nanofluid was sprayed in the form of MQL onto the surface of the workpiece during the cutting process. Samples were cut using the six cutting lubricants mentioned in Table 6 to evaluate surface finish roughness and heating temperature immediately after the cutting process.

Table 6. Lubricant types used in this study.

Lubricant 1	Flood coolant
Lubricant 2	Pure mineral oil
Lubricant 3	0.2% Al_2O_3 nanoparticles
Lubricant 4	0.5% Al_2O_3 nanoparticles
Lubricant 5	1% Al_2O_3 nanoparticles
Lubricant 6	2% Al_2O_3 nanoparticles

3. Results and Discussion

For each lubricant mixture, the experiments were repeated five times to ensure the accuracy of the collected data. The workpiece temperature was 65 °F immediately before the cutting process.

3.1. Surface Roughness and Surface Micromorphology

Surface finish plays an essential role in product quality and manufacturing process planning. The surface finish of the workpiece can be quantitatively determined through surface roughness measurements. Figures 2 and 3 show the surface roughness and surface micromorphology of the workpieces cut using six different lubricant mixtures, respectively. The surface roughness (R_a value) was measured using a profilometer (make: Mitutoyo;

model: SJ-310). The roughness value of Ra can be defined as the arithmetic mean of the absolute values of the profile heights over the sampling length. When dealing with the roughness profile, the roughness measurements were repeated three times on each sample in order to calculate the mean deviation.

