The Impact of Cutting Conditions and Cooling Lubrication on Hard Milling of SKD11 Alloy Steel–An Approach Using the Taguchi Method

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***Abstract*—Recent machining processes have increasingly focused on the application of Minimum Quantity Lubrication (MQL) nanofluid. This research specifically explores the remarkable performance of nanofluid in the hard milling of SKD11 steel. A well-organized series of experiments was conducted to examine the effects of various cutting fluids, including dry machining, MQL, and nanofluid-based MQL, as well as cutting parameters such as cutting speed, depth of cut, and feed rate, on surface roughness, cutting force, and cutting temperature. The Taguchi method and Analysis of Variance (ANOVA) were applied to determine the optimal values for cutting fluids and cutting parameters. The research findings indicate that to achieve the minimum surface roughness and cutting force, the cutting conditions should be performed with a cutting speed of 80 m/min, a depth of cut of 0.2 mm, a feed rate of 0.01 mm/tooth, and the application of MQL nanofluid as the lubrication condition. The conditions to minimize the cutting temperature are a cutting speed of 40 mm/min, a depth of cut of 0.2 mm, and a feed rate of 0.01 mm/tooth. In addition, the findings also demonstrate the significant efficacy of MQL nanofluid in enhancing surface roughness, diminishing cutting force, and decreasing cutting temperature during the hard milling process of SKD11 alloy steel.**

***Keywords*—Al_2O_3 nanofluid, Minimum Quantity Lubrication (MQL), hard milling, cutting force, surface roughness, thermal cutting, Taguchi, Analysis of Variance (ANOVA)**

I. Introduction

Hard machining refers to machining materials with a hardness typically ranging from 40 to 70 HRC [1]. It involves using a tool equipped with geometrically-defined cutter blades. Hard machining plays a vital role in manufacturing due to its numerous advantages, including high material removal rate, the capability to process complex surface materials, and the ability to perform multiple machining operations in a single setup [2, 3]. Hard milling is widely employed in the manufacturing industry among the various techniques used in hard machining. Its application in mold and die manufacturing is particularly crucial, as mold surfaces are often intricate and challenging to finish through conventional methods. However, there is a need for more research studies addressing this specific issue.

The generation of heat in the machining zone during the cutting process presents various challenges, including limitations on cutting velocity [4], the impact on cutting tool sharpness, and the risk of tool breakage [5, 6]. Consequently, effective cooling methods are necessary to reduce temperatures in the cutting zone. Techniques such as wet cooling and mist cooling have been employed to address this issue. Nevertheless, in recent times, an innovative cooling technique known as minimum quantity lubrication has emerged as a viable substitute for flood cooling methods, which have been proven to have detrimental effects on the environment and human health. [7–12]. MQL offers several advantages, including reduced production costs, lower consumption of cutting fluid, improved overall cutting performance, and enhanced surface characteristics [11–15]. Numerous studies have been conducted on MQL technology due to its increasing importance in lubrication. As an example, the authors Quang-Cherng Hsu and The-Vinh Do [16] conducted a study to identify the best conditions for Minimum Quantity Lubrication and cutting parameters to achieve desired surface roughness when cutting AISI H13. They explored the effectiveness of various lubricating oils, including straight cutting oil, vegetable oil, and water-soluble oil. Additionally, other authors, including Sreejith [17], Das [18], Nouioua *et al*. [19], Khatri *et al*. [20], and Sharma *et al*. [21], have also investigated MQL and highlighted its superiority compared to both dry and flood lubrication conditions.

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A significant advancement in MQL machining occurred in 1995 with the introduction of nanofluid, a lubricant technology pioneered by Choi, which involves incorporating minuscule solid particles (smaller than 100 nanometers in size) into the cutting fluid [22]. This breakthrough opened up a new research avenue for exploring the application of nanoparticles in MQL machining. The utilization of nanoparticle-based cutting fluids in the machining process addresses the limitations of conventional fluids, which have low heat conductivity [10]. In addition, incorporating nanoparticles increases the nanofluid's thermal conductivity, density, and viscosity, enhancing heat transfer capabilities. This observation aligns with previous studies [23–28].

