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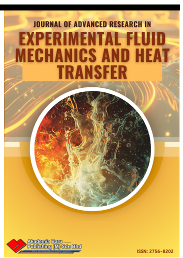

Effect of Coolant Concentration Ratio on Surface Roughness in Machining Aluminium 6061: A Case Study

Nur Hanis Othman Ali[1,2], Aidid Ezmi Admi[2], Saliza Azlina Osman[2], Shahrul Azmir Osman[2,*]

[1] AME Manufacturing Sdn. Bhd., Jalan Pelepas Utama, Taman Perindustrian Tanjung Pelepas, Gelang Patah, 81550 Johor Bahru, Johor, Malaysia
[2] Department of Mechanical Engineering, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja, 86400 Batu Pahat, Johor, Malaysia

ABSTRACT

Machining of Aluminium 6061 alloy is critical in various industries, but achieving optimal surface finish while maintaining cost-effectiveness remains a challenge. The concentration of coolants significantly impacts machining characteristics, yet its optimal ratio for specific alloys and processes is not fully understood. This study addresses this gap by investigating the effect of coolant concentration on surface roughness during the machining of Aluminium 6061 alloy. Two coolants, Coolant A andCoolant B, were evaluated at concentrations of 5%, 7%, 9%, 10% and 11%. The research employed a Hision VMC 850 CNC machine with carefully controlled parameters, including a spindle speed of 1500 RPM and specific feed rates. Surface roughness measurements were taken using a Mitutoyo SJ-410 Electronic SurfaceRoughness tester before and after machining operations. Results demonstrated a clear correlation between increased coolant concentration and improved surface finish for both coolants. For Coolant A, the optimal 11% concentration yielded the lowest post- machining Ra values of 2.63-2.74 µin, with minimal variability. Similarly, Coolant B achieved its best performance at 11% concentration, with Ra values ranging from 2.35µin to 2.60 µin. A notable performance leap was observed between 9% and 10% concentrations for both coolants, suggesting a critical threshold for optimal coolant effectiveness. The enhanced surface finish at higher concentrations is attributed to improved lubrication and cooling properties, reduced tool wear, better chip evacuation and more stable cutting conditions. However, the marginal improvement from 10% to 11% concentration raises cost-effectiveness considerations for industrial applications. This study provides valuable insights into optimizing coolant concentration for improved surface quality in aluminium machining processes, emphasizing the importance of balancing performance requirements with economic factors in manufacturing scenarios.

Keywords:
Aluminium; Al6061; coolant concentration; surface roughness

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1. Introduction

Aluminium 6061 alloy has extensive applications in various industries, including aerospace, automotive and construction, due to its excellent mechanical properties and corrosion resistance [1,2]. Coolants are pivotal in machining operations by improving machinability, enhancing productivity and extending tool life through effective cooling and lubrication of the workpiece and cutting tool.

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[*] *Corresponding author.*
E-mail address: shahrula@uthm.edu.my

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However, coolants can rapidly become contaminated with foreign materials, leading to a loss of effectiveness and the development of undesirable odours [3].

Coolant concentration is a critical parameter that significantly influences machining characteristics such as tool wear, surface roughness and cutting forces [4]. Optimizing coolant concentration is essential for maximizing tool life, improving surface finish and reducing machining power consumption. Consequently, research on the effect of coolant concentration on the machining characteristics of aluminium 6061 has been an active area of investigation for decades.

Numerous studies have investigated the influence of coolant concentration on various machining parameters. Findings have demonstrated that coolant concentration significantly impacts tool wear rate, with higher concentrations leading to lower wear rates due to improved lubrication and cooling [5]. Optimal coolant concentrations can produce smoother surfaces by reducing chip formation and adhesion [6]. Furthermore, cutting forces are influenced by coolant concentration, with higher concentrations resulting in reduced cutting forces, leading to lower power consumption and decreased machine tool wear [7].

The mechanisms underlying the effect of coolant concentration on machining characteristics are complex and involve several factors. Coolant acts as a lubricant, reducing friction between the tool and the workpiece and decreasing tool wear and cutting forces. It also removes heat from the cutting zone, preventing chip formation and improving surface finish [8]. Moreover, coolant can help flush away chips, preventing them from adhering to the tool and workpiece, which can improve surface finish and reduce tool wear [9].