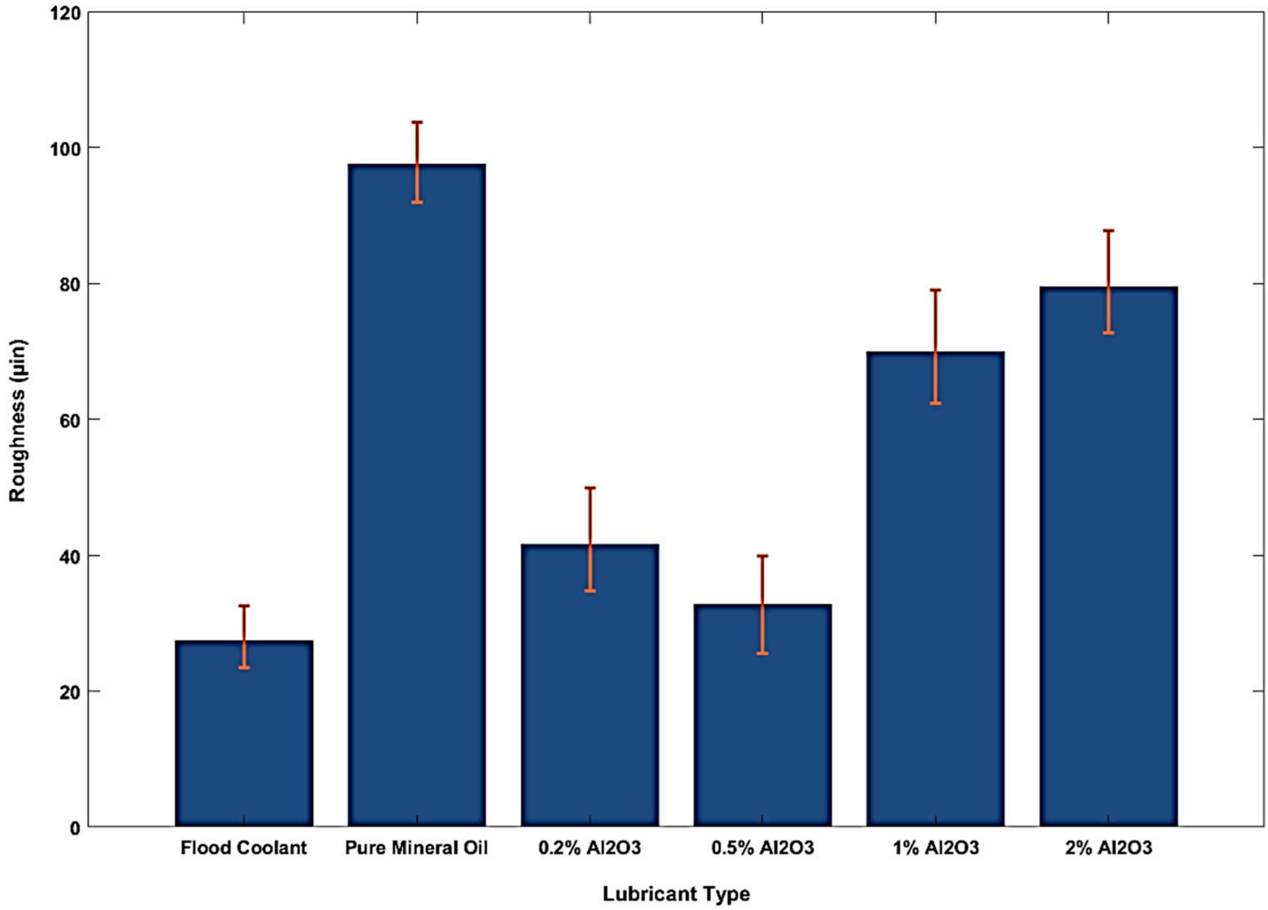
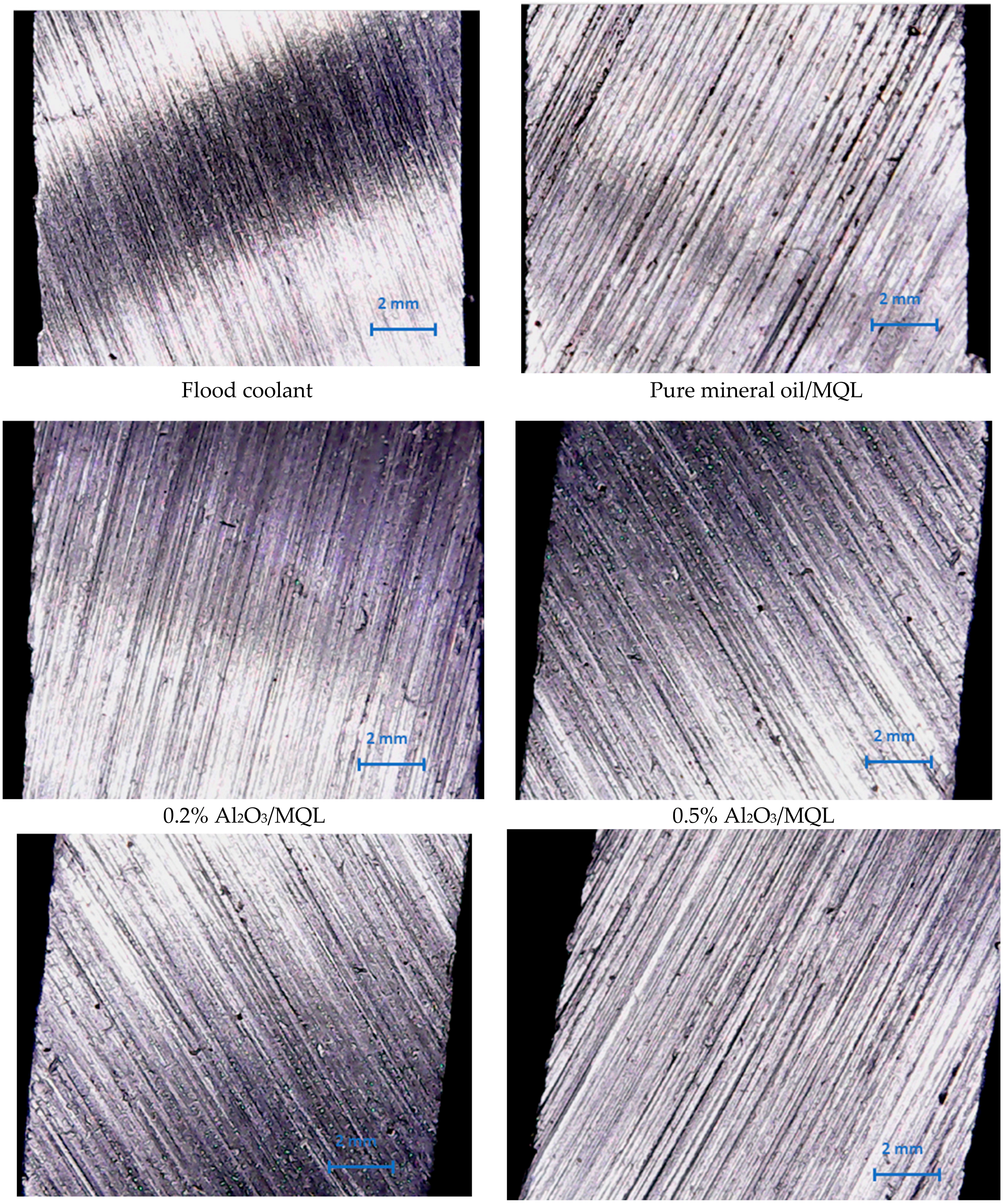


