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A Comparative Performance Investigation of Single- and Double-Nozzle Pulse Mode Minimum Quantity Lubrication Systems in Turning Super-Duplex Steel Using a Weighted Pugh Matrix Sustainable Approach

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Abstract: This study investigates the performance comparison of machining of UNS S32750 super-duplex stainless steel under single- and double-nozzle pulse mode minimum quantity lubrication (MQL) conditions. The pulse mode MQL system delivers lubricant pulses at specific intervals. The Taguchi L_9 design, with three factors and their three levels, was taken to perform the CNC turning experiments under both single-nozzle and double-nozzle MQL cooling environments. The surface roughness (Ra), tool-flank wear (VB), tool-flank temperature (Tf), power consumption (Pc), and material removal rate (MRR) are evaluated and compared as performance indicators. In comparison to single-nozzle MQL, the responses of Ra, VB, Tf, and Pc were found to be decreased by 11.16%, 21.24%, 7.07%, and 3.16% under double-nozzle conditions, respectively, whereas MRR was found to be 18.37% higher under double-nozzle conditions. The MQL pulse time was found to be an important variable that affects Ra, VB, Tf, and MRR significantly. Under both cooling scenarios, common wears such as abrasion, built-up edges, adhesion, and notch wear are detected. Furthermore, the Pugh matrix-based sustainability evaluation results revealed that the double-nozzle MQL technique was superior to single-nozzle MQL, achieving improved sustainability for machining super-duplex stainless steel.

Keywords: super-duplex stainless steel; turning; pulse mode MQL; tool-flank wear; surface roughness; power consumption; tool-flank temperature; MRR; sustainability

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1. Introduction

Super-duplex stainless steel is a modern-generation steel. It consists of a mixed microstructure of both austenite and ferrite in equal proportions. This improves its strength and toughness over conventional austenitic and ferrite grade steels [1]. It has an excellent corrosion resistance ability due to the presence of high percentages of chromium and molybdenum. It also possesses additional properties like higher tensile and yield strength, greater ductility and toughness, excellent stress corrosion cracking resistance, and a lower cost of production compared to similar grades of austenitic and ferrite steels. It contains chromium of around 20 to 33% and nickel of 1 to 9%, which increase its hardenability and corrosion resistance. Moreover, 0.1 to 0.6% of nitrogen is also added to improve its weldability [2,3]. The presence of all these properties makes duplex steel one of the most desired materials in the manufacturing sector, and many manufacturing sectors are considering super-duplex steel as the best replacement for austenitic and ferrite steels. Duplex steel finds its applications in high-pressure storage tanks or vessels associated with chemical and food–beverage industries, oil and gas pipelines, heat exchanger pipes, desalination plants, and automobile industries [4,5]. Super-duplex steel also has a few negative aspects. On the one hand, it comes with excellent strength, toughness, and corrosion resistivity, but on the other hand, its machining is very difficult. During its machining operations, huge amounts of heat are generated, even whilst using advance cutting tools. Vital aspects such as the surface quality, tool wear, and tool life are directly dependent on the machining temperature, so maintaining a proper machining temperature becomes very necessary. Thus, the dry machining of super-duplex steel is totally unfeasible, as very high temperatures are generated in this process [6].

So, the implementation of suitable coolant and lubrication environments becomes utterly important during its machining. After reviewing different studies within the literature, it was observed that the minimum quantity lubrication (MQL) technique is preferred as one of the best options for machining super-duplex steel, as it delivers limited amounts of air/oil mixture in a mist lubricant form into the machining zone to control the machining temperature [7]. In MQL environments, very limited amounts of lubricant at a very high pressure are sprayed at the targeted tool–workpiece interface [8]. This facilitates excellent heat dissipation from the machining zone with an extremely reduced amount of lubricant consumption. This results in the excellent surface quality of the finished product and greatly reduces the tool wear. So, the service life of the cutting tool increases, and the mean time between tool failures greatly decreases [9]. The MQL technique provides itself as one of the best machining environments by maintaining the cutting temperature at the optimum level. As a lower quantity of lubricant is used with this technique, and most of it evaporates during the machining operation, the lubricant waste management cost becomes zero. This facilitates huge manufacturing cost saving in terms of lubricant cost and its disposal. MQL is also considered to be an eco-friendly cooling technique for many other different machining operations [10].

