Mathematical Modelling of Engineering Problems
Vol. 12, No. 3, March, 2025, pp. 893-899
Journal homepage: http://iieta.org/journals/mmep

Exploring the Synergistic Impact of Air Gun Cooling and Nanoparticle Application on Milling Surface Roughness

Vu-Hai Le, Thi-Nien Nguyen, Trieu Khoa Nguyen*

Faculty of Mechanical Engineering, Industrial University of Ho Chi Minh City, Ho Chi Minh City 70000, Vietnam

Corresponding Author Email: nguyenkhoatrieu@iuh.edu.vn

https://doi.org/10.18280/mmep.120315

Received: 25 November 2024
Revised: 7 February 2025
Accepted: 12 February 2025
Available online: 31 March 2025

Keywords:
cold air gun cooling, Al_2O_3 nanoparticles, surface roughness, milling performance, SKD11 steel, Taguchi method

ABSTRACT

This study investigates the synergistic effects of cold air gun cooling and Al_2O_3 nanoparticle lubrication on the milling process of SKD11 steel (50 HRC) using 10 mm TiAlN-coated end mills. The research focuses on critical process parameters, including nanoparticle concentration (4% by weight), coolant flow rate (100 ml/h), and air pressure (3 kg/cm²), to assess their influence on surface roughness (Ra) and overall machining performance. Experimental results demonstrate that cold air cooling significantly lowers cutting tool temperatures, thereby enhancing tool life and stability during the milling process. Furthermore, an optimized combination of flow rate and moderate pressure notably improves surface quality, as evidenced by a detailed analysis of Signal-to-Noise (S/N) ratios and Analysis of Variance (ANOVA). However, an intriguing finding emerged: increasing air pressure beyond an optimal threshold negatively impacted surface roughness, likely due to turbulence-induced disruptions in cooling uniformity. This challenges traditional expectations regarding the role of air pressure in machining and underscores the importance of understanding vortex cooling dynamics. With a predictive model achieving 95.27% accuracy (R^2), this research provides a comprehensive framework for optimizing the interplay between cooling methods and nanoparticle-based lubrication. The findings highlight the potential of these combined strategies to improve surface finish, machining precision, and overall milling efficiency, paving the way for future innovations in high-precision machining processes.

1. INTRODUCTION

Milling is a critical machining process widely employed in manufacturing, particularly for shaping and finishing high-performance materials such as SKD 11 steel, which is known for its exceptional hardness, wear resistance, and dimensional stability, especially after undergoing heat treatment [1]. This makes SKD 11 steel a popular choice in industries requiring precision and durability, such as mold and die manufacturing [2-4]. However, the inherent hardness of SKD 11 poses significant challenges during machining, including increased tool wear, high cutting forces, and elevated temperatures [5]. For instance, according to Denkena et al. [5], machining hardened steels generates significant heat and cutting forces, which can adversely affect tool life and surface quality [6, 7]. The intense heat generated at the cutting zone not only accelerates tool degradation but also risks compromising the surface integrity and dimensional accuracy of the workpiece [8]. These challenges highlight the necessity for advanced cooling and lubrication strategies, such as Minimum Quantity Cooling Lubrication (MQCL), to manage thermal effects effectively, reduce tool wear, and ensure superior machining efficiency and product quality [9-11].

In traditional machining processes, various cooling and lubrication methods have been employed to mitigate the adverse effects of heat generation and reduce tool wear. Flood cooling, is one of the most common techniques, where large volumes of coolant are applied directly to the cutting zone. While effective in cooling the tool and workpiece, this method consumes a significant amount of coolant, leading to environmental concerns and increased costs, as well as challenges in cleaning and disposal. Additionally, flood cooling may not always provide adequate lubrication, which can contribute to high friction and wear, particularly in hard machining applications like SKD 11 steel [12, 13].

Another widely used technique is conventional minimum quantity lubrication (MQL), where a small amount of lubricant is supplied directly to the cutting area [13, 14]. MQL offers advantages in terms of reduced coolant usage and improved environmental sustainability. However, it still faces limitations in terms of cooling efficiency, particularly when machining high-strength materials such as hardened steels, where heat generation can exceed the cooling capacity of conventional MQL. This can result in tool wear and surface defects, which can impact the overall machining quality and tool life [15, 16].

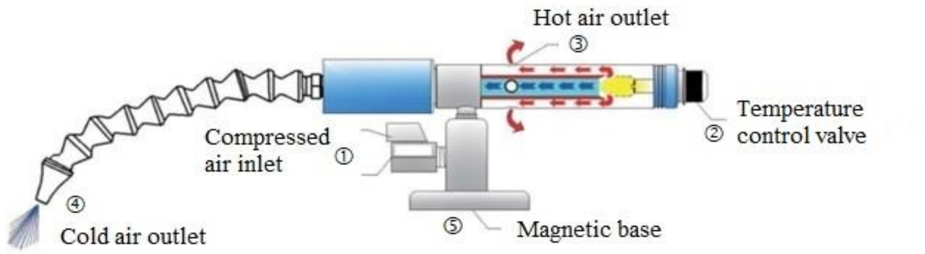


Figure 1. Cold air gun from Sunair brand

In some cases, dry machining has been used as an alternative, eliminating the need for any cooling or lubrication altogether. While this method eliminates coolant-related issues, it often leads to increased tool wear, higher temperatures, and poorer surface finish, especially when machining materials with high hardness like SKD 11. Dry machining also fails to prevent built-up edge (BUE) formation, which can further degrade the machining performance and tool life [17].