Figure 2. Surface roughness (R_a value) obtained using different lubricant types.

The figures indicate that the 0.5% Al_2O_3 nanofluid produces the best surface finish among the various MQL combinations (63% improvement relative to pure MQL). The result of 0.5% MQL is comparable (within 10%) to the surface finish obtained by flood coolant machining. The lowest surface roughness value and good surface quality were observed in the case of flood coolant, which can be attributed to the lubricating layer provided by the flood coolant, its higher heat-transfer capability compared to MQL conditions, and the frequent removal of machining debris from the machining zone, resulting in a smoother surface.

Under MQL conditions, nanofluid application improves the surface finish, as the nanoparticles result in rolling friction as opposed to sliding friction (in the case of pure MQL). Furthermore, the tribological properties were improved with increased concentration of nanoparticles. MQL-based nanofluid mists form a tribological film at the interface between the cutting tool and the workpiece, providing a lower tribological temperature. Additionally, the nanofluid film operates as a spacer that reduces the friction, plowing, and rubbing actions of the cutting zone, leading to an improved surface finish and tribological performance. However, with an increased concentration of MQL beyond 0.5%, the resulting surface shows higher surface roughness values. Similar observations were made in the past by other researchers on nanoparticle-enhanced MQL-based high-speed machining [8,29]. This can be explained by the fact that beyond a specific concentration (0.5% in this case), nanoparticles tend to precipitate on the workpiece surface and penetrate the machined regions, micro grooves, slits, and chips. This prevents MQL fluid from reaching the machined cavities because of increased viscosity, resulting in inadequate lubrication and increased surface roughness.



Flood coolant | Pure mineral oil/MQL

0.2% Al_2O_3/MQL | 0.5% Al_2O_3/MQL

1% Al_2O_3/MQL | 2% Al_2O_3/MQL

Figure 3. Surface micromorphology under different lubricant types.

3.2. Temperature Generated during High-Speed Saw Cutting

The heat generated on the workpiece and cutting tool tip is vital for the tool's performance and the quality of the finished product. High cutting temperatures are detrimental to both the tool and the workpiece. The temperature of the cutting zone immediately after machining with different lubricant types was measured using a non-contact laser thermometer with a laser target at a point, as shown in Figure 4. According to this graph, the best cooling occurred during under flood coolant condition because of the presence of vast quantities of coolant. Additionally, less heat was generated when nanoparticle fluid was used compared to pure mineral oil MQL. This also results from the fact that rolling friction causes less heat than sliding friction. When a nanoparticle concentration exceeding 0.5 was used, the Al_2O_3 particles were possibly clogged on the surface and changed the form of the friction from rolling to sliding. Sliding friction creates more heat and a rougher surface than rolling friction. The temperature gradually drops when the Al_2O_3 concentration is increased. However, with increased concentration beyond 0.5%, the magnitude of the heat temperature rises again. Among all the concentrations of nanoparticle-enhanced lubricants considered, 0.5% achieved the best result, and the highest temperature was generated when pure mineral oil was applied in MQL form.

