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Optimized Machining Parameters for High-Speed Turning Process: A Comparative Study of Dry and Cryo+MQL Techniques

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Abstract: Hard turning is a precision machining process used to cut materials with hardnesses exceeding 45 HRC using single-point tools. It offers an efficient alternative to traditional grinding for finishing operations in manufacturing. This paper explores the machinability of hardened AISI 4340 steel for a hard turning process utilizing dry and cryogenic (Cryo) plus minimum quantity lubrication (MQL) (Cryo+MQL) techniques, focusing on critical machinability aspects such as cutting force, surface roughness, and tool life. The orthogonal dry turning was performed with a cutting speed (V) ranging from 300–400 m/min, a feed rate (f) between 0.05 and 1 mm/rev, and a depth of cut (doc) from 0.1 to 0.3 mm. A statistical analysis of the obtained results revealed that the feed rate was the most influential parameter, contributing 50.69% to the main cutting force and 80.03% to surface roughness. For tool life, cutting speed was identified as the dominant factor, with a contribution rate of 39.73%. Multi-objective optimization using Grey relational analysis (GRA) identified the optimal machining parameters for the hard turning of AISI 4340 alloy steel as V = 300 m/min, f = 0.05 mm/rev, and doc = 0.1 mm. The Cryo+MQL technique was subsequently applied to these parameters, yielding significant improvements, with a 48% reduction in surface roughness and a 184.5% increase in tool life, attributed to enhanced lubrication and cooling efficiency. However, a slight 4.6% increase in cutting force was observed, likely due to surface hardening induced by the low-temperature LN_2 cooling. Furthermore, reduced adhesion and tool fracture on the principal cutting edge under Cryo+MQL conditions justify the superior surface quality and extended tool life achieved. This research highlights the industrial relevance of hybrid lubrication in addressing challenges associated with hard turning processes.

Keywords: dry condition; cryogenic; minimum quantity lubrication; tool life; surface roughness; cutting force; wear mechanisms

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1. Introduction

Hard turning has become a key technique in advanced manufacturing, particularly within the framework of sustainable machining. As an alternative to conventional grinding, it enhances productivity and machining efficiency while minimizing environmental impact [1]. Sustainable manufacturing aims to reduce ecological damage while maintaining

a balance between cutting performance and environmental conservation. This approach enables high-quality machining outputs with excellent surface finishes, especially for difficult-to-cut materials such as titanium, nickel, and high-strength alloy steels [2]. Among various shape-forming processes, hard turning is increasingly preferred for machining cylindrical components made from pre-heat-treated materials, due to its ability to deliver superior surface quality and dimensional accuracy [3]. Despite its advantages, hard turning presents significant challenges, particularly at high cutting speeds. The process generates high stresses and intense temperatures in the cutting zone, which can degrade tool life, compromise surface integrity, and diminish overall machining performance. These factors are critical in modern manufacturing industries, where product quality and production efficiency are paramount [4]. In this context, advancements in research have primarily focused on three key areas: (a) tool materials, (b) tool coatings, and (c) sustainable cooling and lubrication techniques. Despite these innovations, achieving optimal machining performance remains a challenge. Optimizing machining parameters is critical to addressing machinability issues and ensuring high-quality outputs. Parameters such as cutting speed, feed rate, and depth of cut play a pivotal role in determining cutting forces, surface roughness, tool wear, and chip morphology [5]. Effective optimization of these parameters not only improves machining performance but also extends tool life and reduces energy consumption, contributing to more efficient and sustainable manufacturing practices. Yaqoob et al. [6] optimized machining parameters for the hard turning process using Grey relation analysis (GRA) and found that a CVD-coated tool, operating at a cutting speed of 300 m/min, a feed rate of 0.05 mm/rev, and a depth of cut of 0.1 mm, yielded the longest tool life and the best surface finish. In addition to optimizing the machining parameters, using an effective cooling and lubrication medium can further enhance machinability. For instance, the recent adoption of hybrid lubrication, which combines cooling and lubrication, has been shown to significantly improve the production efficiency of hard-to-machine materials [7]. In a recent study, Sirin [8] reported a 34–39% reduction in surface roughness and a 36.7–42% decrease in vibration peaks with the application of Cryo+MQL lubrication, compared to dry and initial cryogenic conditions, during the turning of Hastelloy C22 superalloy using a TiAlN-TiN PVD-coated tool. Wu et al. [9] conducted high-speed machining on heat-treated steel and found that the LN_2+MQL environment can delay accelerated tool wear, thereby extending tool life. Additionally, they reported exceptional surface quality, with a roughness value below 0.7 μm even when using a worn tool, highlighting the effectiveness of Cryo+MQL in machining difficult-to-cut materials.

Among the categories of difficult-to-cut materials, AISI 4340 steel with a hardness of 45 HRC or higher presents significant challenges, particularly in high-speed orthogonal turning process using a single-point cutting insert. Its high strength and toughness lead to increased tool wear and elevated cutting forces, especially when the machining parameters are not optimized [10]. Studies conducted by Da Silva et al. [11] demonstrated that high-speed turning achieves comparable results to grinding, offering superior dimensional accuracy, tighter tolerances, and significantly reduced cycle times. Ensuring high-quality machining is critical for operational efficiency, production effectiveness, and product reliability [12]. This is especially important in industries such as aerospace, automotive, and oil and gas, where materials like AISI 4340 alloy steel are commonly used [13]. In response to the industrial demand for higher precision and efficiency, recent studies have focused on improving the machining performance of AISI 4340 steel under various conditions. These include the use of vegetable-based cutting fluids, cryogenic turning methods, and optimization studies aimed at enhancing process efficiency and product quality [6].

The study conducted by Gunjal and Patil [14] evaluated the effects of cutting speed on tool life, surface roughness, and chip thickness in sustainability machining using a

vegetable-based MQL approach that could reduce the environmental pollution and costs associated with conventional cutting fluids. The study revealed that the cutting speed significantly affects tool life, with higher speeds leading to reduced tool life due to increased heat and cutting forces at the machining zone. At a high cutting speed, canola oil under MQL was observed to provide superior performance in terms of tool life and surface finish compared to coconut oil, soybean oil, and synthetic. They also found that the MQL with vegetable-based cutting fluids showed better performance, demonstrating the longest tool life and decreased surface roughness compared to dry-cutting environments. According to Noor and Hadi [15] the effectiveness of MQL in machining various advanced materials can be further improved with nanoparticles and simultaneously spraying cryogenic coolant in milling titanium alloy.