Additionally, the incorporation of nanoparticles in lubricants results in improved properties, reduced surface roughness, decreased cutting force, enhanced tribological performance, and minimized tool wear. In research conducted by Sharma *et al*. [21], the primary focus was on characterizing and conducting experiments using cutting fluid based on Al_2O_3 nanoparticles under MQL conditions. According to the findings, the utilization of nano-cutting fluid led to a substantial reduction in cutting force and enhanced machining performance by minimizing tool wear. Additionally, the average surface roughness was reduced by approximately 40% compared to conventional lubrication methods. Similar objectives were also addressed in the literature by Sayuti *et al*. [29, 30], Hadi *et al*. [31], Günan *et al*. [32] and Vasu *et al*. [33]. Additionally, Sharma *et al*. introduced an exciting new research prospect by studying the hybrid utilization of two nanoparticle-enriched cutting fluids. The studies demonstrated that the hybrid nano-cutting fluid exhibited enhanced performance and tribological properties. The hybrid nano-lubrication that was developed resulted in a noteworthy decrease in tool flank wear and nodal temperature [34], surface roughness, and cutting force by 12.29%, 5.79%, 20.28%, and 9.94%, respectively. In further research on nanofluids, the investigation carried out by Y. Wang *et al*. focused on evaluating the inherent lubrication properties of six different types of nanoparticles combined with vegetable oil in the context of MQL. The primary objective was to assess their heat transfer performance during the lubrication process. The experimental results indicated that the application of nanofluids yielded improvements in surface morphology and demonstrated excellent lubrication performance. The six nanofluids were ranked in the following order based on their performance: ZrO_2, CNTs, ND, MoS_2, SiO_2, and Al_2O_3 [35]. These findings highlight the significant benefits of incorporating nanoparticles in lubrication, particularly Al_2O_3 nanoparticles. However, there remains to be more research on Al_2O_3 nano-lubrication, necessitating further investigation using nanofluids in MQL to establish the superiority of nano-lubrication in the overall machining process.

Extensive research has been conducted on challenging-to-machine materials, including titanium alloys [36–38], inconel alloy [33, 39, 40], and Al6061-T6 alloy [29, 41, 42]. These materials find widespread application in industries such as construction, aerospace, marine, and engineering. Additionally, SKD11 steel finds widespread application in the mold and die industry due to its exceptional toughness and fatigue resistance. The utilization of nanoparticles to enhance surface quality is particularly significant for the molding industry, which consistently demands minimal surface roughness.

Building upon the abovementioned research, our study should have considered the wet lubrication method with its numerous disadvantages. Instead, our study centered around examining three different lubrication conditions, namely dry lubrication, MQL, and MQL with the incorporation of nanoparticles. Using the Taguchi method, we investigated the effects of these lubrication conditions in the hard-milling process of SKD11 alloy steel. Our objective was to identify the ideal cooling condition and cutting parameters, which encompass cutting speed, feed rate, and depth-of-cut, in order to achieve enhanced surface roughness, minimized cutting force, and reduced cutting temperature. In order to determine the factors that had the most substantial influence on the output parameters, we utilized ANOVA analysis.

II. EXPERIMENT SETUP

In this study, a Design of Experiments approach was employed to identify the significant variables that impact surface roughness, cutting force, and cutting temperature. The Taguchi method and ANOVA were utilized to optimize the cooling and cutting parameters with the objective of minimizing surface roughness, cutting force, and cutting temperature. The experiments were designed using Taguchi's L27 orthogonal array, a technique for experimental design. The input factors considered were cutting speed, feed rate, depth of cut, and cooling condition, each assigned three levels as specified in Table I. The selection of these input factors and their levels was based on their expected influence on the selected output factors [32, 43, 44].

TABLE I. THE INPUT PARAMETERS

Level	Input factor			
	Cooling condition	**Cutting speed (m/min)**	**Feed rate (mm/tooth)**	**Depth of cut (mm)**
1	Dry	40	0.01	0.2
2	Nanofluid	60	0.02	0.4
3	MQL	80	0.03	0.6

To conduct the experiments, a 5-axis milling machine DMU50 was utilized. The experimental setup can be visualized in Fig. 1. The workpiece chosen for the experiments was made of SKD11 steel and had the following dimensions: 50 mm in width, 150 mm in length, and 80 mm in height. The hardness of the workpiece was measured to be 50 HRC. For the experiments, TiAlN-coated end mill tools with a diameter of 10 were employed. Detailed technical specifications of the tool can be found in Table II.