Coolants in Computer Numerical Control (CNC) machining processes are crucial in managing the thermal challenges inherent to cutting operations. During machining, significant heat is generated at the tool-workpiece interface due to plastic deformation of the workpiece material and friction between the cutting tool and the chip [10]. This heat generation can harm both the cutting tool and the machined part. Ejieji *et al.,* [10] demonstrated that excessive heat can dramatically reduce toollife by accelerating wear mechanisms such as adhesion, abrasion and diffusion. Moreover, thermal expansion and distortion of the workpiece can lead to dimensional inaccuracies and poor surface finish in the final product. To address these issues, coolants are employed to dissipate heat, reduce friction and flush away chips from the cutting zone.

The effectiveness of coolants in CNC machining is not solely dependent on their application but also on their composition and concentration. Stefánsson [11] highlighted that the concentration ratio of coolants significantly impacts the machining process. The optimal concentration can vary depending on the machining operation, workpiece material and desired outcomes. For instance, higher concentrations may provide better lubrication and cooling effects but can also increase costs and lead to environmental concerns.

Furthermore, the type of coolant used can influence machining performance. While traditional oil-based and water-based coolants are common, recent research has explored advanced options such as cryogenic coolants. Stefánsson's study [11] particularly focused on applying cryogenic coolants in machining metal matrix composites, suggesting that these ultra-cold fluids can offer unique advantages in certain high-performance machining scenarios.

Researchers have investigated various types of coolants commonly used in machining processes, each with its advantages and limitations [12]. Water-based emulsions or soluble oils, are mixtures of water and mineral oil or synthetic additives. These emulsions are cost-effective and widely used due to their excellent cooling and lubricating properties, making them suitable for various machining applications and materials, including ferrous and non-ferrous alloys [13]. Straight oils, also known as neat or mineral oils, are traditional coolants primarily composed of petroleum-based oils. They offer excellent lubrication and cooling properties, making them suitable for heavy-duty machining operations and applications where high lubricity is essential [14]. However, they have some drawbacks, such as poor heat dissipation, increased oil mist formation and potential health and environmental concerns due to their petroleum content. Synthetic coolants, also known as chemical coolants or semi-synthetic coolants, are made from synthetic chemicals and offer several advantages over other coolant types. They provide superior cooling and lubricating properties compared to water-based emulsions and straight oils [15]. Synthetic coolants have better thermal stability, ensuring consistent performance at high cutting speeds and temperatures. Additionally, they are environmentally friendly, as they have lower oil mist generation and are less likely to cause skin irritations, making them safer for machine operators [16].

The optimal coolant concentration for machining aluminium 6061 depends on several factors, including the specific machining operation, the tool material and the desired machining characteristics [17]. However, general guidelines suggest that 5% to 10% coolant concentrations are effective for most machining operations. Research on the effect of coolant concentration on the machining characteristics of aluminium 6061 continues to be an active area of investigation [18]. Researchers are exploring new coolant formulations and optimizing coolant delivery methods to improve machining performance and quality further.

This research has significant practical implications for various industries that rely on machining operations, including aerospace, automotive and manufacturing. By optimizing coolant concentration, manufacturers can reduce machining costs, improve tool life and produce high-quality aluminium components [19,20]. Previous studies have shown that coolant concentration affectsmachining outcomes for aluminium 6061, but the optimal concentration for specific alloys and processes is not fully known. This study aims to fill this gap by examining how coolant concentration impacts surface roughness when machining Aluminium 6061 alloy. This study aims to better understand this relationship and improve machining performance and efficiency. This research seeks to establish a clearer relationship between coolant concentration and surface finish quality, potentially leading to more precise guidelines for coolant usage in industrial applications involving Aluminium 6061. The findings are expected to enhance our theoretical understanding of coolant behaviour in machining and provide practical recommendations for improving machining outcomes and efficiency in manufacturing processes involving this widely used aluminium alloy.

2. Methodology

2.1 Sample Preparation

In conducting experimental research, careful attention must be paid to selecting materials and determining machining parameters, as these factors play a pivotal role in ensuring the results' reliability and reproducibility. The following subsection explains the rationale behind selectingspecific materials and the machining parameters employed in the current study.