Khare and Agarwal [16] focuses on optimizing the cryogenic turning of AISI4340 using the Taguchi methodology which aims to minimize surface roughness by determining the optimal machining variables, including cutting speed, feed rate, depth of cut, and rake angle. The robust L_9 orthogonal array was employed to accommodate the experiments. The study found that the cutting speed and depth of cut had the most significant effect on the surface roughness, with cutting speed being the most significant factor, contributing to 50.85% of the surface roughness. The confirmation experiment conducted with these parameters showed a 5.32% error in the predicted signal-to-noise ratio. This indicates the effectiveness of the Taguchi method in optimizing the cryogenic turning process under investigation. Another similar study conducted by Ochengo et al. [17] also used the Taguchi method, along with an analysis of variance (ANOVA), to examine the influence of tool type, and turning parameters on surface roughness (R_a) and cutting power (Cp). The study concluded that coated tools are superior for both responses and recommended for machining hardened steel. The optimal parameter settings for minimizing Cp and R_a were determined by an uncoated tool at 320 m/min and 0.1 mm/rev for Cp and a coated tool at the same speed and feed rate for R_a. The study validated the effectiveness of the Taguchi method through confirmation experiments, demonstrating that the method is reliable for optimizing machining parameters.

Kumar et al. [18] systematically analyzed the effects of cutting speed, feed rate, and depth of cut on surface roughness and tool wear under wet and dry-machining conditions using the Taguchi L_9 orthogonal array. Their findings revealed that dry machining led to higher surface roughness (R_a) and significant tool wear compared to wet machining, highlighting the importance of lubrication in optimizing machining parameters for enhanced performance. For an optimal surface finish under wet conditions, the study identified a high cutting speed (350 m/min), a low feed rate (0.04 mm/rev), and a low depth of cut (0.2 mm) as the ideal parameters. Maximum tool life was achieved with a low cutting speed (150 m/min), a low feed rate (0.04 mm/rev), and a low depth of cut (0.2 mm) under wet conditions. Feed rate was found to have the most significant influence on surface roughness, while depth of cut was the primary factor affecting tool wear, followed by cutting speed. The study concluded that hard turning under wet conditions provides a superior surface finish and extended tool life compared to dry conditions. Another study on hardened AISI 4340 alloy steel revealed that a blend of semi-vegetable oil reduces friction and enhances the machining efficiency [19].

Despite extensive research on high-speed turning with advanced tool materials and lubrication conditions, determining the optimal operating parameters for baseline dry turning of AISI 4340 steel remains a challenge. Our recent study [20], on the same material found that CVD-coated carbide tools provided better tool life and surface quality than PVD-coated carbide tools in dry cutting. However, feed rate remained the most influential factor for both parameters, with its lower range being more favorable for improved output

variables. Building upon previous work, this research optimizes machining parameters by incorporating cutting force as well in the machinability criteria. Additionally, cooling and lubrication techniques will be evaluated for a comparative assessment. Thus, this study systematically examines the machinability of dry-turning AISI 4340 steel at high cutting speeds by analyzing the influence of critical machining parameters on key performance outputs. The primary objective is to explore the interrelationships between cutting speed, feed rate, and depth of cut concerning tool life, surface roughness, and cutting force. Furthermore, the study aims to determine the optimal machining parameters for cylindrical processing of heat-treated AISI 4340 steel using GRA. Based on the optimized parameters, this research also investigates the machinability improvements achieved through the application of an advanced Cryo+MQL (LN_2 + MQL) strategy, comparing the results to baseline dry machining under optimized parametric settings.

2. Materials and Methods

2.1. Experimental Apparatus and Material

AISI 4340 is a medium carbon, low-alloy steel that is widely recognized for its high toughness and strength, which can be achieved through heat treatment. It is widely used in industries for components such as heavy-duty gears, shafts, etc. In this experiment, hardened AISI 4340 alloy steel with dimensions of Ø60 × 120 mm is used as a workpiece material. The hardening process involved austenitizing, quenching, and tempering, resulting in a hardness of 50 ± 2 HRC, classifying it as a high-hardness steel. Table 1 shows the mechanical properties of the common AISI 4340. Table 2 shows the chemical composition of heat treated AISI 4340 steel used for this research. The experiments were conducted on a Colchester–Harrison CNC Turning Center (TORNADO T4 model), designed for precision and consistency in turning operations. The T4 features an X-axis working travel of 200 mm, enabling lateral movement across the workpiece for operations up to 200 mm in width, and a Z-axis working travel of 450 mm, facilitating longitudinal movement along the workpiece for operations up to 450 mm in length.

Table 1. Mechanical properties of AISI 4340 [21].

Mechanical Properties	Values
Tensile strength	951 MPa
Elongation	13%
Hardness	282 BHN
Impact strength	44 J
Yield Strength	651 MPa

Table 2. Chemical composition of AISI 4340.

Element	Wt%
Fe	Balance
C	0.39
Mn	0.71
P	0.015
S	0.006
Si	0.26
Ni	1.73
Cr	0.80
Mo	0.22

The experiments were conducted under dry and Cryo+MQL conditions. In the Cryo+MQL setup, liquid nitrogen (LN_2) serves as the cryogenic coolant, reducing the

machining temperature at the cutting zone. It is applied through a nozzle at 3 bar, targeting the deformation zone. Simultaneously, Coolube 2210XP lubricant, derived from natural vegetable oils and designed for ferrous metals, is applied to the tool's flank face at 120 ml/h. This lubricant has the ability to adhere to the tool surface, reducing friction more effectively than typical mineral oils and forming a durable lubrication layer during cutting. The application of the coolant and lubricant is illustrated in Figure 1.

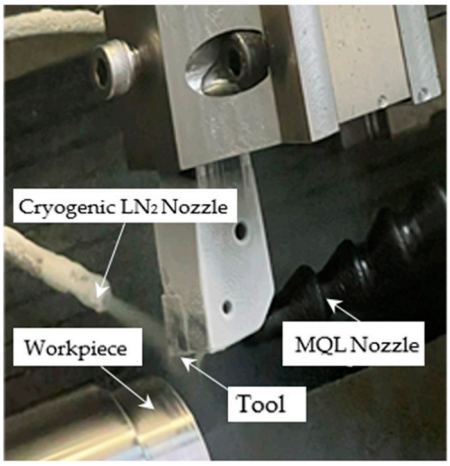


Figure 1. Application of cryo-lubricant during the turning process.

The cutting tool used is a carbide insert coated with aluminum oxide (Al_2O_3) and titanium carbon nitride (TiCN) via chemical vapor deposition (CVD), as detailed in Table 3. Classified as a CNMG 120404 multi-cornered tool with a negative rake angle of −80°, it features a cutting-edge diameter of 12.7 mm, a thickness of 4.76 mm, a hole diameter of 5.16 mm, and a corner radius of 0.4 mm. This tool is suitable for machining various steels, including carbon steel, alloy steel, and mild steel.

Table 3. Details of the cutting insert utilized in experimentation.