TABLE II. THE PARAMETERS OF THE TOOL

Overall length (mm)	Cutting length (mm)	Shank diameter (mm)	Tool diameter (mm)	Number of flutes	Helix angle (º)	Axial rake angle (º)	Coating material	Coating thickness (μm)	Machining capability (HRC)
75	25	10	10	4	35	12	TiAlN	0.6	< 55

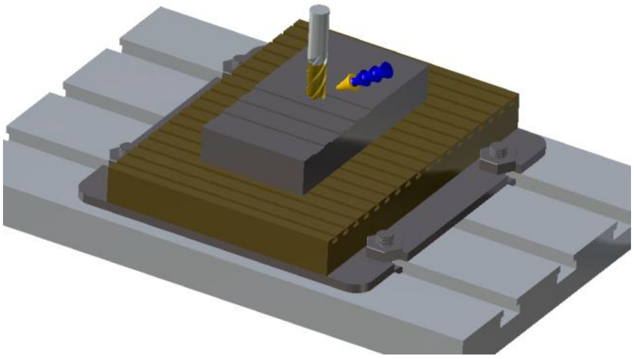

Fig. 1. Experimental scheme.

For the MQL cutting experiments, the lubricant used was the cutting oil CT232, which was applied at a flow rate of 100 mL/h [38] and an air pressure of 3 kg/cm². In the case of MQL with nanofluid, aluminum oxide (Al_2O_3) nanoparticles were specifically chosen due to their advantageous tribological properties and non-toxic nature. The nanoparticles had an average diameter of 20 nm. The concentration of nanoparticles in the cutting oil was 2wt%. To ensure a uniform dispersion and stable suspension of the nanoparticles within the cutting oil, the magnetic stirring device was utilized for a continuous period of 12 hours to achieve a well-mixed mixture.

Regarding the positioning of the MQL nozzle, it was fixed at an angle of 60 degrees on the relief face of the tool [45], with a distance of 30 mm [46]. To mitigate potential experimental errors, each trial was replicated three times to ensure accuracy and reliability.

III. RESULTS AND DISCUSSIONS

To organize the experiments, the researchers utilized the Taguchi's L27 orthogonal array, which involved considering four factors at three levels. The experimental results and the corresponding Signal-to-Noise (S/N) ratio can be found in Table III. The four observed factors are cooling condition (C), cutting speed (v), depth of cut (d), and feed rate (f), each having three levels denoted as "1", "2", and "3".

TABLE III. THE EXPERIMENTAL OUTCOMES AND SIGNAL-TO-NOISE RATIOS

No.	Cooling condition (C)	Cutting speed (v)	Depth of cut (d)	Feed rate (f)	Ra (μm)	F (N)	T (°C)	S/N (Ra)	S/N (F)	S/N (T)
1	1	1	1	1	0.293	141.93	47.5	10.66265	−43.0415	−33.5499
2	1	1	2	2	0.463	248.18	64.3	6.68838	−47.8954	−36.1738
3	1	1	3	3	0.666	368.04	68.6	3.523997	−51.3181	−36.7302
4	1	2	1	2	0.380	207.38	60.7	8.392907	−46.3355	−35.6655
5	1	2	2	3	0.442	307.54	71.5	7.081734	−49.7583	−37.0886
6	1	2	3	1	0.286	238.20	69.3	10.85751	−47.5391	−36.8197
7	1	3	1	3	0.357	235.30	68.9	8.934479	−47.4328	−36.7724
8	1	3	2	1	0.255	218.17	73.8	11.85218	−46.776	−37.3689
9	1	3	3	2	0.372	307.91	76.2	8.589141	−49.7687	−37.6441
10	2	1	1	2	0.162	178.15	41.1	15.78293	−45.0162	−32.2937
11	2	1	2	3	0.216	227.75	46.0	13.31092	−47.1494	−33.2665
12	2	1	3	1	0.132	168.96	48.3	17.58852	−44.5557	−33.6807
13	2	2	1	3	0.211	167.70	51.0	13.4979	−44.4912	−34.1514
14	2	2	2	1	0.129	156.82	55.2	17.78821	−43.9083	−34.8482
15	2	2	3	2	0.202	237.23	56.5	13.89297	−47.5036	−35.041
16	2	3	1	1	0.121	77.91	61.1	18.27993	−37.8319	−35.7293
17	2	3	2	2	0.140	160.62	60.6	17.04647	−44.1164	−35.6523
18	2	3	3	3	0.199	240.90	73.6	14.00114	−47.6367	−37.3482