Among various cooling methods, air gun cooling has gained attention for its effectiveness in reducing heat at the cutting interface through the use of compressed air. The cold air used for cooling was supplied by a cold air gun system, consisting of a vortex tube, a hot muffler, and a cold muffler (Figure 1). The vortex tube separates compressed air into cold and hot streams. Compressed air enters the vortex tube through an inlet, where it is split into two lower-pressure air streams. These streams, one cold and one hot, are then expelled into the surrounding environment through the respective cold and hot mufflers. This technique not only lowers the temperature during milling but also helps prolong tool life by minimizing thermal degradation. Using cold air gun in fine grinding process, Chou et al. [18] observed that the cold air gun cooling system offered superior penetration into the grinding zone, providing effective cooling and lubrication between the grinding wheel and the workpiece surface. It minimized surface damage and facilitates the formation of fine, brittle chips with ease. Stachurski and Nadolny [19] suggested further investigation should focus on improving the lubricating and cooling performance of the MQL-CCA (i.e., minimum quantity lubrication and compressed cold air) method. Singh et al. [20] introduced a system that integrates a minimum quantity lubrication (MQL) setup with a Ranque-Hilsch vortex tube (RHVT) for use in the turning of grade two titanium. Their findings revealed that this combination resulted in a 15–18% improvement in surface roughness compared to the standalone MQL system. Furthermore, reductions in tool wear and cutting force were observed with the use of the MQL and RHVT approach.

Comparatively, advanced cooling methods, such as cryogenic cooling [20] and flood coolant systems, have also been explored in recent years. Cryogenic cooling [21], which utilizes liquid nitrogen, can achieve lower temperatures but may involve higher costs and safety concerns. In addition, EkiCi and Uzun found out that cryogenic treatment was unable to provide a significant difference in terms of cutting force or surface roughness based on grey relational analysis (GRA) method [22]. Flood coolant systems, while effective in heat dissipation, can lead to environmental issues and require extensive clean-up. In contrast, air gun cooling offers a cleaner, more straightforward approach that can be adapted to various machining environments.

As for the lubricating goal, recent researches have highlighted the potential benefits of incorporating nanoparticles into cooling strategies. In a comprehensive review, Kadirgama [23] systematically labeled different type of cutting fluids. The conclusion of the research summarized all the advantages of the nanofluids compared to other applications. Nano-sized Al_2O_3 particles, in particular, have been shown to improve thermal conductivity and reduce friction at the cutting edge, leading to enhanced machining performance. Dong et al. [24] compared the effectiveness of different nanofluids and concluded that Al_2O_3 and SiO_2 not only exhibited superior surface quality and cooling capacity but were also highly suitable as environmentally friendly additives. Various authors have contributed their studies on the performance of nanoparticles [25-28]. On the other hand, Dong et al. [29] introduced a machining setup utilizing a minimum quantity cooling lubrication (MQCL) technique with MoS2 nanofluid, integrated with a Ranque–Hilsch vortex tube, known as the Frigid-X Sub-Zero Vortex Tool Cooling Mist System. The researchers claimed that this setup provided excellent cooling and lubricating capabilities, allowing the use of standard cutters at 2.0 to 2.2 times the cutting speed recommended by the manufacturer. In an effort to enhance machining performance while supporting sustainable production, Celent et al. [30] introduced a compressed cold air cooling (CACC) system, which they referred to as smart manufacturing. This approach was compared to both dry machining (DM) and traditional machining with the use of cutting fluids (CFs). Through extensive experimental research, the CACC system achieved the best surface roughness results. The CACC system was also implemented with a Ranque–Hilsch vortex tube.

The application of cold air in machining has been considered by researchers for a long time [31, 32]. Previous studies have consistently demonstrated its undeniable benefits, including enhanced tool life, improved surface finish, and its role as an environmentally friendly alternative to conventional cooling methods. The combination of cold air cooling with nanoparticle-based minimum quantity lubrication (nano-MQL) presents an optimal approach for machining hard materials, leveraging both effective heat dissipation and superior lubrication. Therefore, further research is needed to explore this synergy in machining specific materials and to investigate the potential of novel nanoparticles and lubricant formulations for enhanced performance. This study investigates the combined effects of using a cold air gun and nano-sized Al_2O_3 particles during the milling of heat-treated SKD 11 steel, a material known for its hardness and wear resistance. Specifically, the research focuses on examining the impact of several key factors on the milling performance, including cooling conditions, nanofluid concentration, flow rate, and applied pressure. These variables are critical in determining the effectiveness of the cooling and lubrication mechanisms, which play a significant role in reducing tool wear and improving surface finish. The study aims to assess how different concentrations of Al_2O_3 nanoparticles, coupled with optimized cooling conditions, can minimize surface roughness, a key performance indicator. By analyzing these variables, the research seeks to identify the optimal parameters that not only enhance the machining quality but also improve the overall efficiency of the milling process. This approach promises to contribute to more effective, sustainable, and cost-efficient machining practices, addressing the challenges of high-performance material processing in modern manufacturing environments.