Specifications	CVD Tool
Grade	P-grade
Coating	Al_2O_3/TiCN
Coating thickness	18 µm
Hardness of substrate	90.5 HRA
Nose radius	0.4 mm
Rake angle	−6°
Cutting edge angle	95°

Machinability data were recorded using various instruments. For analysis, only the main component of cutting force (F_c) was monitored and recorded during machining using an in-house-developed Neo-MoMac system. This comprehensive system is specifically designed for measuring cutting forces in both turning and milling operations. It incorporates multi-component force sensors aligned along the x, y, and z-axes to capture the force dynamics accurately. The dynamometer is initially connected to the tool and subsequently linked to a data acquisition system for real-time recording. The force recording system, displayed on a GUI computer interface, initiates data collection as the tool engages with the work material and continues to record throughout the cutting process until its completion. This setup ensures comprehensive data collection to analyze the forces exerted during the machining of hardened AISI 4340. The scheme of the Neo-MoMac system is shown in Figure 2.

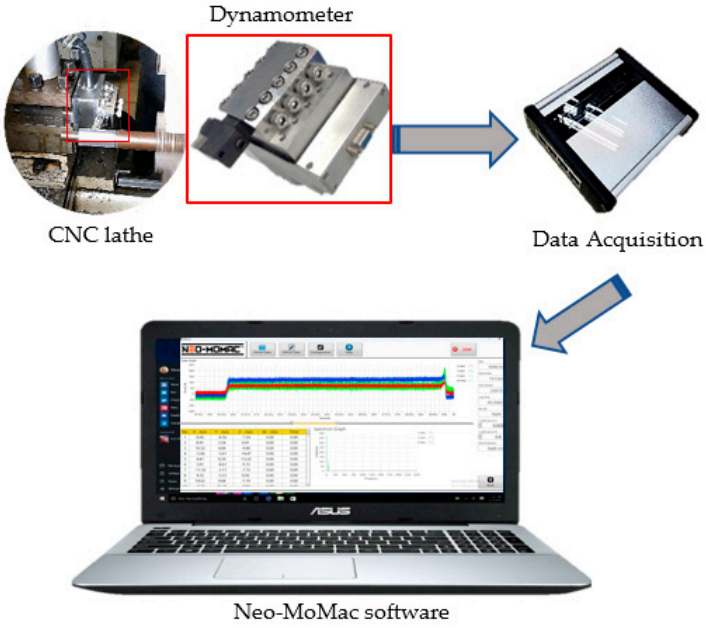


Figure 2. Neo-MoMac system.

The Mitutoyo Surftest SJ-210 was used to measure the surface roughness of the workpiece after each parametric run. This compact and portable device is ideal for on-site use. During measurement, the workpiece was stabilized to prevent vibrations, and the drive unit was positioned so that the stylus was perpendicular to the surface. As the stylus traversed the workpiece, the device recorded the roughness profile. The width of the flank wear on the cutting insert was monitored and measured using the ZEISS Stemi 305 stereo microscope. Integrated software ZEN 2012 SP2 with this setup allows for images to be captured and saved according to the machining time. Furthermore, a magnified view of tool wear was obtained using a scanning electron microscope (SEM) to investigate the underlying wear mechanism with the worn tools processed with different machining conditions. Figure 3 represents the experimental setup for evaluating the different machinability variables in this study.

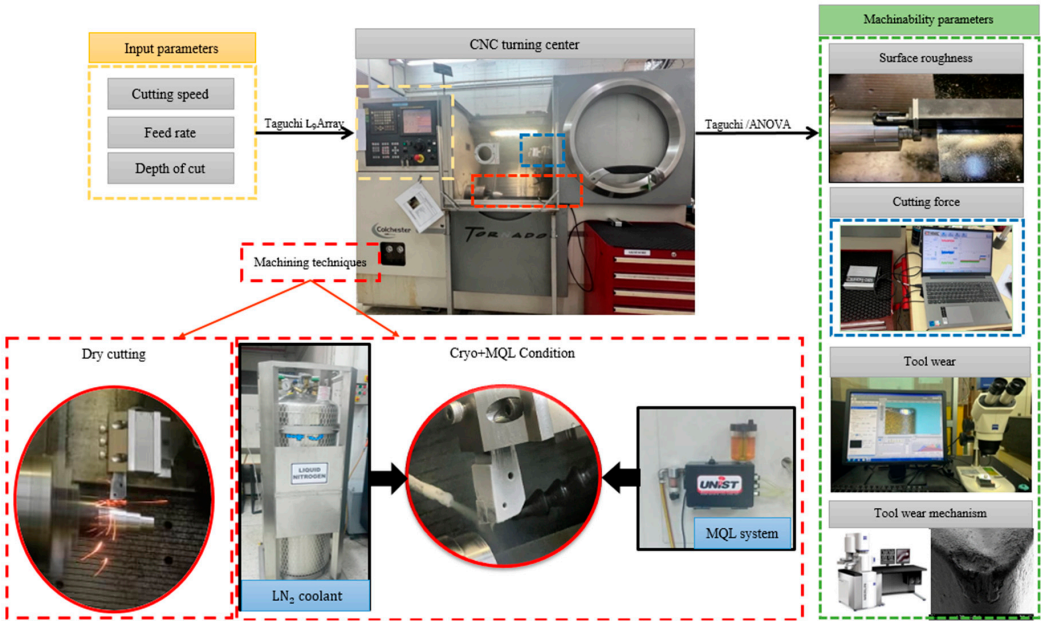


Figure 3. Experimental setup illustrating employed dry, LN_2+MQL schemes, input variables, and output machinability parameters.

2.2. Design of Experiment

This study employs the Taguchi L_9 orthogonal array for the design of experiments, chosen to systematically organize the parameters influencing the turning process and their respective levels. This method ensures efficient data collection with a minimal number of experiments. The L_9 array consists of nine distinct experiments, each representing a unique combination of parameter settings. The levels in the array should be replaced with the actual values used during the experiments. Table 4 presents the factors (parameters) and their respective levels for the turning process under dry and hybrid conditions in the finishing operation. Table 4 also illustrates the arrangement of these factors within the L_9 array, with each row representing a distinct experimental run based on the specified parameter levels in Table 5. This structured approach facilitates the efficient evaluation of how different parameter combinations impact the quality and performance of the turning process.

Table 4. Factors with their levels for the turning parameters.

Factors/Level	1	2	3
Cutting speed, V (m/min)	300	350	400
Feed rate, f (mm/rev)	0.05	0.075	0.1
Depth of cut, *doc* (mm)	0.1	0.2	0.3

Table 5. Taguchi L_9 orthogonal array.