No.	Cooling condition (C)	Cutting speed (v)	Depth of cut (d)	Feed rate (f)	Ra (μm)	F (N)	T (°C)	S/N (Ra)	S/N (F)	S/N (T)
19	3	1	1	3	0.342	178.02	48.5	9.319478	−45.0095	−33.7204
20	3	1	2	1	0.206	157.31	53.7	13.7016	−43.9351	−34.6124
21	3	1	3	2	0.240	286.96	62.2	12.3777	−49.1566	−35.8817
22	3	2	1	1	0.187	111.91	52.8	14.56317	−40.9776	−34.4658
23	3	2	2	2	0.224	225.20	56.4	12.99504	−47.0515	−35.0273
24	3	2	3	3	0.262	297.09	65.6	11.61741	−49.4578	−36.3398
25	3	3	1	2	0.221	128.16	59.2	13.11215	−42.1555	−35.4508
26	3	3	2	3	0.252	255.97	62.0	11.97199	−48.1639	−35.8523
27	3	3	3	1	0.174	254.28	61.9	15.16409	−48.1065	−35.8428

A. *Surface Roughness*

Surface roughness is a crucial indicator for evaluating the output quality in metal machining [47]. This study assessed the workpiece surface roughness using the Mitutoyo SJ-401 surface roughness measuring device. The findings, as presented in Table IV, demonstrate the average Signal-to-Noise (S/N) response for surface roughness. The analysis reveals that the highest rankings within their respective levels are observed for the second level of C, the third level of v, the first level of d, and the first level of f. Experiment No. 16, which corresponds to the optimal experimental conditions of (2-3-1-1), stands out as the most favorable choice. These results clearly indicate that the cooling condition exerts the most significant influence on surface roughness, closely followed by the feed rate.

TABLE IV. THE MEAN OF S/N FOR RA

Level	Cooling condition (C)	Cutting speed (v)	Depth of cut (d)	Feed rate (f)
1	8.509	11.440	12.505	14.495
2	15.688	12.299	12.493	12.098
3	12.758	13.217	11.957	10.362
Delta	7.178	1.777	0.548	4.133
Rank	1	3	4	2

The S/N response graph, depicted in Fig. 2, demonstrates the relationship between the various cutting parameters and surface roughness. The analysis of the S/N response led to the identification of optimal values for achieving lower surface roughness. These values include the utilization of nanofluid-based minimum quantity lubrication for C, v of 80 m/min, d of 0.2 mm, and f of 0.01 mm/tooth.

The ANOVA results are presented in Table V, providing insights into the levels of influence exerted by different factors. According to the ANOVA table, the cooling condition emerges as the factor with the highest level of influence, followed by the feed rate. These factors contribute 60.1% and 19.3% respectively to the overall effect. The statistically significant impact of the cooling condition, feed rate, and velocity is indicated by their respective P-values (< 0.05). The R-Sq value of 86.2% indicates that the input factors examined in this study account for 86.2% of the variation in surface roughness.

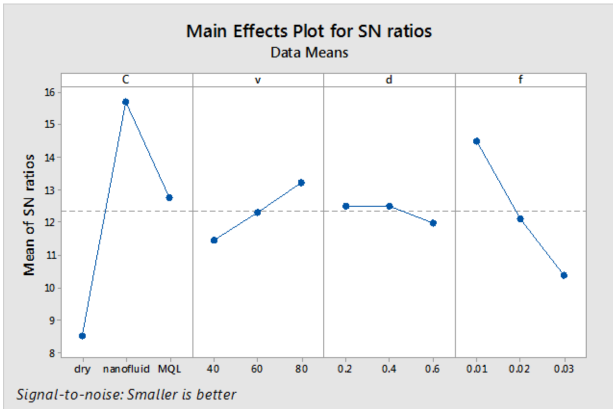

Fig. 2. The S/N ratio plot for surface roughness.

The findings of the research highlight the efficacy of nanofluid-based minimum quantity lubrication in enhancing surface roughness compared to both dry cutting and conventional MQL conditions. In addition, achieving enhanced surface roughness was facilitated by optimizing the cutting parameters. Specifically, adopting the lowest feed rate, lowest depth of cut, and highest cutting speed yielded notable improvements in surface roughness.