2.1.1 Material selection

The selection of Aluminium Alloy 6061 as the primary material for the manufacturing line in this study was driven by several key factors. This precipitation-hardening aluminium alloy offers an advantageous combination of high strength, good corrosion resistance and excellent machinability. Its favourable strength-to-weight ratio and workability make it suitable for various manufacturing processes, including extrusion, forging and machining. Moreover, the naturally formed oxide layer on Aluminium Alloy 6061 provides superior corrosion resistance compared to many other aluminium alloys, allowing it to withstand harsh environments and prolonged service conditions. Table 1 shows the material composition of aluminium alloy 6061.

Table 1
AL6061 composition [21,22]

Alloy	Mg	Si	Fe	Mn	Cu	Cr	Zn	Ti	Al
AL6061	0.95	0.54	0.22	0.13	0.17	0.09	0.08	0.01	Bal.

2.1.2 Work piece

The following drawing illustrates the detailed dimensions of the machined component, with the units specified in millimetre (mm). Before the machining process, the raw mat was prepared based on these dimensions. Typically, the size of the raw material was augmented by approximately 5mm more for both length and width and up to 8mm for thickness, relative to the target dimensions of the final machined part as shown in Figure 1.

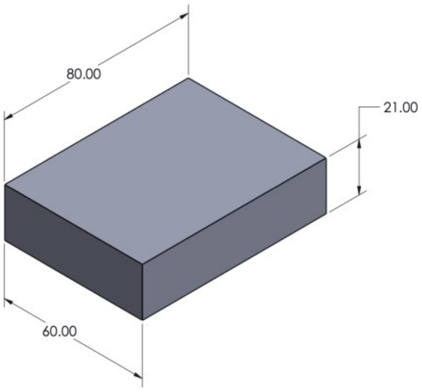

Fig. 1. The detailed dimensions of the workpiece

To ensure precision and accommodate the material removal during machining, the raw material was intentionally oversized in comparison to the desired final dimensions. This practice is common in manufacturing processes, as it allows for removing excess material and achieving the specified tolerances. The machining operation can effectively shape the component to the required dimensions while maintaining dimensional accuracy and surface finish by starting with a slightly larger workpiece.

2.1.3 Machining parameters

Before machining using the Hision VMC 850 CNC machine, the aluminium 6061 sample was securely mounted in a vise, ensuring a minimum protrusion of 15 mm to prevent dislodgement during the cutting process. Work offset was meticulously established by referring to the setup sheet and validated for accuracy. The selected tool was a 32mm insert cutter (tool number 76 or T76) with a 150mm protrusion length (PL) and an FMB X100 Arbor type. Strict adherence to sample preparation protocols, including dimensional checks, ensured precise and consistent machining operations, contributing to reliable and replicable results. As outlined in Table 2, the machining parameters and settings were carefully followed.

Table 2
Machine parameters

No.	Parameters	Setting
1	Spindle speed	1500 RPM
2	Feed Rate: -	
	z-axis	2000 mm/min
	y-axis	300 mm/min

Additionally, Figure 2 and Figure 3 depict the surface layout of the sample,illustrating the upper and bottom surfaces, respectively, to be machined using the Hision VMC 850 CNC machine.

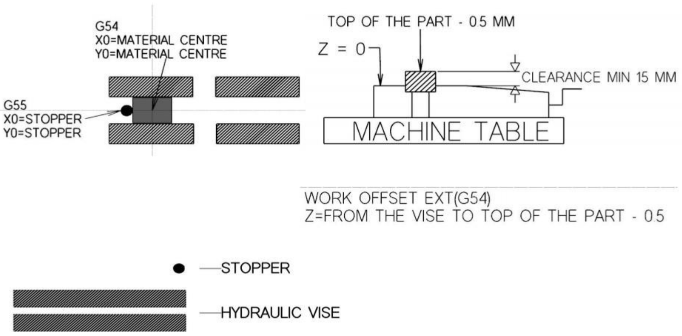

Fig. 2. Experimental setup for upper surface

2.2 Coolant Preparation

Selecting and preparing an appropriate coolant ensures efficient material removal, prolonged tool life and desirable surface finishes. For the present study, two types of coolants, Coolant A (water-based) and Coolant B (Synthetic-based), were employed to investigate their influence on the machining process and the resulting workpiece characteristics. Five (5) distinct concentrations were chosen to evaluate the effects of coolant concentration on the machining process: 5%, 7%, 9%, 10% and 11%. While the coolant provider typically recommends a 9% concentration for optimal performance, the inclusion of lower and higher concentrations in this study aimed to provide a comprehensive understanding of the influence of coolant concentration on various machining parameters and output characteristics. The total capacity of the coolant used is approximately 50 litres and it is located in the CNC tank. This approach enables the identification of an optimal coolant concentration that balances machining performance, cost-effectiveness and environmental sustainability.