Experiment	V (m/min)	f (mm/rev)	*doc* (mm)
1	V 1	f 1	*doc* 1
2	V 1	f 2	*doc* 2
3	V 1	f 3	*doc* 3
4	V 2	f 1	*doc* 2
5	V 2	f 2	*doc* 3
6	V 2	f 3	*doc* 1
7	V 3	f 1	*doc* 3
8	V 3	f 2	*doc* 1
9	V 3	f 3	*doc* 2

Experimental data analysis was conducted using Minitab statistical software version 20 to compute the Taguchi signal-to-noise ratio (S/N) and analysis of variance (ANOVA), identifying the controllable variables demonstrating significant effect on the output variables. For this study, the 'larger the better' quality characteristic was applied to tool life (T), while 'smaller is better' was used for cutting force (F_c) and surface roughness (R_a). The Taguchi method helps identify the key parameters that significantly affect performance, enabling focused experimentation on these parameters while disregarding those with minimal impact. A multi-objective optimization technique was then employed to determine the optimal machining parameters. After identifying the optimal settings for dry conditions, the Cryo+MQL technique was applied to these parameters, and the results were compared to the dry conditions to assess the performance benefits of using coolant and lubricant in the hard turning process. Figure 4 shows the steps involved in conducting this study.

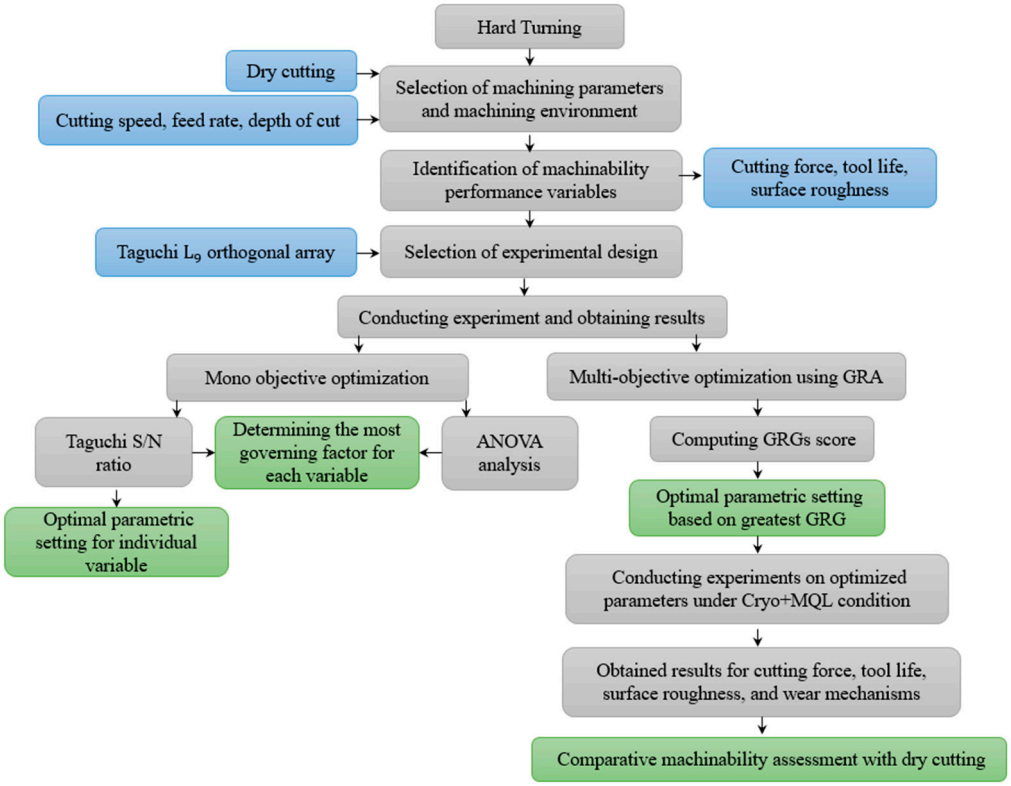


Figure 4. Stepwise research scheme for conducting hard turning experiments.

3. Results and Discussion

The CNC lathe was configured to conduct turning experiments under various combinations of machining input variables in a dry-cutting environment without lubrication or coolant. The results of the output variables, including cutting force, surface roughness, and tool life, are systematically presented in Table 6. Based on these key performance indicators, the analysis aimed to elucidate the interrelationships between the machining variables and their influence on process efficiency and surface quality.

Table 6. Recorded results of machinability variables.

No.	Cutting Force F_c (N)		Surface Roughness R_a (µm)		Tool Life T (s)	
	Measured Value	S/N Ratio	Measured Value	S/N Ratio	Measured Value	S/N Ratio
1	43.3	−32.7298	0.465	6.6509	1155	61.256
2	91.59	−39.2370	0.685	3.2862	713	57.059
3	128.8	−42.1983	0.895	0.9635	339	50.064
4	68.88	−36.7619	0.305	10.314	847	58.553
5	99.22	−39.9320	0.541	5.3361	380	51.604
6	76.65	−37.6902	0.696	3.1478	554	54.876
7	49.55	−33.9009	0.307	10.2572	290	49.242
8	47.68	−33.5667	0.535	5.4329	388	51.767
9	97.3	−39.7623	0.726	2.7813	206	46.294

3.1. Cutting Force (F_c)

Measuring cutting force (F_c) is crucial, as it provides insights into tool performance, energy consumption, and the mechanical load on the cutting tool, which are essential for optimizing machining processes and ensuring tool longevity [22]. Table 6 presents the cutting force measurements obtained under various machining settings. According to

the signal-to-noise (S/N) ratio plot shown in Figure 5, the feed rate exerts the greatest influence on cutting force, followed by depth of cut and cutting speed in dry conditions. These findings are corroborated by the ANOVA analysis results in Table 7, which indicate that feed rate and depth of cut have the highest percentage contributions of 50.69% and 36.01%, respectively, making them the most influential variables affecting cutting force. The influence of the highest feed rate can be attributed to its imposition of a larger cross-sectional area of the uncut chip and the greater volume of deformed workpiece material, particularly at elevated levels of feed and depth of cut.

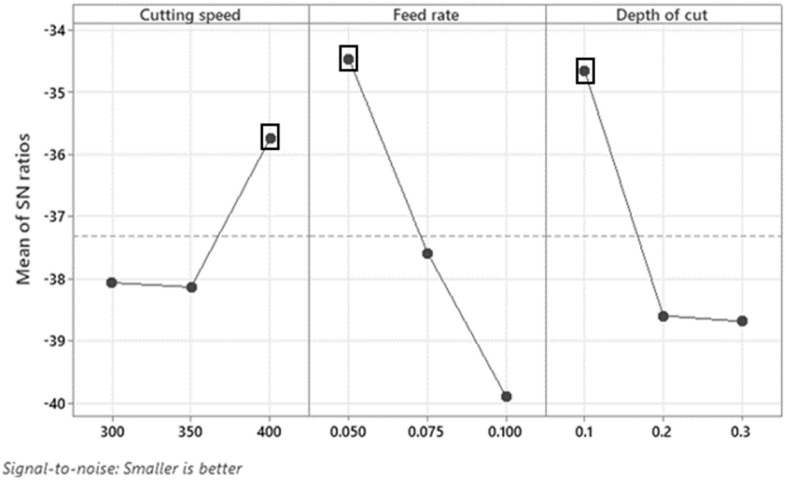


Figure 5. Main effect S/N ratio plot for cutting force.