The roughness value heavily depends on the cooling condition, followed by the feed rate. Meanwhile, cutting speed and depth of cut have a lesser impact on surface roughness. Notably, the cooling condition significantly impacts roughness, leading to abrupt changes. The utilization of nanofluid showcases remarkable effectiveness in enhancing surface roughness, primarily due to its exceptional anti-friction and anti-wear properties at the nanoscale level.

TABLE V. THE ANOVA TABLE FOR ROUGHNESS

Source	DF	Adj SS	Adj MS	F-Value	P(*R-sq=86.2%*)-Value	PC %
C	2	0.234915	0.117458	39.19	0.000[a]	60.1
v	2	0.022390	0.011195	3.74	0.044[a]	5.7
d	2	0.004176	0.002088	0.70	0.511	1.07
f	2	0.075380	0.037690	12.58	0.000[a]	19.3
Error	18	0.053947	0.002997	-	-	-
Total	26	0.390808	-	-	-	-

[a] significant.

Influencing surface roughness, the feed rate plays a crucial role, where higher values of the feed rate result in elevated roughness values. This can be attributed to the phenomenon observed in studies conducted by T-V. Do *et al*. [1], Aouici *et al*. [16], and H-T. Nguyen *et al*. [48], indicating that machining at a higher feed rate leads to the formation of deeper and larger furrows on the machined surfaces.

In contrast, the cutting speed and the depth of cut have a relatively lesser influence on surface finish, acting as minor controlling factors.

The surface roughness probability plot is depicted in Fig. 3, revealing that the data points are closely distributed around the centerline. This observation signifies the statistically significant impact of the chosen factors on the output response.

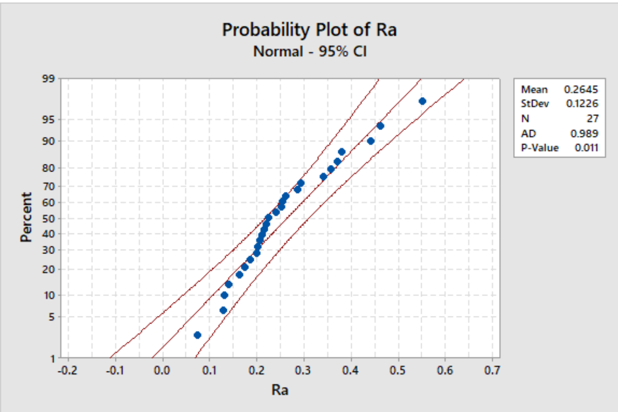

Fig. 3. The surface roughness probability plot.

B. *Cutting Force*

When designing a cutting technology system, which includes the machine, cutting tools, fixtures, and workpiece, the cutting force is a crucial parameter. The cutting force data in this study was collected using a three-component piezoelectric cutting force measurement system from Kisler. The average S/N response for the cutting force is presented in Table VI. After conducting the analysis, it was determined that the second level of the C, the third level of v, the first level of d, and the first level of f hold the highest ranks within their respective levels. Therefore, the optimal experimental conditions correspond to (2-3-1-1), specifically Experiment No. 16. The ranking highlights that the depth of cut exerts the highest level of influence on the cutting force, with the feed rate following closely behind.

Fig. 4 visually represents the S/N response graph. By analyzing the S/N response, it was deduced that to minimize the cutting force, the optimal values for the cutting parameters and cooling condition were as follows: Nanofluid-based MQL for C, v of 80 m/min, d of 0.2 mm, and f of 0.01 mm/tooth.

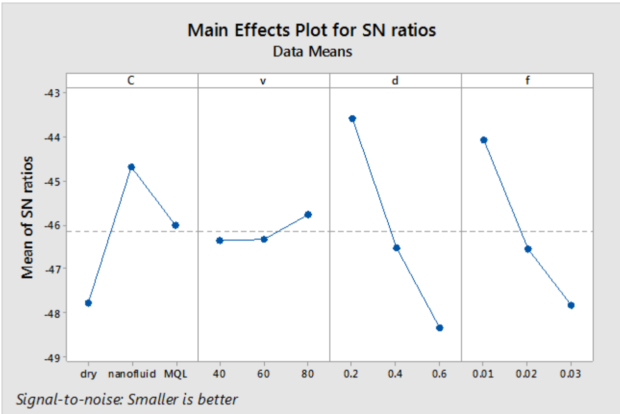

Fig. 4. The S/N ratio plot for cutting force.