2. EXPERIMENTAL SETUP

To conduct the experiments, a 5-axis DMU50 milling machine was employed, as shown in Figure 2. The room temperature was maintained around 30℃ using an air-conditioning system to ensure consistent thermal conditions. The workpiece used in the tests was fabricated from SKD11 steel, with dimensions of 50mm in width, 150 mm in length, and 80 mm in height. The material had been heat-treated to achieve a hardness of 50HRC. The workpiece was securely clamped on the CNC machine table using a universal fixture. For the cutting tools, TiAlN-coated end mills with a diameter of 10 mm were selected.

Figure 2. Experimental setup

The cooling and lubrication were achieved using a cutting oil, CT232, combined with nano-sized Al_2O_3 particles that had a purity of 99.9% and an average particle size of 20 nm. For the preparation of the nanofluid, nano-sized Al_2O_3 particles were dispersed into the cutting fluid using an ultrasonic vibrator for 6 hours to ensure uniform dispersion and prevent agglomeration. The prepared nanofluid was used immediately after preparation. A dedicated MQL nozzle was used for the delivery of this nanofluid, separate from the cold air gun system. The cold air gun, sourced from Sunair (China), delivered compressed air with a nozzle tip temperature ranging between 6-8℃, while the ambient room temperature was maintained around 30℃. The combination of the cold air gun and nanoparticles was carefully chosen to enhance the cooling and lubrication effects during the milling process.

Surface roughness was measured immediately after each experiment at three different positions on the workpiece, and the average value was taken as the final result. The surface roughness tester used was the Mitutoyo SJ-401 model from Mitutoyo. For data analysis, Minitab V17 software was employed to perform statistical analysis and identify optimal milling parameters. Table 1 shows the selection of investigating parameters.

Table 1. Parameters level

Parameters		Levels		
Notations	**Meanings**	**1**	**2**	**3**
CL	Cooling with air gun	1 (no)	2 (yes)	
C	Nanoparticle concentration (w%)	0	2	4
F	Flow rate (ml/h)	60	80	10
P	Pressure (kg/cm^2)	3	4	5

3. RESULTS AND DISCUSSIONS

The experimental results, presented in Table 2, reflect the 18 runs performed according to the Taguchi method. The Taguchi design allowed for the systematic variation of key parameters, such as pressure, flow rate, and nanoparticle concentration, to assess their effects on surface roughness and tool performance during the milling of SKD11 steel. The surface roughness (Ra) ranged from a minimum of 0.141 µm (experiment 15) to a maximum of 0.333 µm (experiment 1). At the lowest Ra (experiment 15), the parameters were: cooling method CL=2 (cold air), nanoparticle concentration C=2% w, flow rate F=100 ml/h, and pressure P=3 kg/cm². Conversely, at the highest Ra (experiment 1), the parameters were: cooling method CL=1 (no cold air), nanoparticle concentration C=0% w, flow rate F=60 ml/h, and pressure P=3 kg/cm².

Main effects plot for SN ratios presented on Figure 3. Applying the cold air gun, highest nanoparticle concentration (4%), highest flow rate (100 ml/h), and lowest pressure (3 kg/cm²) are likely to provide the best surface finish based on this S/N ratio analysis. The unexpected finding that higher pressure decreases surface quality challenges conventional thinking, offering a new avenue of investigation. It suggests that beyond a certain threshold, increasing pressure might induce turbulent flow, disrupting the cooling effect. A new investigation into the dynamics of the flow and pressure in vortex-based systems could lead to better designs that maintain cooling effectiveness without introducing excessive turbulence. This situation also aligns with the findings of Zhang et al. [33], who investigated the effect of nanoparticle concentration on the lubricating properties of nanofluids in MQL grinding of Ni-based alloys. Their study revealed that as the nanoparticle concentration increases beyond an optimal level, the viscosity of the nanofluid rises significantly, leading to diminished lubricating efficiency. This suggests that while increasing concentration initially enhances the cooling and lubricating effects, exceeding a saturation threshold induces adverse effects on machining performance.