Table 7. ANOVA for cutting force in dry conditions.

Parameter	DF Value	Seq SS	Adj SS	Adj MS	F Value	*p* Value	% Contribution
V	2	11.0364	11.0364	5.5182	18.25	0.052	12.61%
f	2	44.3830	44.3830	22.1915	73.38	0.013 *	50.69%
doc	2	31.5308	31.5308	15.7654	52.13	0.019 *	36.01%
Residual Error	2	0.6048	0.6048	0.3024			
Total	8	87.551					

* significant.

These results align with the findings of Sivaraman et al. [23] in the turning of microalloyed steel. They reported that feed rate and depth of cut significantly influence cutting force while cutting speed demonstrated a lesser effect. Specifically, a lower feed rate reduces the material volume removed per unit of time, decreasing resistance on the cutting tool. Similarly, a shallower depth of cut reduces the material thickness removed in each pass, requiring less force for machining. Together, these adjustments lower cutting force, improve machining efficiency, reduce tool wear, and enhance surface finish quality [24]. Therefore, the lowest F_c of 43.3 N was recorded at a low parametric setting, including a cutting speed of 300 m/min, a feed rate of 0.05 mm/rev, and a depth of cut of 0.1 mm. In contrast, Experiment 3, which involved higher feed rates and greater depths of cut, produced the highest F_c of 128.8 N. Another key finding, as shown in the S/N plot in Figure 5, is that increasing the cutting speed significantly reduces the main cutting force. This reduction is due to a shorter tool–chip contact length at higher surface speeds of the rotating workpiece, which decreases frictional force. Additionally, the combined effect of thermal softening, resulting from high heat generation during machining, reduces the material's strength, making it easier to shear [25].

Mono-optimization using the Taguchi S/N ratio (Figure 5) indicated that the optimum conditions for minimizing cutting force in dry conditions are achieved at a cutting speed

of 400 m/min, a feed rate of 0.05 mm/rev, and a depth of cut of 0.1 mm. Higher cutting speeds, along with lower feed rates and depths of cut, contribute to reduced cutting forces, which are crucial for minimizing energy consumption and extending tool life [26].

3.2. Surface Roughness

Surface quality is a critical factor in hard turning, as it significantly influences the performance and longevity of components, particularly those engaged in sliding mechanisms. Since hard turning is progressively being considered as a viable alternative to traditional grinding processes, the need for a superior surface finish becomes even more pronounced [27]. Therefore, surface roughness (R_a) was identified as one of the key factors representing the state of the surface finish. According to Jouini et al. [28], the profile length ratio (Lr) and R_a are the most relevant roughness parameters for distinguishing the effects of cutting parameters in the hard turning process. In this study, R_a was evaluated based on the average roughness value. Table 6 presents the R_a measurements obtained for various dry-machining conditions. Overall, the results show a decreasing trend with an increasing cutting speed and an increasing trend with an increasing feed rate. The S/N plot in Figure 6 highlights that the feed rate with a wider spread indicates the dominating effect on R_a. This finding is consistent with the ANOVA results presented in Table 8, where the feed rate, with a *p*-value of 0.012, is identified as the most significant factor, contributing 83.03% to R_a. In comparison, cutting speed has a relatively small impact, with a contribution rate of 15.59%, while the depth of cut has a minimal contribution of only 0.40%. Referring to Das et al. [29], increasing the cutting speed optimized the frictional and shear plane energy, which leads to higher temperatures at the shear plane area and machine surface. High temperature facilitates the thermal softening of the workpiece material, thereby reducing the cutting forces requirement for material removal. On the contrary, higher feeds require greater force to effectively remove material, which can lead to the onset of vibrations during the machining process. Özbek and Saruhan [30] states that vibrations disrupt the stability of the cutting operation and result in poor surface quality.

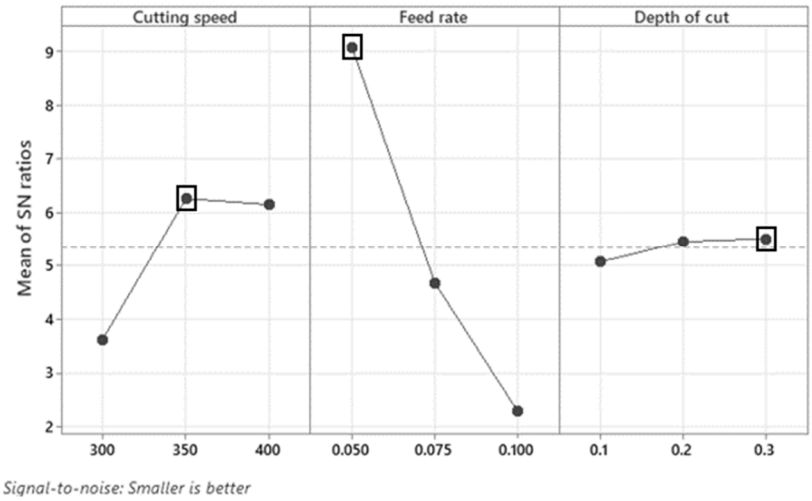


Figure 6. Main effect S/N ratio plot for surface roughness in dry condition.

Table 8. Analysis of variance for cutting force in dry conditions.

Parameter	DF Value	Seq SS	Adj SS	Adj MS	F Value	*p* Value	% Contribution
V	2	13.099	13.099	6.6549	16.04	0.059	15.59%
f	2	70.8848	70.8848	35.4424	85.40	0.012 *	83.03%
doc	2	0.3454	0.3454	0.1727	0.42	0.706	0.40%

Table 8. *Cont.*

Parameter	DF Value	Seq SS	Adj SS	Adj MS	F Value	*p* Value	% Contribution
Residual Error	2	0.8300	0.8300	0.4150			
Total	8	85.370					

* significant.

Mono-optimization using the Taguchi S/N ratio (Figure 6) indicated that the optimum conditions for reduced surface roughness in dry conditions is achieved at a cutting speed of 350 m/min, a feed rate of 0.05 mm/rev, and a depth of cut of 0.3 mm. This result is in line with previous findings by Ochengo et al. [17]; the higher cutting speed and lower feed rate led to decreased power consumption and surface roughness.