The results of the analysis of variance are shown in Table VII. According to the ANOVA table, the depth of cut emerges as the most influential parameter, followed by the feed rate. These factors contribute 44.6% and 27.0% to the overall effect. The cooling condition factor accounts for 20.4% of the total effect. The *P*-values (<0.05) for the cooling condition, feed rate, and depth of cut indicate that these factors have a statistically significant impact. The R-Sq value of 92.3% suggests that 92.3% of the variation in cutting force can be attributed to the input factors studied in this work.

The findings of the research indicate that nanofluid-based minimum quantity lubrication is effective in reducing cutting force compared to both dry cutting and conventional MQL conditions. Furthermore, utilizing the lowest feed rate, lowest depth of cut, and highest cutting speed leads to lower cutting force.

The study results reveal that the cutting force is predominantly influenced by the depth of cut, followed by the feed rate and then the cooling condition. Cutting speed has the most negligible impact on determining the cutting force. However, increasing the depth of cut and feed rates leads to higher cutting forces. This can be attributed to the increased chip load, requiring more energy for chip formation in the shear zone [1], [49]. Consequently, material removal during the milling process becomes more challenging.

TABLE VI. THE MEAN OF S/N RESPONSE FOR THE CUTTING FORCE

Level	Cooling condition (C)	Cutting speed (v)	Depth of cut (d)	Feed rate (f)
1	−47.76	−46.34	−43.59	−44.07
2	−44.69	−46.34	−46.53	−46.56
3	−46.00	−45.78	−48.34	−47.82
Delta	3.07	0.57	4.75	3.75
Rank	3	4	1	2

TABLE VII. THE ANOVA TABLE FOR THE CUTTING FORCE

Source	DF	Adj SS	Adj MS	F-Value	P (*R-sq = 92.3%*)-Value	PC %
C	2	24134	12066.8	23.80	0.000[a]	20.4
v	2	396	198.2	0.39	0.682	0.33
d	2	52755	26377.6	52.03	0.000[a]	44.6
f	2	31937	15968.6	31.50	0.000[a]	27.0
Error	18	9126	507.0	-	-	-
Total	26	118348	-	-	-	-

[a] significant.

Moreover, using nanofluid containing Al_2O_3 nanoparticles demonstrates a reduction in cutting force compared to both dry cutting and conventional MQL conditions. The viscosity of the cutting fluid can explain this, as it plays a significant role in reducing cutting force [43], [50], [51]. Cutting fluids containing Al_2O_3 nanoparticles consistently exhibit high viscosity [32].

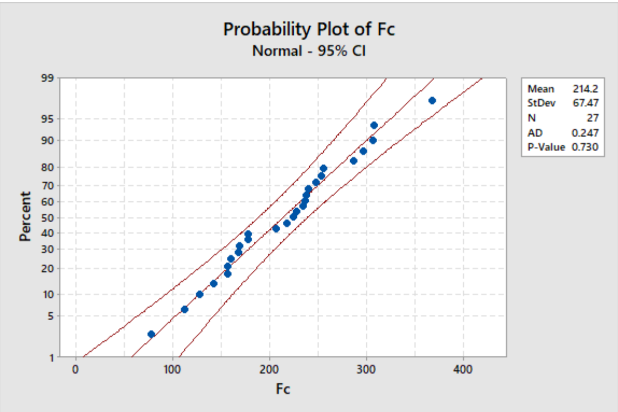

Fig. 5. The cutting force probability plot.

The probability plot of cutting force is depicted in Fig. 5. The data points of cutting force are distributed around a central line. This suggests that the selected input factors have a statistically significant influence on the output factor, which is the cutting force.

C. Cutting Temperature

The generation of heat during the metal-cutting process has a significant impact on cutting forces, tool life, and chip formation [52]. In this study, the cutting temperature was measured by using an infrared camera IRM_P384A3-20 manufactured by Ching Hsing. The temperature value recorded represents the temperature at the tooltip. The infrared camera's position remained fixed throughout all the experiments.

The average S/N response for the cutting temperature is presented in Table VIII. After conducting the analysis, it was found that the second level of C, the first level of v, the first level of d, and the first level of f hold the highest ranks within their respective levels. Therefore, the optimal experimental conditions would be (2-1-1-1), which were not initially included in the experimental design presented in Table III. To validate the research results, a confirmation test was conducted using the optimized parameters: Nanofluid for C, v of 40 m/min, d of 0.2 mm, and f of 0.01 mm/tooth.

