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Improving Efficiency and Surface Quality in Hard Turning of SKD61 Steel Through Cooling and Cutting Parameter Optimization

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ABSTRACT

The Taguchi method is used in this work to optimize the machining conditions for hard turning SKD61 steel. The combined effects of cooling conditions and cutting parameters on surface roughness (Ra) and material removal rate (MRR) are the main emphasis. Three cooling conditions (dry, minimum quantity lubrication (MQL), and nanofluid) and various cutting parameters, including cutting speed, cutting depth, and feed rate, were examined through 27 experimental runs based on the L27 orthogonal array. Ra and MRR were selected as the response variables, with ANOVA conducted to assess the significance of each parameter. The findings show that, in contrast to MQL and dry circumstances, nanofluid cooling greatly enhances surface quality. The cutting depth of 0.2 mm, feed rate of 0.10 mm/rev, and cutting speed of 80 m/min were found to be the ideal machining settings for the lowest Ra. Additionally, optimal circumstances for the greatest MRR and minimum Ra were determined using multi-objective optimization using the composite desirability function. These conditions included a feed rate of 0.171 mm/rev under nanofluid cooling, a cutting depth of 0.6 mm, and a cutting speed of 80 m/min. This research addresses gaps in machining optimization for SKD61 steel by demonstrating the superior performance of nanofluid cooling and providing a comprehensive understanding of the interactions between cooling conditions and cutting parameters. The findings offer valuable insights for enhancing machining efficiency and surface quality while reducing operational costs.

1. INTRODUCTION

JIS SKD61 steel, commonly known as H13 tool steel, is a high-performance alloy widely recognized for its exceptional hardness, toughness, and resistance to thermal fatigue and wear. This chromium-molybdenum-vanadium alloy is specifically designed for high-temperature applications, making it an ideal material for hot work tools. Its superior properties stem from its balanced chemical composition, which typically includes 0.32-0.45% carbon, 4.75-5.50% chromium, 1.10-1.75% molybdenum, and 0.80-1.20% vanadium, among other elements. The unique combination of these alloying elements allows SKD61 steel to maintain high hardness and strength at elevated temperatures, offering excellent thermal stability and resistance to heat checking. However, these characteristics also contribute to the difficulty level in machining especially in the heat-treated state [1, 2].

In the hard turning of heat-treated SKD61 steel, the choice of cooling and lubrication methods is critical to achieving improved tool performance, workpiece quality, and overall machining efficiency [3, 4]. Due to insufficient heat dissipation and lubrication, dry machining [5, 6], which depends on the lack of any coolant or lubricant, is straightforward and eco-friendly, but it frequently leads to high cutting temperatures, excessive tool wear, and subpar surface finish. MQL has been routinely used as a substitute to get around these problems. MQL entails applying a tiny, regulated quantity of lubricant directly to the cutting zone, usually in the form of an oil mist [7-9]. This technique reduces friction, minimizes heat generation, and lowers cutting forces while using significantly less lubricant compared to traditional flood cooling, making it both effective and environmentally sustainable.

Building on the benefits of MQL, nanofluid-based lubrication has emerged as a cutting-edge solution in machining applications. Nanofluids are engineered fluids in which nanoparticles, such as aluminum oxide (Al_2O_3) or silicon dioxide (SiO_2), are dispersed into a base lubricant. In comparison to traditional lubricants, these nanoparticles improve the fluid's lubricating, heat-dissipating, and thermal conductivity, resulting in better performance [9-11]. Because of their minuscule size, the nanoparticles can generate a strong lubricating layer that lowers wear and friction by penetrating the minute asperities between the tool and workpiece. Additionally, the high thermal conductivity of nanofluids effectively dissipates heat generated during cutting, thereby prolonging tool life and improving surface quality.