3.3. Tool Life

Tool life is a crucial factor in hard turning, as it directly impacts productivity, machining efficiency, and cost-effectiveness. A longer tool life allows for a more accurate estimation of machining time and reduces the frequency of tool changes, which can otherwise increase setup costs and process inefficiencies [31]. Frequent tool wear disrupts production flow, leading to increased downtime and reduced overall output [32]. To address these challenges, researchers are optimizing machining parameters and cooling techniques tailored to specific materials. In this study, tool life values were obtained for various combinations of machine settings, as presented in Table 6. Longer tool life is typically achieved with lower cutting speeds, feed rates, and depths of cut, as corroborated by the obtained results. Specifically, the combination of V = 300 m/min, f = 0.05 mm/rev, and doc = 0.1 mm resulted in the longest tool life of 1155 s. This finding aligns with Roy et al. [33], who observed longer tool life at lower cutting parameters. They attributed tool wear at higher cutting speeds and feed rates to thermal effects, including tool and workpiece softening, increased mechanical stresses, and the abrasive cutting environment. Consequently, the highest machining combination in Experiment 9 resulted in the shortest tool life of 206 s. However, Experiment 3, characterized by a high feed rate and depth of cut, also exhibited the shortest tool life. Grzesik et al. [34] explained that, at higher feed rates and cutting depths, plowing action may persist, increasing friction and promoting micro-chipping and crater wear, thereby reducing tool life.

Figure 7 shows the SN ratio plots for the factors affecting tool life. The plot indicates that cutting speed is the most influential parameter, followed by feed rate and depth of cut. This observation is supported by the ANOVA results from Table 9, where all of the parameters are deemed significant, as their p-values are less than 0.05. The percentage contribution analysis reveals that cutting speed has the largest impact on tool life, contributing 39.73%, while feed rate and depth of cut contribute similarly, with 32.26% and 27.08%, respectively. Higher cutting speeds typically lead to increased temperatures, which can accelerate tool wear mechanisms, such as diffusion and oxidation [35].

Table 9. Analysis of variance for tool life.

Parameters	DF Value	Seq SS	Adj SS	Adj MS	F Value	*p* Value	% Contribution
V	2	304342	304342	152171	43.30	0.023 *	39.73%
f	2	247172	247172	123586	35.16	0.028 *	32.26%
doc	2	207461	207461	103731	29.51	0.033 *	27.08%
Residual Error	2	7029	7029	3515			
Total	8	766004					

* significant.

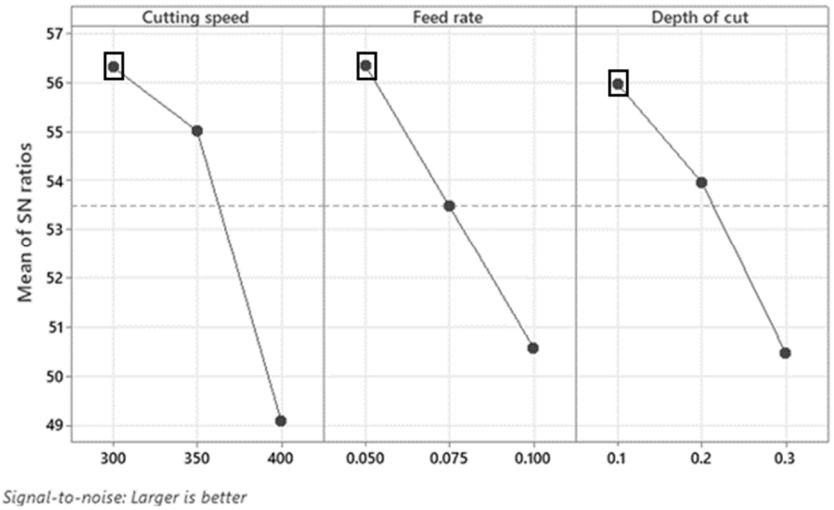


Figure 7. Main effect S/N ratio plot for tool life.

3.4. Multi-Objective Optimization Studies for Best Parametric Setting

The optimization of machining parameters is important to balance productivity, surface quality, and tool life. To determine the optimal parametric combination for hard turning AISI 4340 alloy steel, a multi-objective optimization approach using GRA was employed. In this approach, the obtained data was processed by following these steps:

Step 1—normalization: The data was normalized in the range between 0–1 using two quality characteristics, the smaller the better using Equation (1) and the larger the better using Equation (2). For this study, cutting force and surface roughness data were normalized using Equation (1) and tool life data using Equation (2).

$$X_{ij} = \frac{\text{Max(yij)} - \text{yij}}{\text{Max(yij)} - \text{Min(yij)}} \tag{1}$$

$$X_{ij} = \frac{\text{yij} - \text{Min(yij)}}{\text{Max(yij)} - \text{Min(yij)}} \tag{2}$$

where X_{ij} represents the normalized value for the jth dependent response factor for the ith experimental run and yij is the corresponding term in a row.

Step 2—computing the Grey relation coefficient ζ_{ij} (GRC): The Grey relational coefficient, determined using Equation (3), quantifies how closely a set of actual results aligns with the desired outcomes by measuring the variation between the ideal and experimental values.

$$\zeta_{ij} = \frac{\min\limits_{ij} |\Delta_{ij}| + \zeta \max\limits_{ij} |\Delta_{ij}|}{|\Delta_{ij}| + \zeta \max\limits_{ij} |\Delta_{ij}|} \tag{3}$$

where Δ_{ij} is the difference between the ideal (y_i^0) and actual sequence (y_{ij}) and ζ is the distinguishing coefficient in the range between zero and one, however, we used 0.5 to compute the Grey relation coefficient ζ_{ij}.

Step 3—computing the Grey relation grade (GRG): In the following step, the Grey relation degree is calculated by summing the product of GRC and its corresponding weightage (β_i) using Equation (4). An equal weightage of 33.33% was assigned to all output variables, as they are equally important in machinability performance evaluation.

$$\gamma_j = \frac{1}{n} \sum_{i=1}^{n} \beta_i \zeta_{ij} \tag{4}$$

Step 4—Ranking: In the final step rank is assigned based on descending order to values that are close to one. The set of experimental run scored the maximum GRG identified as the optimal parametric setting for the conducted experimental scheme. The related step-wise computation of GRA is shown in Table 10, where it can be seen that a cutting speed at 300 m/min, a feed rate at 0.05 mm/rev, and a depth of cut at 0.1 mm achieved the highest GRG score of 0.879. Thus, this setting is optimal for the selected machinability criteria.

Table 10. Computation of GRA.