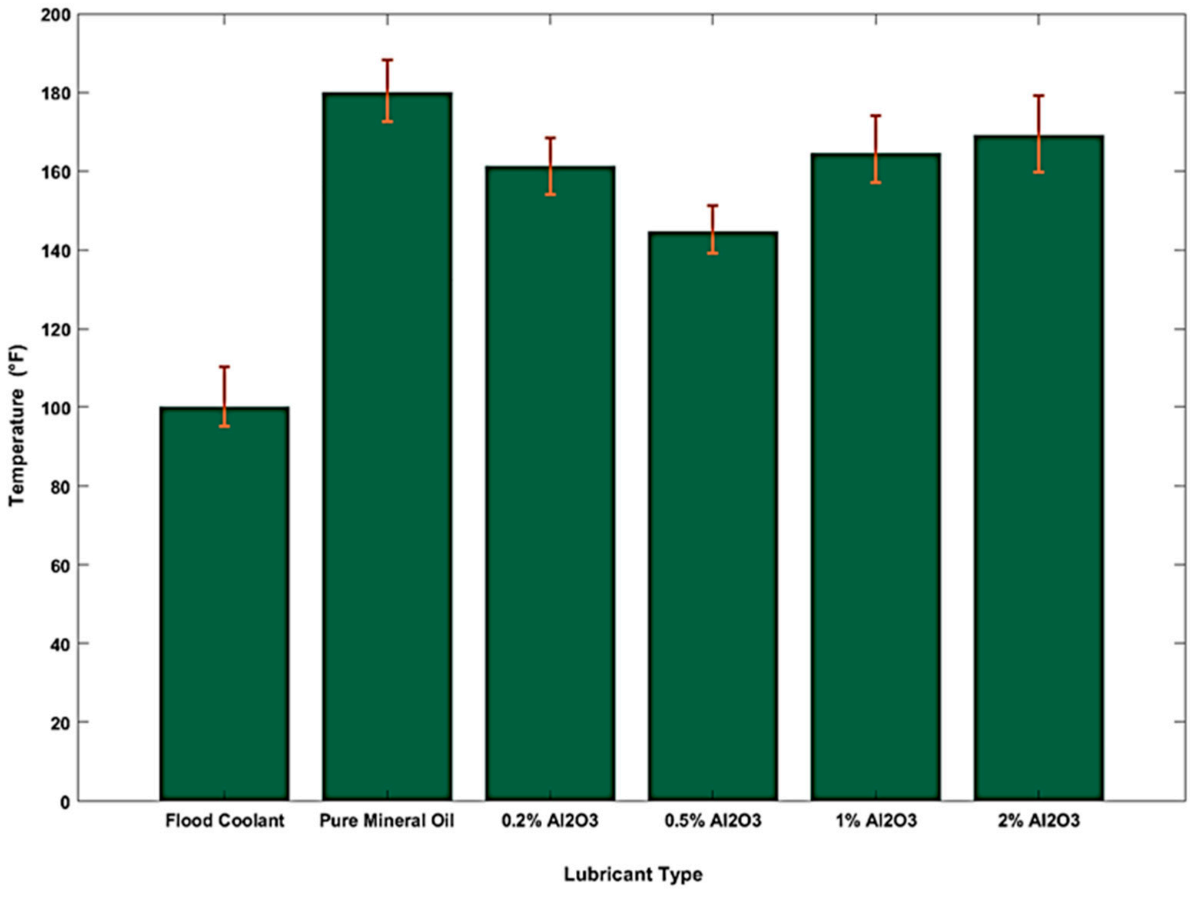


Figure 4. Temperature of the cutting zone immediately after the high-speed saw-cutting process with different lubricant types.