Both MQL and nanofluid lubrication have demonstrated their effectiveness in addressing the limitations of dry machining. While MQL significantly reduces the environmental impact and improves lubrication efficiency, nanofluids take these advantages further by offering enhanced cooling and wear resistance. These technologies enable better control of machining conditions, resulting in improved surface finish, extended tool life, and higher productivity, making them highly suitable for the demanding conditions of hard-turning SKD61 steel.

In MQL, a tiny quantity of lubricant—usually in the form of an aerosol is applied straight to the cutting zone. This technique significantly reduces the volume of lubricant needed compared to traditional flood cooling, thus minimizing environmental impact and operational costs [12]. The impact of MQL on tool wear and Ra during the turning of AISI-4340 steel is examined in the study by Dhar et al. [13]. The research highlights that MQL significantly improves machining performance compared to dry cutting. The application of MQL reduces cutting temperature and tool wear primarily due to its enhanced cooling and lubrication effects. Pham Van Trinh used sesame oil MQL in his experiments. The results showed that MQL effectively helps reduce cutting force as well as keep the machining process clear and stable [14]. In a similar vein, Elbah et al. found that applying MQL to hard-turning AISI 4140 high-strength low-alloy steel significantly improved cutting [15]. The performance of dry versus near-dry machining on AISI D2 steel using vegetable oil-based MQL was investigated by Sharma and Sidhu [16]. Their results show that, in comparison to dry machining, MQL produces better outcomes by reducing cutting forces, tool wear, and Ra. The study emphasizes how effective and environmentally beneficial vegetable oil-based MQL may be as a substitute for conventional machining methods.

Conversely, nanofluids are specially designed colloidal suspensions of nanoparticles in a base fluid, such water or oil. The fluid gains improved lubricating qualities and superior heat conductivity when nanoparticles—typically metals or oxides—are added. Nanofluids can offer remarkable cooling and lubrication in machining heat-treated SKD61, assisting in the more efficient dissipation of heat from the cutting zone. Lower cutting temperatures, less tool wear, and enhanced surface integrity of the machined item are the outcomes of this [10, 17, 18]. The referenced studies provide significant insights into the mechanisms underlying the lubrication efficiency of nanofluids. Viesca et al. investigated the antiwear properties of carbon-coated copper nanoparticles as additives in polyalphaolefin lubricants and highlighted their ability to reduce friction through a rolling mechanism [19]. Similarly, Chinás-Castillo and Spikes [20] analyzed the behavior of colloidal solid dispersions and confirmed the effectiveness of nanoscale particles in minimizing frictional forces by acting as rolling elements. Wu et al. [21] introduced the concept of a self-repairing effect, where nanoparticles fill micro-cracks on surfaces, enhancing durability and restoring surface integrity. The ability of the nanoparticles to restore worn surfaces was further corroborated by Shen et al. [22] through tribochemical examination of sulfurized isobutene and nano-cerium oxide in titanium grease. Finally, Peng et al. [23] investigated the size effects of SiO_2 nanoparticles as lubricant additives and revealed their role in forming a tribo-film that protects surfaces while providing a polishing effect that smoothens surfaces during operation, thus improving tribological performance [23]. These studies collectively explain how nanofluids achieve superior machining quality compared to conventional cutting fluids.