Exp. No	Normalized Values			Grey Relation Coefficient			Grey Relation Grade (GRG)	Ranking
	R_a	F_c	TL	R_a	F_c	TL		
1	0.729	1.000	1.000	0.648	1.000	1.000	0.879	1.0
2	0.356	0.435	0.534	0.437	0.470	0.517	0.473	6.0
3	0.000	0.000	0.140	0.333	0.333	0.368	0.343	9.0
4	1.000	0.701	0.674	1.000	0.626	0.606	0.741	2.0
5	0.600	0.346	0.183	0.556	0.433	0.380	0.455	7.0
6	0.337	0.610	0.367	0.430	0.562	0.441	0.476	5.0
7	0.997	0.927	0.088	0.993	0.872	0.354	0.738	3.0
8	0.610	0.949	0.191	0.562	0.907	0.382	0.615	4.0
9	0.286	0.368	0.000	0.412	0.442	0.333	0.394	8.0

3.5. Application of Cryo+MQL Lubrication and Its Comparative Analysis with Dry Conditions

After identifying the optimized parameters for the dry environment, a hybrid lubrication approach, combining coolant (LN_2) applied from the tool rake side and lubricant (MQL) from the flank side was employed to minimize the cutting temperature and enhance performance. The same machinability variables, including cutting force, surface roughness, and tool life, were examined and compared with those in the dry environment to evaluate the improvements.

The results from both machining environments, as shown in Table 11, reveal significant improvements in surface roughness and tool life by approximately 48% and 184.5%, respectively, with the application of Cryo+MQL. This demonstrates that hybrid conditions enhance cooling and lubrication, effectively reducing friction and dissipating heat. Consequently, surface quality and tool life improved significantly. The hybrid cooling approach minimized mechanical and thermal stresses on the cutting tool edge, slowing the wear rate by lowering cutting temperatures and friction. In contrast, dry machining resulted in higher temperatures and friction, accelerating tool wear and reducing tool life. These findings are consistent with Sivaiah et al. [36], who reported a 70% reduction in machining temperature with MQL compared to dry conditions, highlighting the critical role of lubrication in metal cutting. Furthermore, the hybrid Cryo+MQL approach offers additional benefits, and the approach provides additional benefits, as confirmed by a study conducted by Shokrani et al. [37]. They reported that combining LN_2 and MQL reduces cutting and thrust forces by 30% compared to MQL and flooding methods alone, improving efficiency and tool longevity.

Table 11. Machinability results for dry and hybrid lubrication environments.

Output Variable	Dry Condition	Cryo+MQL Condition	Remarks
Cutting force (N)	43.3	45.4	A 4.6% increase in main cutting force is noticed when machining was performed with hybrid lubrication.
Surface roughness (μm)	0.465	0.24	A 48% decrease in surface roughness was realized with hybrid environment.
Tool life (s)	1155	3288	A 184.5% improvement in tool life results was achieved with hybrid lubrication.

However, a 4.6% increase in cutting force was observed under the Cryo+MQL condition. This can be attributed to the fact that, in dry-cutting environments, the workpiece material softens due to higher cutting temperatures, leading to reduced cutting forces. In contrast, the cooling and lubrication effects of Cryo+MQL prevent excessive temperature rise, thereby influencing the mechanical behavior of the workpiece. Additionally, the introduction of LN_2 creates a favorable temperature gradient, which may alter the material properties, potentially increasing the force required for effective machining. This observation aligns with the findings of Liu et al. [38], who reported an increase in cutting force due to the work-hardening effect induced by the hybrid lubrication environment. While the observed increase in cutting force is relatively small, its broader implications must be carefully evaluated through future studies. By focusing on tool wear, process efficiency, and industrial scalability, along with the optimization of the LN_2 flow rate and its integration with other machining parameters, future research can enhance the practical benefits of Cryo+MQL while mitigating any unintended drawbacks, making it a more viable and sustainable alternative to conventional machining methods.

Figure 8 shows the plot of flank wear land (Vb) versus cutting time (t) for both dry and hybrid conditions. The tool wear progressions for both conditions show rapid wear at the start of cutting, followed by the development of uniform flank wear until 500 s of machining time. Afterward, the wear enters a stable stage, eventually progressing to a severe stage, reaching the maximum tool life criterion of Vb $\geq$ 0.3 mm. Notably, the stable wear stage is longer in hybrid environments, contributing to extended tool life. The initial wear stages were significantly reduced, and the steady wear stage was prolonged, indicating that the hybrid approach effectively mitigates the wear mechanisms that typically accelerate under dry cutting. The absence of lubrication leads to greater heat generation, causing severe wear on the tool's cutting edge. In contrast, Cryo+MQL provided effective cooling and lubrication, which has significantly reduced the frictional and thermal stresses on the cutting tool, resulting in minimized tool wear and longer tool life. Zainol et al. [39] reported that the use of MQL in conjunction with LN_2 resulted in better tool life and lower wear rates due to the effective boundary lubrication and efficient heat dissipation characteristics provided by both methods.

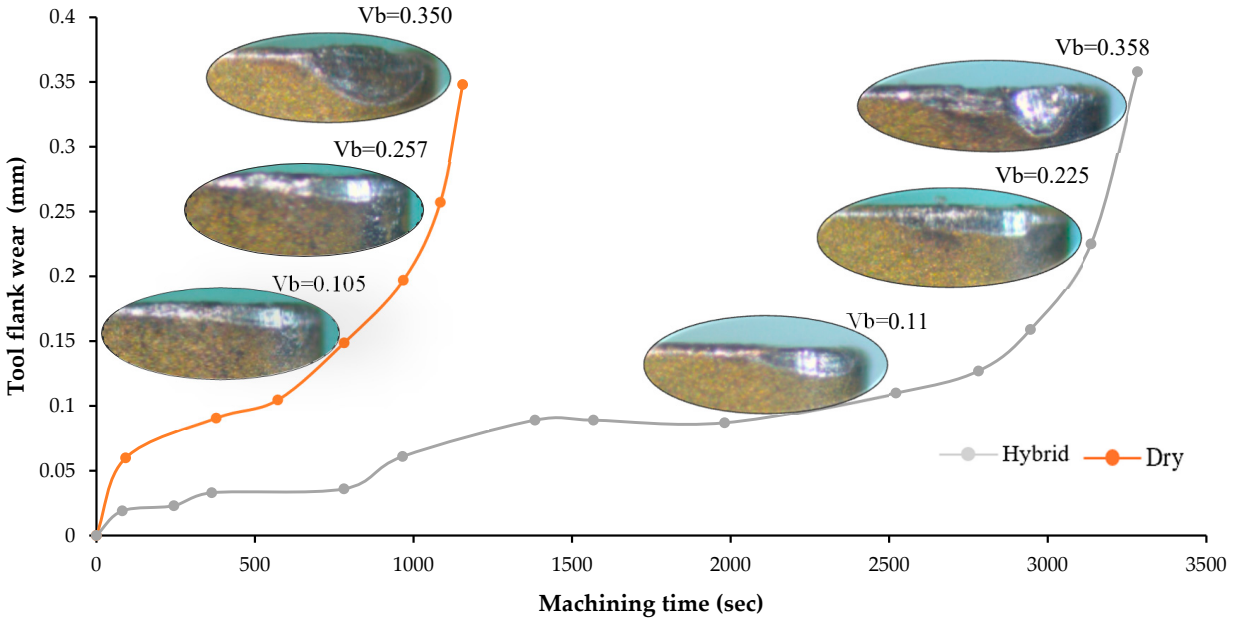


Figure 8. Flank wear land (mm) Vs machining time (sec) in both conditions.