TABLE VIII. THE MEAN OF S/N RESPONSE FOR THE CUTTING TEMPERATURE

Level	Cooling condition (C)	Cutting speed (v)	Depth of cut (d)	Feed rate (f)
1	−36.42	−34.43	−34.64	−35.21
2	−34.67	−35.49	−35.54	−35.43
3	−35.24	−36.41	−36.15	−35.70
Delta	1.76	1.97	1.50	0.48
Rank	2	1	3	4

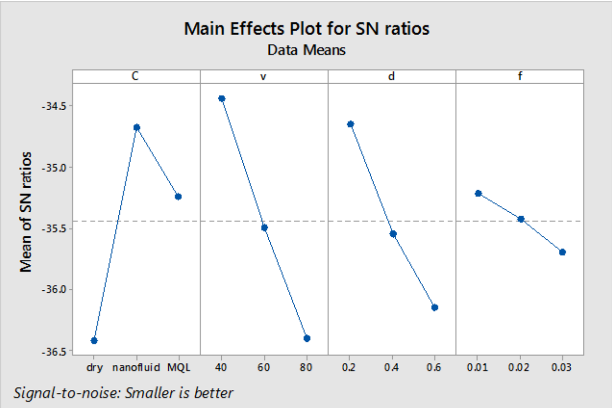

Fig. 6. The S/N ratio plot for the cutting temperature.

The cutting temperature recorded during the confirmation test was 39.8 ℃. This value is lower than the cutting temperature obtained in Experiment No. 10 (2-1-1-2), which had the smallest value of 41.1 ℃, as shown in Table III. This outcome confirms the validity of the research findings. Furthermore, the ranking demonstrates that the cutting speed exerts the highest level of influence on the cutting temperature, with the cooling condition following closely behind.

Fig. 6 illustrates the S/N response graph. Based on the analysis of the S/N response, to achieve a lower cutting temperature, the optimal values for the cutting parameters and cooling condition are as follows: Nanofluid-based minimum quantity lubrication for C, v of 40 m/min, d of 0.2 mm, and f of 0.01 mm/tooth.

The analysis of variance result is displayed in Table IX. The ANOVA table identifies the cutting speed as the most influential parameter, followed by the cooling condition. These factors contribute 33.5% and 30.2%, respectively, to the overall effect. The *P*-values (<0.05) for the cooling condition, cutting speed, and depth of cut indicate that these factors have a statistically significant impact. The coefficient of determination (R-Sq) is 86.8%, implying that 86.8% of the variability in the cutting temperature can be attributed to the investigated input factors.

TABLE IX. THE ANOVA TABLE FOR THE CUTTING TEMPERATURE

Source	DF	Adj SS	Adj MS	F-Value	P (*R-sq = 86.8%*)-Value	PC %
C	2	687.11	343.56	20.54	0.000[a]	30.2
v	2	761.53	380.76	22.77	0.000[a]	33.5
d	2	466.62	233.31	13.95	0.000[a]	20.5
f	2	57.00	28.50	1.70	0.210	2.5
Error	18	301.06	16.73			
Total	26	2273.32				

[a] significant.

The research results provide evidence of the superior performance of nanofluid-based MQL in lowering cutting temperatures compared to both dry and MQL conditions. Additionally, lower cutting temperatures were observed when using the lowest feed rate, the lowest depth of cut, and the lowest cutting speed.

The research findings emphasize the dominant role of cutting speed in determining the cutting temperature, with cooling condition and depth of cut following in significance. Conversely, the feed rate has a minimal effect on the cutting temperature. Notably, elevating the cutting speed substantially raises the cutting temperature due to heightened friction between the tool and workpiece at higher velocities, resulting in increased temperatures at the interface [53].

Furthermore, the effectiveness of nanofluid in reducing the cutting temperature is noteworthy when compared to both dry and MQL conditions. This can be attributed to the remarkable increase in the thermal conductivity of the nanofluid due to the presence of suspended particles [24].

Fig. 7 displays the probability plot of the cutting temperature. The data points of the cutting temperature are distributed closely around a central line. These results demonstrate that the selected input factors exert a statistically significant influence on the output factor, which is the cutting temperature.