Nowadays, modern manufacturing sectors demand continuous improvements in machining techniques; the MQL machining technique also needs more modernization to enhance its machining performances. The machinability index of hard-to-machine metals is greatly dependent on different MQL operating parameters, such as the lubricant pulse rate, flow rate, air pressure, and number of nozzles. The amount of heat dissipation is highly influenced by the directions and positioning of the MQL nozzles during the machining operations. All of these above-mentioned parameters help in achieving a superior surface finish, greater machining tolerance, lower tool wear, and a longer tool life [11,12]. Using dual-nozzle MQL in machining hard materials is a revolutionary idea to improve the effectiveness of cooling systems. Placing the dual nozzle on two distinct sides of the cutting zone is advantageous to boost its cooling and lubricating capacity. Dual nozzles are also useful for quickly removing the evolved chip from the cutting zone, which can enhance the features of machinability. Additionally, using multi-nozzle cooling, enough lubricant can be released into the shearing zone, improving the cooling and lubricating characteristics of cooling systems [13,14]. Additionally, pulse mode MQL reduces lubricant usage, which has a positive economic impact by lowering the final product cost. Mia and Dhar [15] studied the performance of dual-nozzle MQL during the turning operation of hard-to-machine alloys. Machining performances such as the surface finish, tool wear, and chip morphology improved, whereas the machining temperature and cutting forces were reduced during machining under the dual-nozzle technique. As per the studies conducted by Sohrabpoor et al. [16], when the positioning of the lubricant jet nozzles is directed toward the flank and rake surfaces of the cutting tool, the heat dissipation performance of the coolant is highly enhanced. Gupta et al. [17] measured and analyzed the performance of the duel-jet MQL technique during the turning operation of duplex steel. The machining operation under duel-jet MQL produced lower power consumption and tool wear rates of 23.67% and 52.38%, respectively. During the experimental research conducted on turning operations using dual-nozzle MQL by Mallick et al. [18], a huge reduction in friction was achieved at the machining interface. This led to subsequent improvements in the surface quality (the Ra was reduced from 1.265 to 0.448 μm), while a reduction in the tool-flank wear from 0.112 to 0.041 mm was observed. The adhesion and abrasion were the prime wear mechanisms influencing the tool wear. The depth of cut, followed by the machining speed, were the most influencing factors for power consumption, accounting for 46.69% and 9.7%, respectively.

In the context of manufacturing and process optimization, using the Taguchi design during a turning operation can bring various benefits and advantages. Taguchi techniques using L_9 designs have been frequently used for performing tests in manufacturing and engineering fields. The L_9 Taguchi design enables a systematic variation of process parameter values in nine experimental sets. As we know that machining parameters have a substantial influence on the quality and efficiency of the machining process, it is critical to investigate the machinability of a certain alloy under various levels of cutting parameters. Thus, the Taguchi design enables us to carry out machining experiments with various combinations of process parameters and their levels. Furthermore, Taguchi design-based experiment design can greatly minimize the number of experiments necessary. In the current study, for example, the trials were designed to take three variables and their three levels. Taking a full factorial design, 27 trials are necessary to carry out the experiments. However, utilizing Taguchi L_9 design methodologies, only nine trials are necessary to complete the study aim. However, by employing the Taguchi L_9 design, the time and resources required to conduct experiments are considerably decreased, thus affecting the cost of the present study. Kechagias et al. [19] employed both the Taguchi L_9 and L_{27} design for the machining of titanium alloys, and it was determined that the L_9 experimental set was adequate for studying the machinability problem. Moreover, many authors have utilized the L_9 Taguchi design to accomplish their experimental research. Jagatheesan and Babu [20] implemented the Taguchi L_9 orthogonal array to execute the experiments on AISI 4320 steel under a nanofluid MQL environment and found satisfactory evaluation. Similarly, Sarıkaya and Gullu [21] performed an optimization of machining parameters with multi-response outputs using a Taguchi L_9 orthogonal array-based design of experiment alongside an MQL turning of Haynes 25 alloy. Alaba et al. [22] selected the Taguchi L_9 orthogonal array for the planning of an experimental design to conduct a performance evaluation of kernel oil during an MQL turning of grade AISI 1039 steel.