4. Conclusions

In the present study, we investigated the nanoparticle-enhanced MQL-based HSM of aluminum alloy 2219. Nanofluids with different nanoparticle concentrations were compared with pure MQL and flood coolant conditions. The following key conclusions can be drawn from this study:

- The addition of nanoparticles helped to improve the surface finish under MQL machining. However, the surface quality decreased beyond a threshold nanoparticle concentration (0.5% in this case);
- The surface roughness obtained using conventional flood coolant is comparable to that of MQL nanofluid with a concentration of 0.5%;

- Compared to pure MQL, a 0.5% concentration of MQL nanofluid resulted in a 63% improvement in surface finish;
- Temperature analysis of the cutting zone immediately after machining showed that a 0.5% nanoparticle concentration resulted in the lowest cutting temperature among the various MQL cutting conditions;
- Further investigations are needed to understand the impact of nanoparticle concentration on tool wear, tool life, and MQL-based machining economics;
- The results of this study could be instrumental in the development of environmental-friendly machining solutions for aluminum alloys at commercial scales.

Author Contributions: S.J. conceived the idea for the research. S.J. and M.M. designed the methodology and experimental setup and outlined the paper. M.M. conducted the literature review, performed experiments, and collected data. S.J. and M.M. analyzed the data and wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

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References

1. Mondol, S.; Kashyap, S.; Kumar, S.; Chattopadhyay, K. Improvement of high temperature strength of 2219 alloy by Sc and Zr addition through a novel three-stage heat treatment route. *Mater. Sci. Eng. A* **2018**, *732*, 157–166. [CrossRef]
2. Sivaprasad, K.; Blessto, B.; Muthupandi, V.; Arumugam, M. Achieving Superior Strength and Ductility Combination through Cryorolling in 2219 Aluminum Alloy. *J. Mater. Eng. Perform.* **2020**, *29*, 6809–6817. [CrossRef]
3. Gatto, A.; Bassoli, E.; Iuliano, L. Performance Optimization in Machining of Aluminium Alloys for Moulds Production: HSM and EDM. *Alum. Alloy. Theory Appl.* **2011**, 355–376. [CrossRef]
4. MuellerHummel, P. Process understanding of dry drilling CFRP/aluminium and AL/AL stacks in IT8 quality. *SAE Int. J. Aerosp.* **2016**, *9*, 217. [CrossRef]
5. Jawahir, I.S.; Van Luttervelt, C.A. Recent developments in chip control research and applications. *CIRP Ann.* **1993**, *42*, 659–693. [CrossRef]
6. Polvorosa, R.; Suárez, A.; de Lacalle, L.L.; Cerrillo, I.; Wretland, A.; Veiga, F. Tool wear on nickel alloys with different coolant pressures: Comparison of Alloy 718 and Waspaloy. *J. Manuf. Process.* **2017**, *26*, 44–56. [CrossRef]
7. Park, K.-H.; Olortegui-Yume, J.; Yoon, M.-C.; Kwon, P. A study on droplets and their distribution for minimum quantity lubrication (MQL). *Int. J. Mach. Tools Manuf.* **2010**, *50*, 824–833. [CrossRef]
8. James, S.; Nejadian, S.M. Experimental study on high-speed saw cutting of hybrid composite stacks using nanoparticle-enhanced minimum quantity lubrication. *Int. J. Adv. Manuf. Technol.* **2020**, *110*, 3077–3090. [CrossRef]
9. Le Coz, G.; Dudzinski, D. Temperature variation in the workpiece and in the cutting tool when dry milling Inconel 718. *Int. J. Adv. Manuf. Technol.* **2014**, *74*, 1133–1139. [CrossRef]
10. Meshreki, M.; Damir, A.; Sadek, A.; Attia, M.H. Investigation of drilling of CFRP-aluminum stacks under different cooling modes. In *ASME International Mechanical Engineering Congress and Exposition*; American Society of Mechanical Engineers: New York, NY, USA, 2016; p. V002T002A011.
11. Sreejith, P.S. Machining of 6061 aluminium alloy with MQL, dry and flooded lubricant conditions. *Mater. Lett.* **2008**, *62*, 276–278. [CrossRef]
12. De Lacalle, L.L.; Angulo, C.; Lamikiz, A.; Sanchez, J. Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. *J. Mater. Process. Technol.* **2006**, *172*, 11–15. [CrossRef]
13. Goindi, G.S.; Sarkar, P. Dry machining: A step towards sustainable machining–Challenges and future directions. *J. Clean. Prod.* **2017**, *165*, 1557–1571. [CrossRef]
14. Boubekri, N.; Shaikh, V.; Foster, P.R. A technology enabler for green machining: Minimum quantity lubrication (MQL). *J. Manuf. Technol. Manag.* **2010**, *21*, 556–566. [CrossRef]
15. Brinksmeier, E.; Janssen, R. Drilling of multi-layer composite materials consisting of carbon fiber reinforced plastics (CFRP), titanium and aluminum alloys. *CIRP Ann.* **2002**, *51*, 87–90. [CrossRef]
16. Khan, I.; Saeed, K.; Khan, I. Nanoparticles: Properties, applications and toxicities. *Arab. J. Chem.* **2019**, *12*, 908–931. [CrossRef]