The mechanical characteristics of parts, including wear, friction, fatigue behavior, corrosion resistance, and creep life, are greatly impacted by Ra, a crucial performance parameter in metal cutting [24, 25]. The primary factors influencing Ra are cutting parameters (depth of cut, feed rate, cutting speed) and cooling conditions. The influence of cutting speed, cutting depth, and feed rate on Ra has been thoroughly examined in machining operations. Cutting speed is known to influence the shear forces during machining, with higher speeds typically resulting in lower Ra due to reduced tool-workpiece contact time, leading to smoother surfaces. However, very high cutting speeds can increase tool wear, negatively affecting the surface finish. Cutting depth has a significant impact as well, with larger depths of cut often leading to increased Ra due to higher cutting forces and greater tool deflection. Conversely, shallower depths diminish cutting pressures, enhancing the surface smoothness. The feed rate, which regulates the MRR, is also essential for surface quality. Higher feed rates generally lead to higher Ra because they increase the size of the cut per pass, leading to more significant tool marks on the surface. However, lower feed rates can improve the surface finish by producing finer cuts. These findings have been supported by numerous studies, including those by Khorasani et al. [26], Abouelatta and Madl [27], and Davim [28] demonstrate how variations in these parameters significantly affect Ra in different machining processes. In the study by Nguyen et al. [29], which focused on the recovery of shaft-type components with a material layer possessing high hardness and wear resistance, optimizing the cutting parameters and cooling conditions plays a crucial role in achieving high-quality Ra. This parameter significantly affects the wear resistance of the shaft.

In recent years, significant advancements have been made in machining optimization techniques, particularly in the use of environmentally friendly cooling methods. However, studies applying nanofluid cooling in the machining of hardened SKD61 steel remain limited. Furthermore, existing research predominantly focuses on optimizing individual objectives, such as Ra or MRR, without considering the combined effects of these parameters. This study seeks to address these deficiencies by examining the impact of nanofluid cooling on machining performance and utilizing a multi-objective optimization strategy to concurrently attain superior surface quality and machining efficiency. The findings contribute valuable insights into sustainable and efficient machining solutions for challenging materials like SKD61.

This study aims to achieve two objectives: first, to examine the effects of distinct cooling conditions (dry, MQL, and nanofluid) on the machining of hardened SKD61 steel, and second, to identify the optimal cutting parameters (cutting speed, cutting depth, and feed rate) for attaining superior surface quality in the turning of this material. The study broadens its focus to incorporate a multi-objective optimization strategy designed to concurrently minimize Ra and maximize MRR, thus reconciling machining efficiency with product quality.

2. EXPERIMENTAL DETAILS

2.1 Overall setup

The experiments were carried out utilizing an EMCO Maxxturn 45 CNC lathe machine, as illustrated in Figure 1. The cutting tool utilized was a Polycrystalline Cubic Boron Nitride (CBN) insert, meticulously engineered for precision finishing applications on hardened steels (45-65 HRC) and nodular cast iron. The insert exhibited a rhombus configuration featuring a vertex angle of 35 degrees, dimensions of 16mm, and a nose radius measuring 0.4mm. Its high hardness and wear resistance made it suitable for the challenging conditions of hard-turning SKD61 steel.

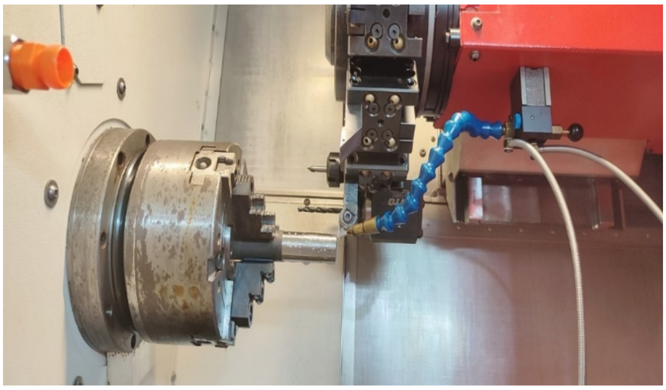

Figure 1. The experimental setup

The workpieces consisted of cylindrical SKD61 alloy steel blocks with an initial diameter of 35mm. The SKD61 workpiece's hardness was assessed with a Mitutoyo Rockwell hardness tester, Model: HR-521. The testing was performed at three different locations on the workpiece to ensure accuracy and consistency, with the average value recorded as 55 HRC. The workpieces were securely fastened in a three-jaw chuck. Table 1 presents the chemical compositions of the SKD61 steel workpiece. The SKD61 steel workpiece's chemical composition is displayed in Table 1.