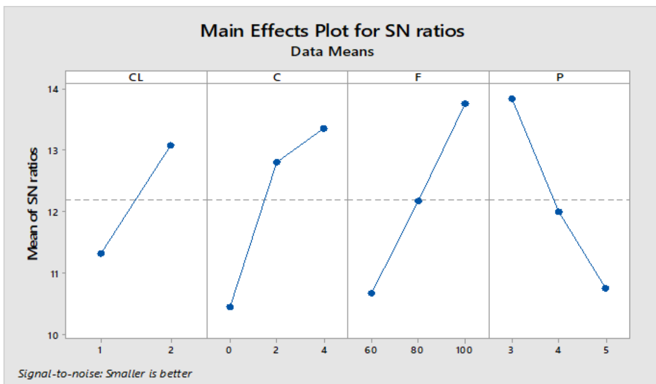


Figure 3. Main effects plot for SN ratios

Table 2. Experimental results

No.	CL	C (w%)	F (ml/h)	P (kg/cm^2)	Ra (μm)	S/N
1	1	0	60	3	0.333	9.551115
2	1	0	80	4	0.329	9.656082
3	1	0	100	5	0.331	9.60344
4	1	2	60	4	0.312	10.11691
5	1	2	80	5	0.301	10.42867
6	1	2	100	3	0.172	15.28943
7	1	4	60	5	0.31	10.17277
8	1	4	80	3	0.199	14.02294
9	1	4	100	4	0.222	13.07294
10	2	0	60	3	0.273	11.27675
11	2	0	80	4	0.279	11.08792
12	2	0	100	5	0.267	11.46977
13	2	2	60	4	0.252	11.97199
14	2	2	80	5	0.253	11.93759
15	2	2	100	3	0.141	17.01562
16	2	4	60	5	0.285	10.9031
17	2	4	80	3	0.161	15.86348
18	2	4	100	4	0.157	16.08201

Table 3. Comparison of surface roughness

The Experiment	Cutting Condition				Ra (μm)
	CL	C (w%)	F (ml/h)	P (kg/cm^2)	
Validation experiment	Yes	4	100	3	0.138
Experiment 15	Yes	2	100	3	0.141

The optimal conditions obtained from the model, with CL at level 2, C at level 3, F at level 3, and P at level 1, are not included in the experimental table (Table 2). Therefore, a validation experiment needs to be conducted under these optimal conditions to determine the surface roughness. The results are then compared with the minimum surface roughness achieved in all experiments (in this case, experiment 15). The comparison is presented in Table 3. From this comparison, it can be observed that the surface roughness obtained under the identified optimal conditions is smaller than that of experiment 15. This demonstrates the reliability of the model.

Table 4 presents the response table for S/N ratios, which summarizes the effects of different levels of the factors CL, C, F, and P on the response. The table shows the S/N ratios for each factor at three levels. For CL, the S/N ratios at levels 1, 2, and 3 are 11.32, 13.07, and missing (indicated by "-"), respectively, with a delta of 1.74, ranking it fourth in terms of influence. Factor C has the second-lowest S/N ratio at level 1 (10.44), and the highest at level 2 (12.79), yielding a delta of 2.91, ranking it third. Factor F exhibits the highest delta of 3.09, with its S/N ratios at levels 1, 2, and 3 being 10.67, 12.17, and 13.76, respectively, earning it the top rank. Factor P has a delta of 3.08, with its S/N ratios being 13.84 at level 1, 12.00 at level 2, and 10.75 at level 3, ranking it second. This table highlights that factor F has the most significant impact on the response, followed by P, C, and CL.

Table 4. Response table for S/N ratios

Level	CL	C	F	P
1	11.32	10.44	10.67	13.84
2	13.07	12.79	12.17	12.00
3	-	13.35	13.76	10.75
Delta	1.74	2.91	3.09	3.08
Rank	4	3	1	2

Table 5. ANOVA

Source	DF	Adj-SS	Adj-MS	F-value	p-value	C (%)
Regression	4	0.066899	0.016725	65.40	0.000	95.27
C	1	0.019040	0.019040	74.45	0.000	27.11
F	1	0.018802	0.018802	73.52	0.000	26.77
P	1	0.018252	0.018252	71.37	0.000	25.99
CL	1	0.010804	0.010804	42.25	0.000	15.38
Error	13	0.003325	0.000256	-	-	
Total	17	0.070224	-	-	-	
R-sq=95.27%						

ANOVA (Table 5) is employed to examine both the individual and combined effects of the input parameters CL, C, F, and P on the output, specifically the surface roughness Ra of the machining process. The p-value in the ANOVA table serves to assess the statistical relevance of the model and the influencing factors. When the p-value is below 0.05, it indicates that the model or a specific factor has significant statistical influence. Additionally, the contribution percentage C (%) of each factor to the overall variation provides insight into the degree of impact that controllable parameters have on the model's response.

The ANOVA table shows that the regression model fits the data very well, with an R-squared value of 95.27%, indicating that the factors C, F, P, and CL explain most of the variation in the data. All of these factors have a significant impact, with a p-value of 0.000, meaning they all strongly affect the dependent variable. Specifically, factor C explains 27.11% of the variation, F accounts for 26.77%, P contributes 25.99%, and CL explains 15.38%. The F-value of the model is 65.40, which is much higher than the critical value, showing that the regression model outperforms random variation and is highly effective in predicting the outcome. These results demonstrate that the factors in the model play a crucial role in improving the research results.

Furthermore, using Minitab software and the experimental data, the second-order regression equations corresponding to the two levels of the CL factor are as follows:

For conditions without the cold air nozzle (CL at level 1):

$$Ra=0.285-0.0512*C-0.00270*F+0.0779*P+0.00592*C^2+0.000004*F^2-0.00442*P^2+0.000096*C*F-0.00050*C*P$$

For conditions with the cold air nozzle (CL at level 2):

$$Ra=0.243-0.0473*C-0.00283*F+0.0766*P+0.00592*C^2+0.000004*F^2-0.00442*P^2+0.000096*C*F-0.00050*C*P$$

The roles of factors such as flow rate (F), compressed air pressure (P), and nanoparticle concentration (C) in influencing surface roughness (Ra) are clearly demonstrated in Figure 4. The contour plot gradients in Figures 4(a) and 4(b) suggest that no single factor overwhelmingly dominates, indicating that these factors have relatively similar impacts on Ra. This observation aligns with the analysis presented in the ANOVA table (Table 5).