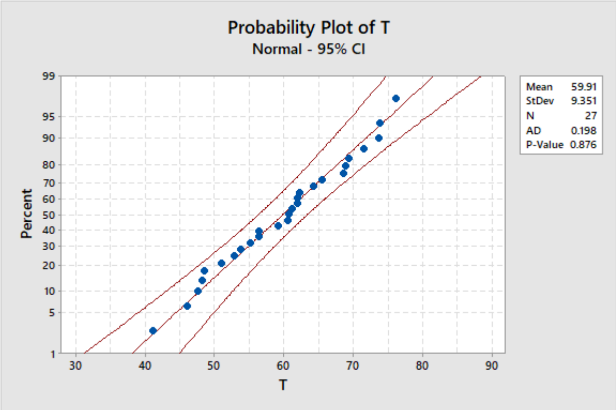

Fig. 7. The cutting temperature probability plot.

The significance of the cooling condition in the hard milling process of SKD11 steel becomes evident through its impact on surface roughness, cutting force, and cutting temperature. As indicated in Tables IV, VI, and VIII, the cooling condition has a ranked effect of “1” on surface roughness, “3” on cutting force, and “2” on cutting temperature. All of these effects are statistically significant. Nanofluid is optimal for improving roughness, reducing cutting force, and minimizing the cutting temperature.

The research results once again confirm the effectiveness of nanofluid in improving lubrication and cooling, leading to reduced surface roughness, cutting temperature, and cutting force. The incorporation of nanoparticles has greatly improved the lubrication and cooling properties of the original cutting fluid [54]. The cooling effectiveness of nanofluids can be attributed to the enhanced heat exchange mechanism facilitated by the presence of nanoparticles in the cutting oil. Furthermore, the introduction of nanoparticles has significantly improved the wetting properties of the nanofluid in comparison to the base cutting fluid [8, 55]. The enhanced lubrication efficiency of the nanofluid can be attributed to four distinct mechanisms: the rolling action of nanospheres [56, 57], the self-repairing effect [58, 59], the formation of a protective tribo-film, and the polishing effect [60].

IV. Conclusions

To optimize the cooling conditions and cutting parameters for surface roughness, cutting force, and cutting temperature in the hard milling process of SKD11 steel, the Taguchi method and ANOVA were utilized in this research study. The main goal was to attain high surface quality, decrease cutting force, and minimize cutting temperature. The key findings of the study can be summarized as follows:

In order to achieve the best surface roughness, the optimal parameters were determined through the utilization of nanofluid-based Minimum Quantity Lubrication for the cooling condition. The identified parameters consisted of a cutting velocity of 80 m/min, a depth of cut of 0.2 mm, and a feed rate of 0.01 mm/tooth. Analysis of the investigated factors highlights the significant influence of the cooling condition on surface roughness, accounting for 60.1% of the overall impact, followed by the feed rate with a contribution of 19.3%.

In order to minimize cutting force, the optimal parameters were identified as nanofluid-based minimum quantity lubrication MQL for the cooling condition, a cutting velocity of 80 m/min, a depth of cut of 0.2 mm, and a feed rate of 0.01 mm/tooth. The analysis reveals that the depth of cut exerts the greatest influence on cutting force, accounting for 44.6% of the total impact, followed by the feed rate, which contributes 27.0% to the overall effect.

To effectively decrease the cutting temperature, the optimal parameters included nanofluid-based minimum quantity lubrication for the cooling condition, a cutting velocity of 40 m/min, a depth of cut of 0.2 mm, and a feed rate of 0.01 mm/tooth. The findings highlight that cutting speed emerges as the primary factor influencing cutting temperature, representing 33.5% of the total impact. Following closely, the cooling condition ranks as the second most significant factor, contributing 30.2% to the overall influence on cutting temperature.

The superiority of nanofluid-based MQL in enhancing surface roughness, reducing cutting force, and minimizing cutting temperature was clearly evident in comparison to both dry cutting and conventional MQL conditions.

Overall, this research provides valuable insights into optimizing the cooling conditions and cutting parameters for achieving enhanced surface quality, decreased cutting force, and reduced cutting temperature in the hard milling process of SKD11 steel.

Conflict of Interest

The authors have no conflicts of interest to declare.

Author Contributions

Conceptualization, M.H.V, M.H.P.T; Methodology, M.H.V, T.V.D, and Q.M.N; Resources, Q.M.N, T.V.D; Visualization and Validation, M.H.V, M.H.P.T, T.V.D; Writing—original draft, M.H.V, T.V.D; Writing—review and editing, T.V.D, Q.M.N; Super-vision, T.V.D, Q.M.N. All authors have reviewed and approved the final version of the manuscript for publication.

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