Table 1. SKD61 steel's chemical composition (weight percentage)

C	Si	Mn	Cr	Mo	V	Ni
0.32-0.42	0.80-1.20	0.20-0.50	4.75-5.50	1.10-1.75	0.80-1.20	0-0.30

2.2 MQL and nanofluid application

The optimization of machining conditions for SKD61 steel requires the consideration of four primary parameters: cooling condition, cutting speed, cutting depth, and feed rate, as illustrated in Table 2. The cooling conditions encompass dry cooling, MQL, and nanofluid cooling. The MQL system utilized a nozzle located 20 mm from the cutting zone. The supply pressure was held constant at 3 kg/cm², while the fluid flow rate into the cutting zone was established at 50 ml/h.

For nanofluid cooling, SiO_2 nanoparticles with an average size of 100 nm were dispersed into CT232 synthetic cutting fluid at a concentration of 4% wt. The mixture was stirred using an ultrasonic vibration device for 6 hours to ensure uniform dispersion and stable suspension. This preparation method provided enhanced thermal conductivity and lubricating properties, making it suitable for the machining of hardened SKD61 steel.

Table 2. Cutting conditions

Cooling Condition	Cutting Speed (m/min)	Cutting Depth (mm)	Feed Rate (mm/rev)
Dry	40	0.2	0.1
MQL	60	0.4	0.15
Nanofluid	80	0.6	0.2

2.3 Ra data collection post-machining

Ra measurements were performed immediately following the completion of each experiment utilizing a Mitutoyo SJ-401 roughness measuring instrument. To ensure the precision and reliability of the data, the measurements were taken at three distinct locations on the machined surface of each workpiece. This approach helped in capturing any potential variations in surface texture and provided a comprehensive understanding of the surface quality.

3. RESULTS AND DISCUSSIONS

Table 3 presents a summary of the results from 27 experimental runs utilizing the L27 orthogonal Taguchi array. The experiments yield data on Ra and MRR across different machining conditions, which encompass cooling methods (dry, MQL, nanofluid), cutting speed (v), depth of cut (d), and feed rate (f). The average Ra values function as the response variable for assessing the impact of these input parameters, whereas the MRR values indicate the machining performance. The table facilitates a detailed analysis of the relationship between machining conditions and performance outcomes.

The Eq. (1) presents the calculation of S/N ratio:

$$\frac{S}{N} = -10log\frac{1}{n}(\sum_{i}^{n} y_i^2) \qquad (1)$$

where, y_i represents the observed data, and n is the number of repeated experiments.

The main effects plot for Signal-to-Noise (S/N) ratios was obtained in Figure 2. By using this plot, researchers can determine which factors and their levels contribute most significantly to minimizing the response, thereby optimizing the machining conditions for improved quality and efficiency. In this instance, Ra serves as the response variable, with lower values being preferable. The optimal Ra value attained with Nanofluid, with a cutting speed of 80 m/min, a depth of cut of 0.2mm, and a feed rate of 0.10 mm/rev, is readily identifiable. The optimal parameters for minimizing Ra identified in the study-cutting speed of 80 m/min, cutting depth of 0.2 mm, and feed rate of 0.10 mm/rev-align with the findings of Do and Phan [12], which found that nanofluid MQL produced better outcomes under similar cutting circumstances. Our multi-objective optimization method, however, goes beyond these results by striking a balance between MRR and Ra innovation that hasn't been highlighted in earlier studies. The adoption of nanofluid cooling as a viable and efficient solution for hard turning applications is further supported by this work.