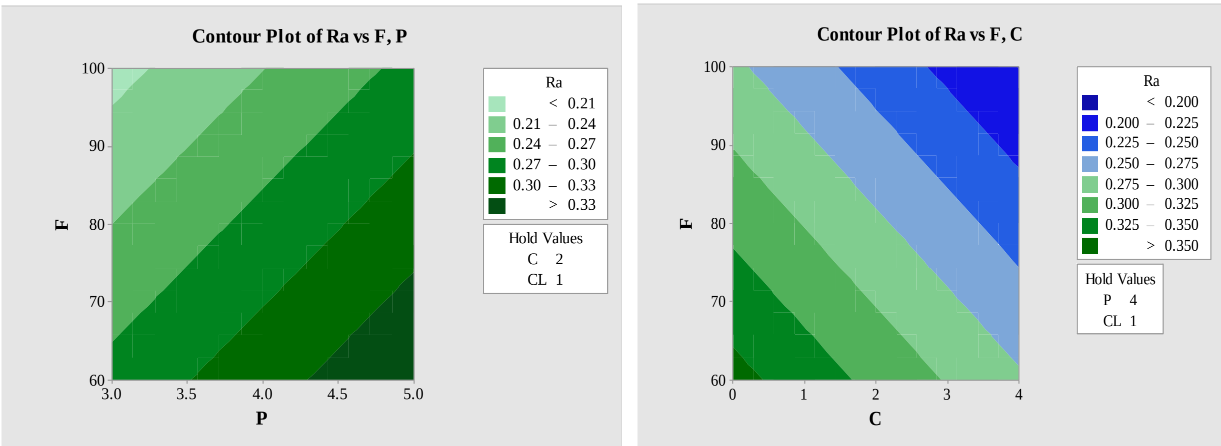
In Figure 4(a), with nanoparticle concentration (C) and lubrication condition (CL) fixed, increasing the flow rate (F) consistently reduces Ra. This can be explained by the increased flow delivering more nanofluid into the cutting zone, thereby enhancing lubrication and cooling efficiency. Similar findings were reported by Nguyen and Do [4], who observed improved surface finish when nanofluid flow was optimized [13]. Additionally, Figure 4(a) reveals an inverse relationship between pressure (P) and Ra, attributed to excessive pressure causing the cutting fluid to be blown away from the machining zone. This reduces the cooling and lubricating effectiveness, as supported by Tuan et al. [34], who highlighted the challenges of high-pressure MQL setups in open machining environments.

Figure 4(b), with pressure (P) and lubrication condition (CL) fixed, provides an additional insight. It shows that increasing the nanoparticle concentration (C) enhances the lubrication and cooling efficiency, leading to reduced surface roughness. This highlights the effectiveness of nanofluids in improving machining performance. The improved performance stems from the incorporation of nanoparticles, which augment the thermal conductivity and wetting behavior of the cutting fluid [4, 35]. This enhancement facilitates efficient heat dissipation through an improved heat exchange mechanism [36, 37].

Additionally, the lubrication efficiency of nanofluids is explained by four critical mechanisms: the rolling action of nanospheres [38, 39], which reduces friction; the self-repairing effect [40, 41], where nanoparticles fill micro-cracks to restore surfaces; the formation of a protective tribo-film that minimizes wear; and the polishing effect, which smoothens the surface during machining [42]. Collectively, these mechanisms contribute to the superior machining quality achieved with nanofluids compared to traditional cutting fluids.

Moreover, the probability plot of Ra in Figure 5 shows that the data points (blue dots) closely follow the straight line, which suggests that the surface roughness values are approximately normally distributed. Although, there are some deviations, particularly near the higher percentiles), but they are not extreme. The red curves represent the 95% confidence intervals. Most data points fall within these boundaries, further supporting the normality assumption.

The scalability of the cooling and lubrication system employed in this study shows promising potential for industrial applications. The modular design of the cold air gun and MQL system allows for flexible adaptation in large-scale CNC machining environments. Economically, the system significantly reduces coolant consumption and disposal costs. While the initial cost of nanoparticles is higher, the long-term benefits in terms of reduced tool wear, improved surface finish, and lower maintenance expenses make this solution cost-effective. Furthermore, the cleaner machining environment aligns with sustainable manufacturing practices, offering potential regulatory and environmental advantages. These factors suggest that the combined cooling and lubrication approach used in this study can be effectively implemented in industrial production settings for enhanced efficiency and sustainability.