The microscopic images in Figure 9a,b represent the tool wear mechanisms observed using a scanning electron microscope (SEM). This representation offers a comparative analysis of dry and hybrid Cryo+MQL techniques. It can be observed that worn tools with dry machining demonstrated severe wear mechanisms, such as coating delamination, adhesion, and a larger fracture area. During the machining, the absence of lubrication and cooling media led to elevated cutting temperatures and mechanical stresses at the tool–workpiece interface, resulting in thermal softening of the tool material and subsequent coating delamination [40]. Additionally, high temperatures promoted diffusion and adhesion between the tool and workpiece materials, causing the formation of a thick buildup layer on the tool's flank face. This is evident in Figure 9b, where severe adhesion of workpiece material can be observed. As machining progresses, abrasive wear, characterized by grooves and scratches from hard workpiece particles, exacerbates tool damage, leading to chipping and edge fractures. These are indicative of cyclic loading and thermal shocks, which compound the wear and result in significantly reduced tool life under dry machining [41]. Conversely, the Cryo+MQL lubrication approach effectively reduced the cutting temperature and friction, mitigating thermal and mechanical stresses on the tool. This resulted in minimal coating delamination, reflecting improved adhesion between the tool substrate and coating due to the stabilized thermal environment. While abrasive wear persisted, it was notably less severe, as shown by the relatively smoother tool surface compared to the dry cutting in Figure 9a. Moreover, slight chipping on the main cutting edge indicated enhanced edge stability, attributed to the cooling effect of LN_2, which preserved the cutting edge's structural integrity. Duc et al. [42] highlighted that effective chip removal facilitated by LN_2 and MQL reduced friction, thereby minimizing potential wear mechanisms.

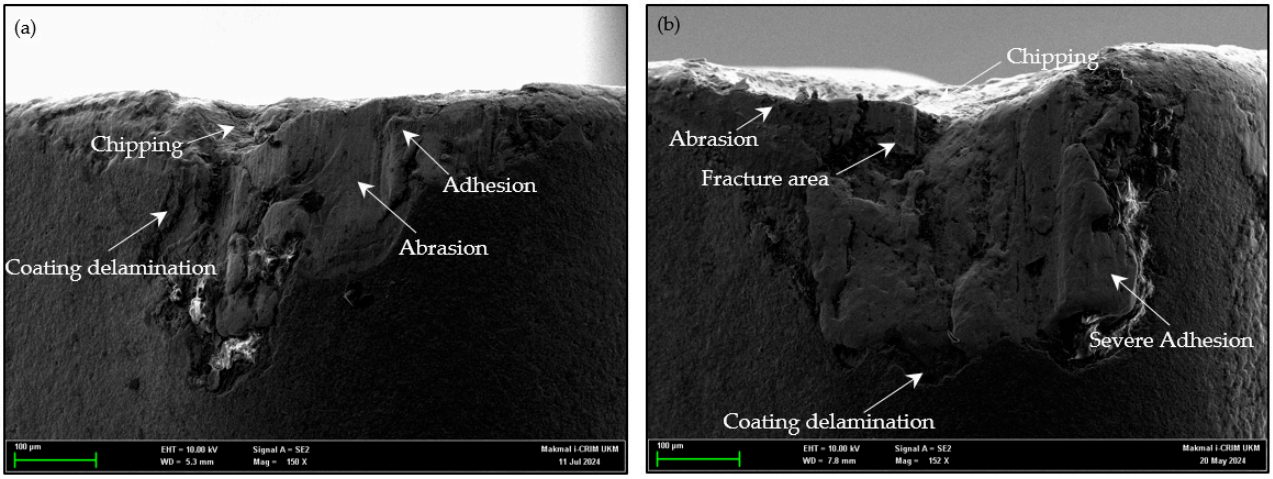


Figure 9. SEM images of worn tools under (**a**) Cryo+MQL and (**b**) dry conditions.

4. Conclusions

The following can be concluded from the study of the high-speed turning of AISI 4340 steel under dry and Cryo+MQL machining conditions:

- The experimental results showed the lowest cutting force of 43.3 N and the longest tool life of 1155 s at the lowest machining settings: a cutting speed of 300 m/min, a feed rate of 0.05 mm/rev, and a depth of cut of 0.1 mm. However, the lowest surface roughness of 0.305 µm was achieved at a moderate cutting speed of 350 m/min, a depth of cut of 0.2 mm, and the lowest feed rate of 0.05 mm/rev. Mono-optimization using the Taguchi signal-to-noise (S/N) ratio revealed that a high cutting speed and the lowest feed rate are favorable for minimizing cutting force and improving surface

roughness, whereas a low cutting speed and feed rate are optimal for maximizing tool life in a dry environment;

- Statistical inference using ANOVA revealed that feed rate was the most significant factor, contributing 50.69% to cutting force and 80.03% to surface roughness, while cutting speed was the primary factor influencing tool life, with a contribution rate of 39.73% during the dry turning of hardened AISI 4340 alloy steel;
- Multi-objective optimization using GRA showed that a cutting speed of 300 m/min, a feed rate of 0.05 mm/rev, and a depth of cut of 0.1 mm yielded the highest GRG score of 0.879, confirming this combination as the optimal setting for the selected machinability criteria. These parameters provided a balanced trade-off, ensuring a smooth surface finish, low cutting forces, and extended tool life;
- The application of hybrid lubrication significantly improved surface roughness by 48% and extended tool life by 184.5%, which are attributed to the enhanced lubrication and cooling efficiency of the system. This demonstrates that concurrent cooling and lubrication are more effective than dry cutting in reducing machining heat. However, a 4.6% increase in cutting force was observed, likely due to the reduced temperature from LN_2 cooling. In contrast, dry cutting typically results in higher temperatures, leading to material softening. Consequently, the lower temperatures in LN_2 cooling may have contributed to surface hardening, increasing cutting force;
- Fracturing at the cutting edge and excessive material adhesion are key factors influencing tool performance in dry cutting. The cooling effect of the Cryo+MQL lubrication approach significantly mitigates thermal and mechanical stresses on the tool, reducing coating delamination and adhesion while maintaining tool integrity and enhancing edge stability.

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