Table 3. S/N table of 27 experiments

Run	c	v (m/min)	d (mm)	f (mm/rev)	Ra (µm)	MRR (mm^3/min)
1	dry	40	0.2	0.1	0.986	800
2	dry	40	0.4	0.15	1.014	2400
3	dry	40	0.6	0.2	1.116	4800
4	dry	60	0.2	0.15	1.003	1800
5	dry	60	0.4	0.2	1.055	4800
6	dry	60	0.6	0.1	0.967	3600
7	dry	80	0.2	0.2	1.036	3200
8	dry	80	0.4	0.1	0.945	3200
9	dry	80	0.6	0.15	0.988	7200
10	MQL	40	0.2	0.15	0.953	1200
11	MQL	40	0.4	0.2	1.066	3200
12	MQL	40	0.6	0.1	0.954	2400
13	MQL	60	0.2	0.2	1.042	2400
14	MQL	60	0.4	0.1	1.009	2400
15	MQL	60	0.6	0.15	1.055	5400
16	MQL	80	0.2	0.1	0.906	1600
17	MQL	80	0.4	0.15	0.977	4800
18	MQL	80	0.6	0.2	1.059	9600
19	Nanofluid	40	0.2	0.2	1.053	1600
20	Nanofluid	40	0.4	0.1	0.92	1600
21	Nanofluid	40	0.6	0.15	0.934	3600
22	Nanofluid	60	0.2	0.1	0.88	1200
23	Nanofluid	60	0.4	0.15	0.914	3600
24	Nanofluid	60	0.6	0.1	1.002	3600
25	Nanofluid	80	0.2	0.15	0.908	2400
26	Nanofluid	80	0.4	0.2	0.985	6400
27	Nanofluid	80	0.6	0.1	0.909	4800

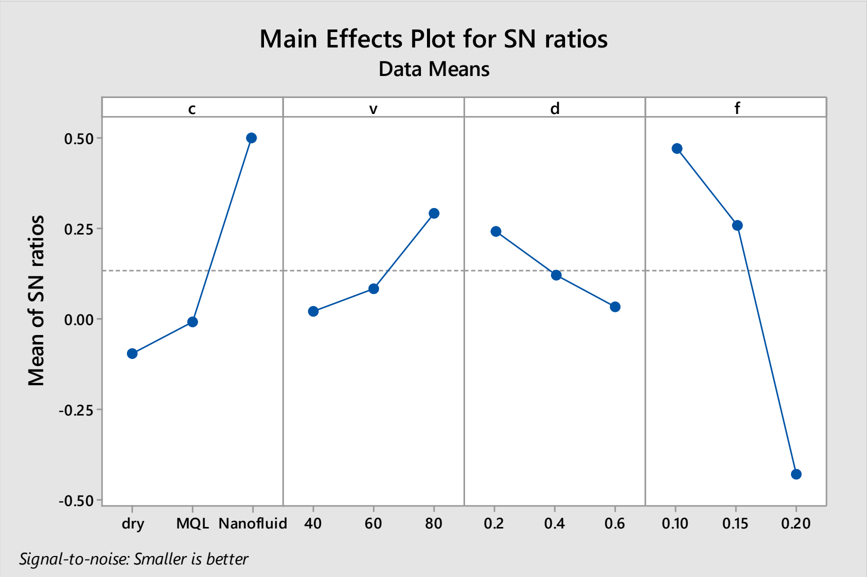

Figure 2. Main effects plot for S/N ratios

Further analysis using the response table for S/N presented in Table 4 provides a comprehensive understanding of how each machining parameter influences the response variable, Ra. The S/N ratios offer a clear metric to evaluate the robustness of the process against variability, with higher S/N ratios indicating better performance.

As shown in the table, the feed rate (f) emerges as the most influential factor, ranking first with the highest delta value of 0.905645. This result highlights its critical role in determining the surface quality and its sensitivity to changes in the machining process. The cooling condition (c) ranks second with a delta value of 0.600360, demonstrating that the choice of cooling and lubrication significantly impacts Ra. Cutting speed (v) and depth of cut (d) follow, with delta values of 0.273305 and 0.212666, respectively, indicating relatively lower, yet notable, contributions to the response.