The properties for both coolants A and B are tabulated in Table 3 and Table 4 below.

Table 3
The properties of Coolant A

Chemical name	Weight-%
pH-value:	9.6 (ASTM D1287)
Flash point:	Not Determined
Density at 20 °C:	0.970 (DIN 51757 | ASTM D1217)

Table 4
The properties of Coolant B

Chemical name	Weight-%
pH-value:	8.5-9.2 @50 g/l H2O (DIN 51369 / ASTM D1287)
Flash point:	136 C° (ISO 2592 / ASTM D92)
Density at 20 °C:	0.96 g/cm° (DIN 51757 | ASTM D1217)
Kinematic at 40 °C:	45.8mm% (ISO 3104 / ASTM D445)

2.3 Instrumentation and Data Collection

The instruments utilized in this study, including precision measuring tools and machining equipment, undergo periodic calibration procedures to ensure accurate and reliable measurements and performance.

The instruments used in this research are listed in Table 5 below: -

Table 5
Instruments list

No	Types of instruments
1	Refractometer
2	Mitutoyo SJ-410 Electronic Surface Roughness
3	Hexagon Captura Volumetric Wear Method (VMM)

Regular calibration practices are implemented to maintain the validity and reproducibility of the experimental results, adhering to industry standards and best practices. To ensure the reliability and accuracy of the results, data collection for each experimental condition was performed five (5) times, allowing for the calculation of mean values and the identification of any potential outliers orvariability in the measurements. Surface roughness measurements were taken eight (8) times randomly and repeated three (3) times for three (3) different samples to ensure the reliability and validity of the results. Measurements were taken both before and after machining. The collected data was statistically analysed to determine the mean, standard deviation and range of surface roughness for each concentration. Importantly, all Ra values must be below 13 µin, where the clientsspecifically set this value.

3. Results

3.1 Cooling Concentration

This section discusses the outcomes derived from analysing the impact of two principal coolants on surface roughness, alongside their consequential influence on the machining process and the resulting characteristics of the workpiece. Subsequent discussions will delve into the outcome of employing varied concentrations of Coolant A and Coolant B coolants, as outlined in the following subsection.

3.1.1 Coolant A concentration

The outcomes of the experimental investigation, focusing on surface roughness measurements before and following machining operations with varied concentrations of Coolant A, are summarized in Table 4 and visually depicted in Figure 3.

Table 6 presents a detailed analysis of surface roughness data for individual specimens across the range of coolant concentrations examined.

Table 6
The detail values of surface roughness for coolant A concentration

	Sample 1				Sample 2				Sample 3			
Concentration	Pre- Machining		Post-Machining		Pre- Machining		Post-Machining		Pre- Machining		Post-Machining	
	Avg. Ra (µin)	Std. Dev. (µin)	Avg. Ra (µin)	Std. Dev. (µin)	Avg. Ra (µin)	Std. Dev. (µin)	Avg. Ra (µin)	Std. Dev. (µin)	Avg. Ra (µin)	Std. Dev. (µin)	Avg. Ra (µin)	Std. Dev. (µin)
5%	32.90	1.62	7.25	1.31	34.12	1.55	8.30	1.45	33.60	1.98	7.57	0.93
7%	32.00	1.92	6.75	1.10	33.98	2.49	6.30	1.68	31.07	4.67	6.51	1.25
9%	32.38	4.68	5.40	1.32	29.27	5.53	5.76	1.03	33.80	3.34	5.02	0.76
10%	32.25	2.19	3.18	1.08	32.55	1.80	3.05	0.99	34.25	2.25	3.06	1.22
11%	31.72	3.68	2.63	0.75	34.10	1.97	2.67	0.67	34.47	3.56	2.74	0.80

Figure 3 complements this information by offering a graphical interpretation of the results, showcasing the average surface roughness values and standard deviation extracted from Table 6 and the average values from Table 6 are tabulated in Table 7. This visual format enables a straightforward assessment of how coolant concentration impacts effectiveness and aids in recognizing patterns of surface quality enhancement. The combination of tabular and graphical data presentation facilitates a comprehensive understanding of the relationship between coolant concentration and machining outcomes, allowing for informed comparisons and trend identificationin surface finish improvement across the spectrum of concentrations studied.