(a) (b)

Figure 4. Plot contour

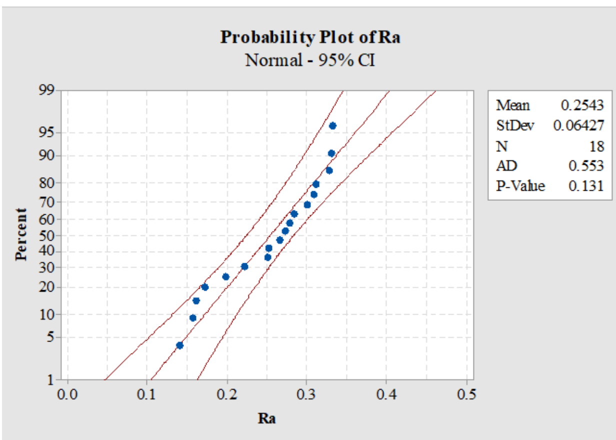


Figure 5. Probability plot of Ra

The cooling and lubrication system employed in this study offers a sustainable alternative to traditional machining processes. By utilizing a combination of cold air gun cooling and nanoparticle-enhanced MQL, the system significantly reduces the environmental impact associated with coolant usage and disposal. The cleaner machining environment not only supports health and safety standards but also aligns with global trends toward eco-friendly manufacturing practices. The scalability and cost-effectiveness of this approach make it a viable solution for industrial adoption, promoting both operational efficiency and sustainability.

This study provides valuable insights into the combined effects of air gun cooling and nanoparticle-based lubrication on surface roughness during the milling of heat-treated SKD11 steel. Future research could explore the long-term effects of nanoparticle-infused coolants on tool wear and dimensional accuracy to validate the durability and stability of this approach over extended machining operations. Moreover, the development of advanced nanoparticle formulations with superior cooling and lubrication properties holds promise for further enhancing machining performance.

4. CONCLUSIONS

This study has provided valuable insights into the combined effects of air gun cooling and nanoparticle application on surface roughness during the milling of heat-treated SKD 11 steel. Based on the results, it is evident that among the four parameters studied: air gun usage CL, nanofluid concentration C, flow rate F, and pressure P, the parameter CL showed the least influence on surface roughness Ra. This finding suggests that, while air gun cooling can contribute to overall machining efficiency, its direct impact on surface finish is minimal compared to other parameters.

In contrast, the flow rate of nanofluid F exhibited the most significant effect on surface roughness, reinforcing the critical role of fluid dynamics in achieving better surface finishes. Moreover, pressure P demonstrated a counterintuitive behavior, where lower pressure levels resulted in improved surface roughness. This could indicate that excessive pressure may cause turbulence or instability in the fluid delivery, negatively affecting the machining process.

The high R-squared value of 95.27% from the ANOVA analysis indicates an excellent fit of the model to the experimental data, validating the reliability of the findings. Furthermore, all factors were statistically significant, as evidenced by p-values of 0, emphasizing the importance of each variable in influencing the surface roughness. This research contributes to the growing body of knowledge on sustainable machining practices, where a strategic combination of advanced cooling techniques and nanoparticle application can enhance surface finish while potentially extending tool life.

REFERENCES

[1] Youssef, H.A., El-Hofy, H. (2008). Machining Technology: Machine Tools and Operations. CRC Press. https://doi.org/10.1201/9781420043402

[2] Do, T.V., Phan, T.D. (2021). Multi-objective optimization of surface roughness and MRR in milling of hardened SKD 11 steel under nanofluid MQL condition. International Journal of Mechanical Engineering and Robotics Research, 10(7): 357-362. http://doi.org/10.18178/ijmerr.10.7.357-362

[3] Özel, T., Karpat, Y. (2005). Predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks. International Journal of Machine Tools and Manufacture, 45(4-5): 467-479. http://doi.org/10.1016/j.ijmachtools.2004.09.007

[4] Nguyen, Q.M., Do, T.V. (2022). Optimal approaches for hard milling of SKD11 steel under MQL conditions using SIO_2 nanoparticles. Advances in Materials Science and Engineering, 2022(1): 2627522. https://doi.org/10.1155/2022/2627522

[5] Denkena, B., Lucas, A., Bassett, E. (2011). Effects of the cutting edge microgeometry on tool wear and its thermo-mechanical load. CIRP Annals, 60(1): 73-76. http://doi.org/10.1016/j.cirp.2011.03.098

[6] Denkena, B., Köhler, J., Bergmann, B. (2015). Development of cutting edge geometries for hard milling operations. CIRP Journal of Manufacturing Science and Technology, 8: 43-52. http://doi.org/10.1016/j.cirpj.2014.10.002

[7] Korkut, I., Donertas, M.A. (2007). The influence of feed rate and cutting speed on the cutting forces, surface roughness and tool-chip contact length during face milling. Materials & Design, 28(1): 308-312. http://doi.org/10.1016/j.matdes.2005.06.002

[8] Dilbag, S., Rao, P.V. (2008). Performance improvement of hard turning with solid lubricants. The International Journal of Advanced Manufacturing Technology, 38: 529-535. http://doi.org/10.1007/s00170-007-1079-8

[9] Davim J.P. (2010). Surface Integrity in Machining. London: Springer London. http://doi.org/10.1007/978-1-84882-874-2

[10] Dong, P.Q., Duc, T.M., Long, T.T. (2019). Performance evaluation of MQCL hard milling of SKD 11 tool steel using MoS2 nanofluid. Metals, 9(6): 658. http://doi.org/10.3390/met9060658