The rankings highlight the significance of prioritizing feed rate and cooling conditions in the optimization of the machining process to reduce Ra. This insight aligns with the findings from the Analysis of variance (ANOVA) (Table 5), further corroborating the critical influence of these parameters on machining performance.

ANOVA is a crucial statistical method employed to evaluate the impact of several factors on a response variable and to determine the significance of each component in an experimental investigation. Table 5 presents the ANOVA results for the Ra in this experiment. The analysis reveals that feed rate (f) and cooling condition (c) are the most significant factors affecting Ra, as indicated by their respective p-values, which are less than 0.05 [30]. Specifically, the feed rate demonstrates the highest impact, with a p-value of 0.000 and contributing to 49.9% of the total variation in Ra. This finding underscores the critical role of feed rate in achieving the desired surface finish during machining processes.

Table 4. Response table for S/N ratios

Level	c	v	d	f
1	-0.095794	0.021021	0.245282	0.473990
2	-0.007397	0.086027	0.123477	0.258412
3	0.504565	0.294326	0.032616	-0.431655
Delta	0.600360	0.273305	0.212666	0.905645
Rank	2	3	4	1

Table 5. Analysis of variance

Source	DF	Adj-SS	Adj-MS	F-value	p-value	C (%)
c	2	0.015652	0.007826	8.27	0.003	16.25
v	2	0.006701	0.003350	3.54	0.051	6.96
d	2	0.005747	0.002873	3.04	0.073	5.97
f	2	0.048048	0.024024	25.38	0.000	49.9
Error	18	0.017040	0.000947	-	-	-
Total	26	0.096261	-	-	-	-
			Rsq = 82.30%			

The cooling condition also plays a notable role, with a p-value of 0.003 and accounting for 16.25% of the total variation. This outcome underscores the efficacy of various cooling and lubricating techniques in affecting Ra. Although cutting speed (v) and depth of cut (d) exhibit a modest impact on Ra, their p-values (0.051 and 0.073, respectively) suggest that these variables lack statistical significance at the 95% confidence level. Together, these two parameters contribute 6.96% and 5.97% to the total variation, respectively.

The high contribution percentages of feed rate and cooling condition to Ra underscore their critical roles in machining performance. Feed rate significantly affects the surface texture because higher feed rates increase the distance the tool travels per revolution, leading to deeper tool marks and a rougher surface finish. In contrast, lower feed rates produce finer cuts, resulting in smoother surfaces. This observation aligns with findings by Abouelatta and Madl [27], who demonstrated that lower feed rates significantly improve Ra due to finer tool passes.

The cooling condition is the second most significant element, accounting for 16.25% of the difference in Ra. Effective cooling and lubrication reduce tool wear, cutting forces, and friction, which collectively enhance surface quality. Nanofluid cooling demonstrates superior performance by enhancing heat dissipation and lubricating properties compared to traditional MQL and dry-cutting conditions.

The interaction between feed rate and cooling conditions has a notable impact on machining outcomes. At lower feed rates, effective cooling conditions like nanofluid maximize heat dissipation and reduce friction, resulting in superior surface finishes. Conversely, at higher feed rates, the thermal and mechanical stresses on the tool increase, making the cooling condition even more critical to maintain acceptable Ra. These findings are consistent with research by Davim [28], which highlighted the importance of balancing feed rate and lubrication to achieve optimal machining results in hard materials

The error term accounts for 17.7% of the variation, reflecting experimental variability not explained by the tested factors. The overall model has an R-squared value of 82.30%, indicating that the selected factors collectively explain a significant proportion of the variability in Ra. These findings provide valuable insights into optimizing machining parameters to enhance surface quality.