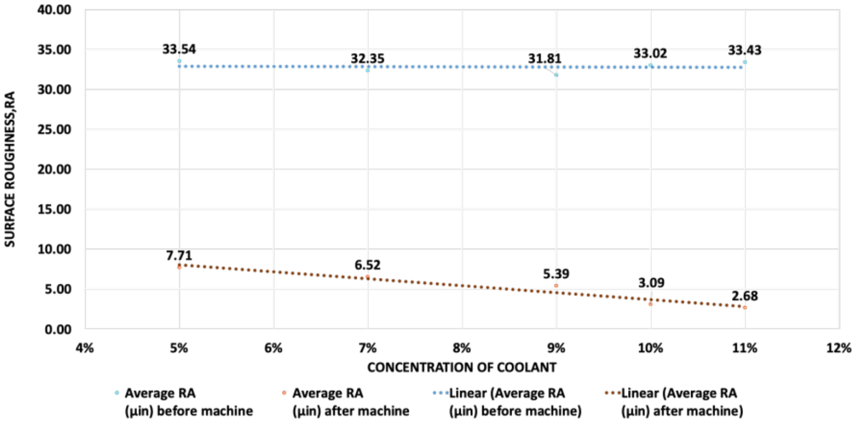

Fig. 3. Surface roughness for coolant A concentration

Table 7
The average value on surface roughness for coolant A concentration

Concentration (%)	Avg. Ra (µin) Pre-Machining	Avg. Ra (µin) post-machining
5%	33.54	7.71
7%	32.35	6.52
9%	31.81	5.39
10%	33.02	3.09
11%	33.43	2.68

The experimental investigation into the effects of Coolant A on the surface roughness of AL6061-T6 aluminium alloy during machining processes has yielded significant insights into the relationship between coolant concentration, chemical properties and machining effectiveness. This study, examining concentrations ranging from 5% to 11%, reveals a clear trend of improving surfacefinish with increasing coolant concentration while highlighting the complex interplay between the coolant's chemical properties and the machining process.

Before machining, the specimens exhibited considerable variability in surface conditions, with average Ra values spanning from 29.27 µin to 34.47 µin across all concentrations. This heterogeneity, reflected in standard deviations ranging from 1.55 µin to 5.53 µin, mirrors real-world manufacturing scenarios, enhancing the practical relevance of our study. Post-machining analysis revealed a substantial reduction in surface roughness across all coolant concentrations, with Ra values ranging from 2.63 µin to 8.30 µin, demonstrating the overall effectiveness of both the machining process and Coolant A in enhancing surface finish.

The performance of Coolant A showed a clear concentration-dependent trend. At 5% concentration, while showing substantial improvement from pre-machining conditions, the coolant yielded the highest post-machining Ra values (7.25 - 8.30 µin). This relatively poorer performance can be attributed to insufficient concentration of key chemical properties. The alkaline nature of Coolant A (pH 9.6) likely provides inadequate corrosion protection and lubricity at this low concentration [23]. The coolant's high kinematic viscosity (> 22 cSt at 40°C) may not be fully leveraged at 5% concentration, resulting in suboptimal lubrication and chip evacuation. As concentration increased to 7% and 9%, a gradual enhancement in surface finish was observed, with post-machining Ra values decreasing to 6.30 - 6.75 µin and 5.02 - 5.76 µin, respectively. This improvement can be linked to the increasing influence of the coolant's chemical properties [24]. The higher concentration likely results in more effective alkalinity at the cutting interface, providing better corrosion protection for the freshly machined aluminium surface. The coolant's density (0.970 at 20°C), slightly lower than water, may also improve heat dissipation and fluid dynamics in the cutting zone as concentration increases.