17. Gharaibeh, N. Vegetable and mineral used oils as cutting fluids: Effect on surface roughness of aluminum alloy. *J. Surf. Eng. Mater. Adv. Technol.* **2016**, *6*, 176–182. [CrossRef]
18. Singh, G.; Singh, S.; Singh, M.; Kumar, A. Experimental investigations of vegetable & mineral oil performance during machining of EN-31 steel with minimum quantity lubrication. *Int. J. Res. Eng. Technol.* **2013**, *2*, 1030–1037.
19. Salur, E.; Kuntoğlu, M.; Aslan, A.; Pimenov, D.Y. The Effects of MQL and Dry Environments on Tool Wear, Cutting Temperature, and Power Consumption during End Milling of AISI 1040 Steel. *Metals* **2021**, *11*, 1674. [CrossRef]
20. Zhang, D.; Li, C.; Jia, D.; Zhang, Y.; Zhang, X. Specific grinding energy and surface roughness of nanoparticle jet minimum quantity lubrication in grinding. *Chin. J. Aeronaut.* **2015**, *28*, 570–581. [CrossRef]
21. Pereira, O.; Martín-Alfonso, J.; Rodríguez, A.; Calleja, A.; Fernández-Valdivielso, A.; De Lacalle, L.L. Sustainability analysis of lubricant oils for minimum quantity lubrication based on their tribo-rheological performance. *J. Clean. Prod.* **2017**, *164*, 1419–1429. [CrossRef]
22. Molaie, M.M.; Zahedi, A.; Akbari, J. Effect of water-based nanolubricants in ultrasonic vibration assisted grinding. *J. Manuf. Mater. Process.* **2018**, *2*, 80. [CrossRef]
23. Duc, T.M.; Chien, T.Q. Performance evaluation of MQL parameters using Al2O3 and MoS2 nanofluids in hard turning 90CrSi steel. *Lubricants* **2019**, *7*, 40. [CrossRef]
24. Jain, A.; Bajpai, V. Introduction to high-speed machining (HSM). In *High Speed Machining*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 1–25.
25. Nouzil, I.; Eltaggaz, A.; Pervaiz, S.; Deiab, I. Toxicity Analysis of Nano-Minimum Quantity Lubrication Machining—A Review. *Lubricants* **2022**, *10*, 176. [CrossRef]
26. Sengul, A.B.; Asmatulu, E. Toxicity of metal and metal oxide nanoparticles: A review. *Environ. Chem. Lett.* **2020**, *18*, 1659–1683. [CrossRef]
27. Girigoswami, K. *Toxicity of Metal Oxide Nanoparticles, in Cellular and Molecular Toxicology of Nanoparticles*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 99–122.
28. Virdi, R.L.; Chatha, S.S.; Singh, H. Performance evaluation of nanofluid-based minimum quantity lubrication grinding of Ni-Cr alloy under the influence of CuO nanoparticles. *Adv. Manuf.* **2021**, *9*, 580–591. [CrossRef]
29. James, S.; Nejadian, S. Preliminary Study on High-Speed Machining of Hybrid Composite Stacks Using Nanoparticle Enhanced MQL. In Proceedings of the International Manufacturing Science and Engineering Conference, Online, 3 September 2020; p. V002T006A034.