The probability plot of Ra, presented in Figure 3, demonstrates a strong alignment between the actual Ra values and the predicted normal distribution. The data points are distributed closely along the center line, indicating that the experimental results conform well to the normality assumption within a 95% confidence interval. The mean Ra value was calculated as 0.9865μm, with a standard deviation of 0.06085μm. Additionally, the Anderson-Darling (AD) statistic of 0.300 and a corresponding p-value of 0.558 further confirm that the data does not deviate significantly from a normal distribution. This result validates the consistency of the experimental measurements and supports the reliability of the statistical analyses conducted in this study.

The multi-objective optimization of cutting parameters was performed utilizing the desirability function approach to concurrently increase MRR and minimize Ra (Figure 4). The optimization results revealed an overall composite desirability (D) value of 0.7473, indicating an effective trade-off between productivity and surface quality. The predicted optimal values for the responses are an MRR of 8038.3220 mm^3/min, with an individual desirability of 0.82254, and a Ra of 0.9558 μm, with an individual desirability of 0.67901. The cutting parameters were established to produce best results: cutting speed (v) of 80 m/min, depth of cut (d) of 0.6 mm, feed rate (f) of 0.171 mm/rev, and Nanofluid cooling condition. The desirability plot shows that higher cutting speeds and depths of cut improve MRR but may increase Ra unless a balanced feed rate is maintained. Moreover, the use of Nanofluid cooling proved to be highly effective in reducing Ra while sustaining high MRR, highlighting its advantage over other cooling methods tested in this study.

Nanofluid cooling exhibits superior performance due to its enhanced thermal conductivity and lubricating properties, which facilitate effective heat dissipation and minimize friction at the tool-workpiece interface. The nano-sized SiO_2 particles (100 nm) penetrate microscopic asperities on the workpiece surface, forming a robust lubricating layer that minimizes wear and improves the surface finish. This finding is consistent with prior studies, such as those by Das et al. [17] and Peng et al. [23], who reported similar improvements in machining performance with nanofluids containing oxide-based nanoparticles

The superior performance of nanofluid cooling compared to MQL and dry cutting can be attributed to several critical mechanisms. Dispersed nanoparticles in the fluid improve thermal conductivity, facilitating enhanced heat dissipation from the cutting zone. This minimizes tool wear and thermal deformation, leading to improved surface finishes. Furthermore, the nanoparticles create a protective tribo-film on the surfaces of the tool and workpiece, thereby reducing friction and wear. The self-repairing effect of nanoparticles, where they fill micro-cracks and restore surface integrity, further contributes to improved machining performance. Lastly, the rolling and polishing effects of nanoparticles help smoothen the workpiece surface during machining [31].

However, implementing nanofluid cooling in industrial settings poses certain challenges. The initial cost of nanoparticle-based cutting fluids is higher than traditional fluids, and specialized equipment is required to maintain stable dispersion and prevent agglomeration. There are also concerns about the long-term environmental impact and potential wear on machine components due to nanoparticle residue. Developing effective filtration systems and establishing proper handling protocols are essential to mitigate these risks. Additionally, further research is required to evaluate the recyclability and economic viability of nanofluids for large-scale production.