[11] Maruda, R.W., Krolczyk, G.M., Feldshtein, E., Nieslony, P., Tyliszczak, B., Pusavec, F. (2017). Tool wear characterizations in finish turning of AISI 1045 carbon steel for MQCL conditions. Wear, 372: 54-67. http://doi.org/10.1016/j.wear.2016.12.006

[12] Khatri, A., Jahan, M.P. (2018). Investigating tool wear mechanisms in machining of Ti-6Al-4V in flood coolant, dry and MQL conditions. Procedia Manufacturing, 26: 434-445. http://doi.org/10.1016/j.promfg.2018.07.051

[13] Do, T.V., Hsu, Q.C. (2016). Optimization of minimum quantity lubricant conditions and cutting parameters in hard milling of AISI H13 steel. Applied Sciences, 6(3): 83. http://doi.org/10.3390/app6030083

[14] Boswell, B., Islam, M.N., Davies, I.J., Ginting, Y.R., Ong, A.K. (2017). A review identifying the effectiveness of minimum quantity lubrication (MQL) during conventional machining. The International Journal of Advanced Manufacturing Technology, 92: 321-340. http://doi.org/10.1007/s00170-017-0142-3

[15] Phafat, N.G., Deshmukh, R., Deshmukh, S.D. (2013). Study of cutting parameters effects in MQL-employed hard-milling process for AISI H13 for tool life. Applied Mechanics and Materials, 393: 240-245. http://doi.org/10.4028/www.scientific.net/AMM.393.240

[16] Dhar, N.R., Kamruzzaman, M., Ahmed, M. (2006). Effect of minimum quantity lubrication (MQL) on tool wear and surface roughness in turning AISI-4340 steel. Journal of Materials Processing Technology, 172(2): 299-304. http://doi.org/10.1016/j.jmatprotec.2005.09.022

[17] Sreejith, P.S., Ngoi, B.K.A. (2000). Dry machining: Machining of the future. Journal of Materials Processing Technology, 101(1-3): 287-291. http://doi.org/10.1016/S0924-0136(00)00445-3

[18] Chou, C.C., Liu, N.M., Chiang, K.T., Chang, H.C. (2016). Investigation and optimization of Ti-6Al-4V titanium alloy in the fine grinding process using cold air gun coolant system. Hsiuping Journal, 33: 1-28. https://libap.nhu.edu.tw:8081/Ejournal/AI01003301.pdf.

[19] Stachurski, W., Nadolny, K. (2018). Influence of the condition of the surface layer of a hob cutter sharpened using the MQL-CCA hybrid method of coolant provision on its operational wear. The International Journal of Advanced Manufacturing Technology, 98: 2185-2200. http://doi.org/10.1007/s00170-018-2379-x

[20] Singh, G., Pruncu, C.I., Gupta, M.K., Mia, M., Khan, A.M., Jamil, M., Pimenov, D.Y., Sen, B., Sharma, V.S. (2019). Investigations of machining characteristics in the upgraded MQL-assisted turning of pure titanium alloys using evolutionary algorithms. Materials, 12(6): 999. https://doi.org/10.3390/ma12060999

[21] Gupta, M.K., Korkmaz, M.E., Sarıkaya, M., Krolczyk, G.M., Günay, M., Wojciechowski, S. (2022). Cutting forces and temperature measurements in cryogenic assisted turning of AA2024-T351 alloy: An experimentally validated simulation approach. Measurement, 188: 110594. https://doi.org/10.1016/j.measurement.2021.110594

[22] Ekici, E., Uzun, G. (2022). Effects on machinability of cryogenic treatment applied to carbide tools in the milling of Ti6AI4V with optimization via the Taguchi method and grey relational analysis. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 44(7): 270. http://doi.org/10.1007/s40430-022-03572-1

[23] Kadirgama, K. (2021). A comprehensive review on the application of nanofluids in the machining process. The International Journal of Advanced Manufacturing Technology, 115(9): 2669-2681. http://doi.org/10.1007/s00170-021-07316-8

[24] Dong, L., Li, C., Bai, X., Zhai, M., Qi, Q., Yin, Q., Lv, X., Li, L. (2019). Analysis of the cooling performance of Ti-6Al-4V in minimum quantity lubricant milling with different nanoparticles. The International Journal of Advanced Manufacturing Technology, 103: 2197-2206. http://doi.org/10.1007/s00170-019-03466-y

[25] Do, T.V. (2022). A case study of minimizing cutting force in hard milling JIS SKD61 steel under nanofluid-MQL condition. In Advances in Engineering Research and Application: Proceedings of the International Conference on Engineering Research and Applications, ICERA 2021. Springer International Publishing, pp. 12-18. http://doi.org/10.1007/978-3-030-92574-1_2

[26] Nguyen, Q.M., Nguyen, H.T., Le, N.A.V., Nguyen, T.N., Dang, T.H.T., Do, T.V. (2021). Investigation on the effect of nanofluid-MQL parameters on surface roughness during milling of hardened 9CrSi steel. In Proceedings of the 2nd Annual International Conference on Material, Machines and Methods for Sustainable Development (MMMS2020), pp. 311-316. http://doi.org/10.1007/978-3-030-69610-8_43