A significant leap in performance was observed at 10% concentration, with post-machining Ra values dropping dramatically to 3.05 - 3.18 µin. This marked improvement suggests a possible threshold effect, where the coolant's effectiveness increases substantially. At this concentration, the synergistic effects of alkalinity, density and viscosity likely reach levels that dramatically enhance the coolant's lubrication, cooling and chip removal capabilities. The higher viscosity at this concentration may promote the formation of a more stable lubricating film between the cutting tool and the workpiece, reducing friction and minimizing surface irregularities [25]. The 11% concentration emerged as the most effective, consistently achieving the lowest post-machining Ra values (2.63 - 2.74 µin) across all three samples. Moreover, it demonstrated the lowest variability in post-machining measurements, with standard deviations ranging from 0.67 to 0.80 µin. This optimal performance can be attributed to this concentration's ideal balance of chemical properties. The maximum alkalinity provides enhanced corrosion protection and lubricity, while the optimized viscosity ensures efficient chip evacuation and stable boundary layer formation on the machined surface [26].

The progressive improvement in surface finish from 5% to 11% concentration reveals a clear positive correlation between coolant concentration and machining effectiveness. This relationship can be attributed to several factors. Firstly, the enhanced lubrication provided by the coolant's high kinematic viscosity becomes more pronounced at higher concentrations, promoting the formation of a more stable lubricating film. Secondly, the coolant's density influences its heat capacity and flow characteristics, potentially optimizing heat dissipation and coolant penetration in the cutting zone as concentration increases. Thirdly, higher concentrations may improve the coolant's ability to flush away chips and debris, preventing the re-deposition of aluminium particles onto the machined surface [27,28]. The consistent decrease in variability across higher concentrations indicates that the machining process, in conjunction with Coolant A, improves the average surface finish and enhances surface uniformity. This dual benefit is particularly valuable in manufacturing processes where consistency is as crucial as the absolute surface roughness value. The alkaline nature of the coolant likely contributes to preventing the re-deposition of aluminium particles onto the machined surface, which becomes more effective at higher concentrations [29].

These findings significantly affect industrial applications, particularly in precision manufacturing, where surface finish quality is paramount. By optimizing coolant concentration basedon its chemical properties, manufacturers can potentially achieve better surface finishes, reduce variability in their processes and improve overall product quality. The optimal performance observed at 11% concentration suggests that this level may be ideal for achieving superior surface finishes in AL6061-T6 machining processes requiring the highest quality. This comprehensive study demonstrates that the relationship between Coolant A concentration and surface roughness is intricately linked to its chemical properties. The alkaline pH, specific density and high kinematic viscosity collectively contribute to the coolant's effectiveness in reducing surface roughness [30]. As concentration increases from 5% to 11%, these properties synergistically enhance the coolant's performance, resulting in progressively better surface finishes and more consistent machining outcomes. These findings contribute to our understanding of coolant behaviour in precision machining and offer practical guidelines for optimizing machining processes in industrial settings.

3.1.2 Coolant B concentration

The experimental results detailing the surface roughness measurements before and after machining, with the application of Coolant B at various concentrations, are presented in Table 8 and graphically illustrated in Figure 4.

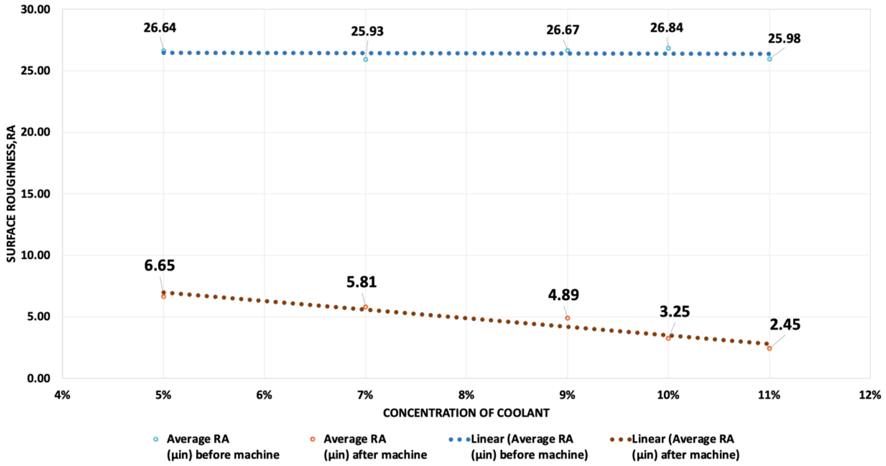

Fig. 4. Surface roughness for Coolant B concentration

Table 8 provides a comprehensive breakdown of the surface roughness values for each sample across different coolant concentrations.