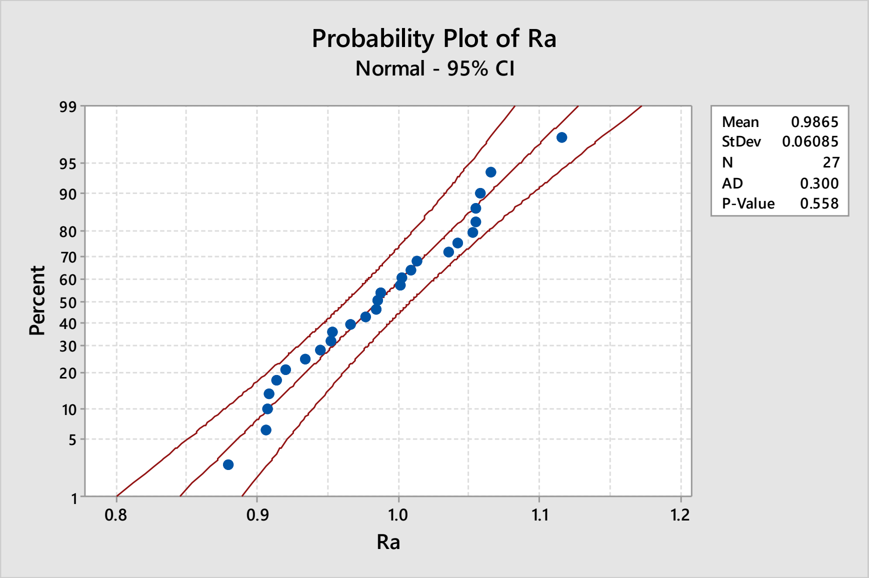

Figure 3. Probability plot of Ra

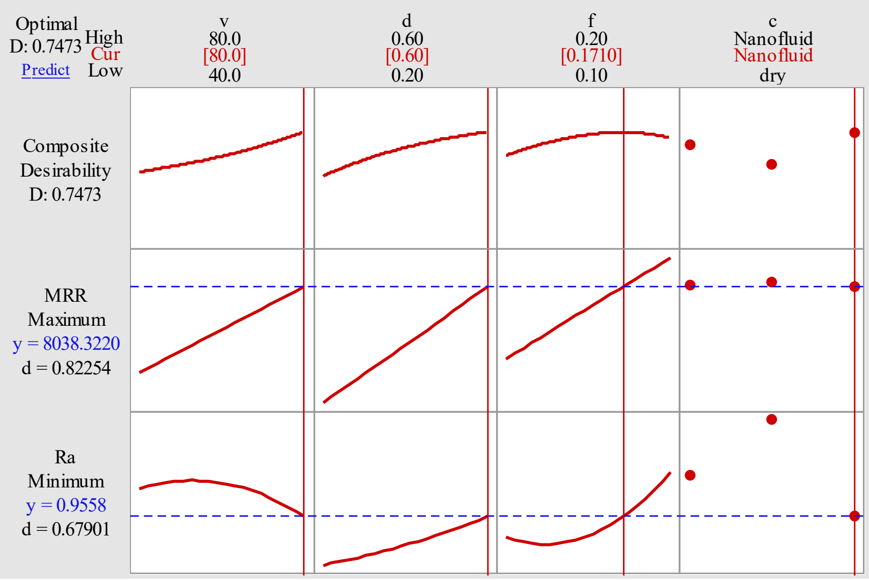

Figure 4. The multi-objective optimization

4. CONCLUSIONS

Following the application of various cooling conditions and cutting parameters during the turning of hardened SKD61 steel, several conclusions emerge:

4.1 Cooling condition impact

- Nanofluid cooling: Delivered optimal overall performance, markedly decreasing Ra and tool wear owing to enhanced heat conductivity and lubrication characteristics.

- MQL: Improved surface finish and tool life compared to dry conditions, though not as effective as nanofluid cooling.

- Dry cutting: Led to increased Ra and tool wear, underscoring the significance of efficient cooling and lubrication in the machining of hardened steel.

4.2 Ra optimization

- The hard turning process of SKD61 steel yields the minimum Ra when utilizing nanofluid, with a cutting speed of 80 m/min, a depth of cut of 0.2 mm, and a feed rate of 0.10 mm/rev.

The concentration of nanoparticles is a significant factor in the milling of hardened steel, such as JIS SKD61. The feed rate remains the most significant parameter.

4.3 Multi-objective optimization

- A multi-objective optimization strategy was utilized to concurrently minimize Ra and maximize MRR, hence balancing machining efficiency and product quality.

- The ideal cutting parameters for attaining this equilibrium were determined to be a cutting speed (v) of 80 m/min, a depth of cut (d) of 0.6 mm, and a feed rate (f) of 0.171 mm/rev under nanofluid cooling conditions. This combination ensures not only high surface quality but also improved machining productivity.

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