[27] Bui, G.T., Nguyen, Q.M., Thi, M.H.P., Vu, M.H. (2024). Multi-Objective optimization for balancing surface roughness and material removal rate in milling hardened SKD11 alloy steel with SiO_2 nanofluid MQL. EUREKA: Physics and Engineering, (2): 157-169. http://doi.org/10.21303/2461-4262.2024.003042

[28] Vu, M.H., Hue, P.T.M., Huynh, N.T., Nguyen, Q.M. (2024). Multi-Objective optimization for enhanced material removal rate and reduced machining roughness in hard turning of SKD61 alloy steel. Mathematical Modelling of Engineering Problems, 11(3): 680-688. http://doi.org/10.18280/mmep.110312

[29] Dong, P.Q., Duc, T.M., Tuan, N.M., Long, T.T., Thanh, D.V., Truong, N.V. (2020). Improvement in the hard milling of AISI D2 steel under the MQCL condition using emulsion-dispersed MoS2 nanosheets. Lubricants, 8(6): 62. http://doi.org/10.3390/lubricants8060062

[30] Celent, L., Bajić, D., Jozić, S., Mladineo, M. (2023). Hard milling process based on compressed cold air-cooling using vortex tube for sustainable and smart manufacturing. Machines, 11(2): 264. http://doi.org/10.3390/machines11020264

[31] Zakaria, M.F., Suhaimi, M.A., Sharif, S., Yang, G.D., Shaharum, M.S., Kamal, M.K.M., Zakaria, K. (2019). The application of cold air and nano-MQL as cooling strategy in high speed milling of titanium alloy Ti-6Al-4V: A review. AIP Conference Proceedings, 2129(1). https://doi.org/10.1063/1.5118183

[32] Swain, S., Patra, S.K., Roul, M.K., Sahoo, L.K. (2022). A short review on cooling process using compressed cold air by vortex tube in machining. Materials Today: Proceedings, 64: 382-389. https://doi.org/10.1016/j.matpr.2022.04.722

[33] Zhang, Y., Li, C., Jia, D., Li, B., Wang, Y., Yang, M., Hou, Y., Zhang, X. (2016). Experimental study on the effect of nanoparticle concentration on the lubricating property of nanofluids for MQL grinding of Ni-based alloy. Journal of Materials Processing Technology, 232: 100-115. https://doi.org/10.1016/j.jmatprotec.2016.01.031

[34] Tuan, N.M., Long, T.T., Ngoc, T.B. (2023). Study of effects of MoS2 nanofluid MQL parameters on cutting forces and surface roughness in hard turning using CBN insert. Fluids, 8(7): 188. http://doi.org/10.3390/fluids8070188

[35] Hemalatha J. (2009). A review of: 'Nanofluids: Science and technology, SK Das, SUS Choi, W. Yu, and T. Pradeep.' John Wiley & Sons, Inc., Hoboken, NJ, USA, Taylor & Francis, pp. 1-397. http://doi.org/10.1080/10426910902748057

[36] Salur, E. (2022). Understandings the tribological mechanism of Inconel 718 alloy machined under different cooling/lubrication conditions. Tribology International, 174: 107677. http://doi.org/10.1016/j.triboint.2022.107677

[37] Vu M.H., Do, T.V., Thi, M.H.P., Nguyen, Q.M. (2024). The impact of cutting conditions and cooling lubrication on hard milling of SKD11 alloy steel-An approach using the Taguchi method. International Journal of Mechanical Engineering and Robotics Research, 13(1): 1-10. http://doi.org/10.18178/ijmerr.13.1.1-10

[38] Viesca, J.L., Battez, A.H., González, R., Chou, R., Cabello, J.J. (2011). Antiwear properties of carbon-coated copper nanoparticles used as an additive to a polyalphaolefin. Tribology International, 44(7-8): 829-833. http://doi.org/10.1016/j.triboint.2011.02.006

[39] Chin˜ as-Castillo, F., Spikes, H.A. (2003). Mechanism of action of colloidal solid dispersions. Journal of Tribology, 125(3): 552-557. http://doi.org/10.1115/1.1537752

[40] Wu, F., Liu, W., Qiu, J., Li, J., Zhou, W., Fang, Y., Zhang, S., Li, X. (2015). Enhanced photocatalytic degradation and adsorption of methylene blue via TiO_2 nanocrystals supported on graphene-like bamboo charcoal. Applied Surface Science, 358: 425-435. http://doi.org/10.1016/j.apsusc.2015.08.161

[41] Shen, T., Wang, D., Yun, J., Liu, Q., Liu, X., Peng, Z. (2016). Tribological properties and tribochemical analysis of nano-cerium oxide and sulfurized isobutene in titanium complex grease. Tribology International, 93: 332-346. http://doi.org/10.1016/j.triboint.2015.09.028

[42] Peng, D.X., Chen, C.H., Kang, Y., Chang, Y.P., Chang, S.Y. (2010). Size effects of SiO_2 nanoparticles as oil additives on tribology of lubricant. Industrial Lubrication and Tribology, 62(2): 111-120. http://doi.org/10.1108/00368791011025656