Table 8
The value of surface roughness for Coolant B concentration

Concentration	Sample 1				Sample 2				Sample 3			
	Pre-Machining		Post-Machining		Pre-Machining		Post-Machining		Pre-Machining		Post-Machining	
	Avg.Ra (µin)	Std. Dev. (µin)	Avg. Ra (µin)	Std. Dev. (µin)	Avg.Ra (µin)	Std. Dev. (µin)	Avg. Ra (µin)	Std. Dev. (µin)	Avg.Ra (µin)	Std. Dev. (µin)	Avg. Ra (µin)	Std. Dev. (µin)
5%	25.02	2.12	6.16	1.13	26.50	2.42	6.87	1.51	28.41	2.93	6.93	1.41
7%	25.63	1.00	5.83	1.25	25.79	3.41	5.93	0.68	26.37	2.15	5.67	0.59
9%	25.99	1.69	5.22	0.59	26.06	2.37	4.54	0.65	27.98	1.29	4.89	0.67
10%	26.62	4.37	2.79	0.75	25.40	2.82	3.81	0.98	28.49	4.86	3.16	0.63
11%	25.12	2.82	2.35	0.29	26.16	2.94	2.60	0.62	26.66	3.10	2.40	0.27

Figure 4 offers a visual representation of these findings, displaying the mean surface roughness values derived from the data in Table 8 and the average values from Table 8 are tabulated in Table 9. This graphical representation allows for a clear comparison of the coolant's effectiveness across different concentrations and facilitates the identification of trends in surface finish improvement.

Table 9
The average value of surface roughness for Coolant B concentration

Concentration	Avg. Ra (µin) Pre-Machining	Avg. Ra (µin) Post-Machining
5%	26.64	6.65
7%	25.93	5.81
9%	26.67	4.89
10%	26.84	3.25
11%	25.98	2.45

Pre-machining surface conditions exhibited average Ra values ranging from 25.02 µin to 28.49µin, with standard deviations between 1.00 µin and 4.86 µin. This variability in initial surfaceconditions closely mirrors real-world manufacturing scenarios, enhancing the practical relevance of the study. Post-machining analysis revealed a substantial reduction in surface roughness across all coolant concentrations, with Ra values decreasing to 2.35-6.93 µin, demonstrating the overalleffectiveness of both the machining process and Coolant B in improving surface finish. The data showed a clear trend of improving surface finish with increasing coolant concentration. The 5% concentration, while showing substantial improvement from pre-machining conditions, yielded the highest post-machining Ra values (6.16-6.93 µin). As concentration increased to 7%, the surface finishwas improved, with post-machining Ra values decreasing to 5.67-5.93 µin. The 9% concentration further enhanced surface quality, producing post-machining Ra values of 4.54-5.22 µin.

A significant leap in performance was observed at 10% concentration, with Ra values dropping dramatically to 2.79-3.81 µin. This marked improvement suggests a possible threshold effect where coolant effectiveness increases substantially. The 11% concentration emerged as the most effective, consistently achieving the lowest post-machining Ra values (2.35-2.60 µin) across all three samples and demonstrating the lowest variability (standard deviations 0.27-0.62 µin). To explain the mechanisms behind this concentration-dependent performance, it is crucial to consider the chemical properties of Coolant B. The moderately alkaline nature of the coolant (pH 8.5-9.2 @50 g/l H2O) plays a significant role in its effectiveness. As concentration increases, the pH at the cutting interface likely shifts towards the upper end of this range, contributing to improved surface finish through several mechanisms [31].

The alkaline nature of the coolant is likely to influence the machining process in several ways. Initially, the oxide layer on the aluminium workpiece may undergo alterations within this environment, potentially enhancing coolant-workpiece interaction. This could manifest in improved lubrication and diminished frictional resistance, especially at elevated coolant concentrations. Furthermore, the coolant's moderately alkaline pH level suggests a possible chemical polishing effect on the aluminium surface during machining. This effect is speculated to intensify with increased coolant concentration, contributing to the observed enhancement in surface finish quality [32-34]. Finally, the pH range of Coolant B appears to foster the creation of a stable emulsion, particularly at higher concentrations. This stability contributes to consistent coolant performance and a uniform surface finish on the machined workpiece.

The high flash point of Coolant B (136°C) indicates its thermal stability, suggesting that the coolant maintains its effectiveness even under high-temperature conditions that may occur during machining. This property could contribute to the consistent performance observed across different concentrations, especially in maintaining coolant integrity during more intensive machining operations.

The density of Coolant B (0.96 g/cm^3 at 20°C), being slightly lower than water, influences its behaviour during the machining process in several ways. The lower density may enhance the coolant's ability to penetrate the cutting zone, particularly at higher concentrations, leading to more effective cooling and lubrication at the tool-workpiece interface [35]. Additionally, the density characteristics of Coolant B might optimize its chip-flushing capabilities. As concentration increases, the altered fluid dynamics could enhance chip removal, preventing re-cutting and surface damage, thus contributing to the smoother finishes observed at higher concentrations.

The relatively high kinematic viscosity of Coolant B (45.8 mm^2/s at 40°C) significantly impactsits performance across different concentrations. The high viscosity likely contributes to forming a strong lubricating film between the cutting tool and the workpiece. As concentration increases, this film may become more robust, reducing friction and improving surface finish [36,37]. Moreover, theviscosity characteristics of Coolant B could promote beneficial hydrodynamic effects in the cutting zone, potentially leading to more stable cutting conditions and reduced tool vibration, contributing to smoother surface finishes. The progressive improvement in surface finish from 5% to 11% concentration can be attributed to the synergistic effects of these chemical properties. At lower concentrations (5-7%), the coolant's performance is limited by insufficient presence of its key components. As concentration increases to 9%, a more optimal balance of these properties is achieved, improving surface finishes.

The significant performance leap observed at 10% concentration suggests a critical threshold where the interplay of pH, density and viscosity reaches a highly effective level. This could be due to the formation of optimal emulsion characteristics or the achievement of a critical concentration necessary for the coolant's chemical and physical properties to fully manifest their benefits. The superior performance at 11% concentration indicates that Coolant B achieves an ideal balance of its chemical properties at this level. The enhanced alkalinity, optimized density and increased viscosity at this concentration likely create a highly stable and effective cutting environment, resulting in the best surface finishes and lowest variability observed in the study. However, it is important to note that while the 11% concentration produced the best results, the marginal improvement over the 10% concentration (approximately 0.4-1.2 µin in Ra value) raises questions about cost-effectiveness in industrial applications. This consideration highlights the importance of balancing performance requirements with economic factors in real-world manufacturing scenarios. This comprehensive analysis also demonstrates that the effectiveness of Coolant B in reducing surface roughness is intricately linked to its unique chemical properties and concentration.

4. Conclusions

This study comprehensively examined the effects of Coolant A and Coolant B at varying concentrations (5%, 7%, 9%, 10% and 11%) on the surface roughness (Ra) of AL6061-T6 aluminium alloy during machining. The findings revealed a clear trend: higher coolant concentrations significantly improved surface finish, reducing RA values more effectively. Coolant A and B showed a substantial reduction in post-machining Ra, with Coolant A's optimal performance at 11% concentration achieving the lowest RA values (2.63-2.74 µin) and highest consistency. Coolant B also exhibited the best results at 11%, with RA values ranging from 2.35 µin to 2.60 µin and minimal variability. In particular, a significant improvement was observed between the 9% and 10% concentrations for both coolants, suggesting a critical threshold for optimal performance. Importantly, all Ra values obtained in this study were below the client's specified limit of 13 µin. This significant improvement in surface finish is attributed to the enhanced chemical properties of the coolant at higher concentrations, such as increased alkalinity, optimized viscosity and better heat dissipation, which collectively contribute to improved lubrication, cooling, chip removal capabilities and more stable cutting conditions. Therefore, the 11% concentration provided the best outcomes, the marginal gains over the 10% concentration highlight important cost-effectiveness considerations for industrial applications. This study underscores the importance of selecting the appropriate coolant concentration to balance performance and economic factors, offering valuable insights for more efficient and cost-effective machining processes.

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