In modern manufacturing sectors, manufacturing organizations are eager to implement sustainable manufacturing practiced for product development. The term "sustainability" may be defined broadly as the system's capacity to promote and survive a healthy existence. Manufacturing has a significant impact on human lives by generating excellent employment, raising living standards, and stimulating economic progress [23]. However, to reduce the consumption of energy and natural resources, sustainable manufacturing is becoming increasingly important. Sustainable manufacturing also attempts to maximize profit while ensuring social and environmental safety across the product life cycle [24,25]. Davim et al. [26] define sustainability as the evaluation of a manufacturing approach's impact on the social, environmental, and economic framework. Pradhan et al. [27] also stated that sustainable manufacturing is an excellent technique to stimulate the adoption of innovative methodologies that are economically beneficial as well as healthy for both the environment and society. In machining research, many authors have implemented a Pugh matrix approach in conjunction with the Kiviat radar diagram to calibrate sustainability tests [27–30]. Their findings strongly support the usefulness of combining the Pugh matrix method with the Kiviat radar diagram as a reliable way for assessing the sustainability of hard machining. When these two methods are used together, they provide a powerful decision-making and sustainability evaluation tool. The Kiviat radar diagram graphically illustrates each option's performance, but the Pugh matrix approach allows for a systematic examination and comparison of options based on particular criteria. This harmonic combination of the two methodologies provides academics and policymakers with useful insights into the sustainability aspects of various processes or alternatives. This supports the adoption of sustainable practiced and allows informed decision making. The Pugh matrix sustainability assessment technique with weight factors is a novel approach for determining process sustainability. The basic Pugh matrix merely provides a systematic technique to evaluate options against a set of criteria; it examines all assessment elements equally and gives no weight to the most influential ones. The Weight Factor Pugh matrix, on the other hand, improves decision making by assigning varying weights to assessment elements that are substantially more essential. This is very useful for prioritizing sustainability factors, and it gives a superior evaluation. As a result, the Weight Factor Pugh matrix provides a more solid framework for decision-makers looking to make educated decisions with sustainability at the forefront of their minds. However, the current study used a weight Pugh matrix sustainability strategy to discover the best sustainability cooling solution for industrial applications. The details of this method are addressed in Section 5.

From the literature review, it is evident that the MQL cooling environment holds a high potential to stand among the most preferred cooling and machining techniques known to the modern world. As this technique has a great heat-dissipating ability along with lesser cutting fluid consumption, it greatly helps the manufacturing sector boost its profitability. In addition, lubricant disposal is not a concern during MQL operations, since the majority of the lubricant evaporation keeps the cutting zone dry [31]. Most of the researchers have tried to increase the performance of the MQL system by altering the nozzle design, nozzle positions, and lubricants. In this present paper, the efficacy of the MQL system is further increased by incorporating another nozzle (called a dual nozzle MQL system) to achieve superior performance. This is the novel concept for this research. Also, the pulse mode MQL concept was not explored extensively in published literature, especially in steel machining research. In the majority of MQL research, the cutting speed was varied; thus, it is very difficult to analyze the real effects of pulse time on distinguishing machinability factors. To accomplish this performance evaluation research, the results of machinability of super duplex stainless steel in turning were compared between the exiting pulse mode MQL (single nozzle) and dual-nozzle pulse mode MQL system by considering a fixed cutting speed. This aspect itself provides novel research for machining research concern. Moreover, machining research on super duplex stainless steel (UNS S32750) was rarely found in the literature; therefore, it is noteworthy to investigate the machinability of this grade of super duplex stainless steel for the benefit of the manufacturing sector. Furthermore, no study reported in the literature to explore the sustainability assessment in machining super duplex steel. Based on the above literature gap, the following objectives are considered for this research:

- Experimental performance comparison of single-nozzle pulse mode MQL and dual-nozzle pulse mode MQL in turning UNS S32750 super duplex stainless steel.
- Machinability evaluation of UNS S32750 super duplex steel by varying feed, depth of cut, and pulse time of MQL flow.
- Sustainability evaluation between single-nozzle and double-nozzle MQL pulse modes in turning UNS S32750 super duplex stainless steel.

2. Materials and Methods

In this research, the CNC turning operation is being performed over a UNS S32750 super duplex stainless steel (2507) specimen with an initial diameter of 60 mm and initial length of 200 mm. The test sample was commercially available and thus directly purchased for the experimentation. According to the supplier, this test sample's microstructure shows equal amounts of austenite and ferrite. Furthermore, the chemical composition of this workpiece is tested using the spark or arc emission spectroscopy technique in a CCD spectro-cast device. The workpiece sample is put on a positively charged metallic specimen table that is connected to the argon gas tank through a pipe and is taken near the specimen. This results in a spark or emission between the electrode and the specimen that is recorded. The emitted radiation's wavelength is then compared to that of the separated elements. Table 1 shows the chemical composition (% by weight) of the workpiece.

Table 1. Chemical composition of workpiece.

Elements	Cr	Ni	Mo	Mn	Si	N	C	P	S	Fe
% Weight	24.8	6.5	3.6	1.1	0.2	0.32	0.02	0.3	0.01	balanced

To execute the turning operation, MT CVD multilayered coated (TiN/TiCN/Al_2O_3/ZrCN) carbide inserts by designation CNMG120404FF (manufactured by WIDIA, Essen, Germany) are being used. This tool is selected due to its good surface finish and the fine turning ability of the steel workpiece. The tool has a rhomboid shape and has an angle of about 80° between its side faces. The clearance angle, rake angle, inclination angle, approach angle and nose radius of this tool were 7°, −6°, −6°, 95° and 0.4 mm, respectively. The turning operation is performed using an automated CNC lathe machine, model DX 200 4A manufactured by Jyoti CNC Automation Pvt. Ltd., Vajdi, India. It has an adjustable spindle speed range from 50 to 4000 rev/min with a power capacity of 7.5 kW.

An industrial-grade MQL cooling system supplied by DROPSA, Italy was used to deliver lubricant into the cutting zone. This system has the ability to eject pulverized lubricant which is a mixture of fine mist droplets of lubricant and compressed air at high pressure exactly on the machining zone to retard the cutting temperature. For the present experimental setup, the continuous lubricant supply mode under a normal MQL system is being changed to pulse mode to achieve control over the frequency or timing of the mist lubricant jet ejection over the cutting zone. This MQL setting was made to study the heat dissipation capability of pulsed mode MQL over different pulsed timing. This mode further decreases the lubricant consumption, which gives economical benefits by decreasing the coolant cost at the end of the finished product. Moreover, single-nozzle and double-nozzle pulse mode MQL strategies were implemented, and their performance in turning super duplex stainless steel was compared. This is the main novelty of this research. The nozzle outlet tip diameter for both lubricating conditions (single-nozzle and double-nozzle pulse mode MQL) is the same as 1 mm. LRT 30 mineral oil (manufactured and supplied by DropsA, Vimodrone, Italy) was used as a lubricant for the MQL system. LRT 30 is an advanced non-polluting, non-toxic lubricant. It does not blot, produce smoke, or cause skin irritation. It is produced using completely innocuous substances, providing excellent lubrication properties. This oil has a viscosity at 40 °C of 24 cSt, the flammability limit is more than 220 °C, and its specific weight at 15 °C is around 0.9 kg per litter. During this entire operation, the spraying nozzle's position (for single-nozzle MQL) is maintained at 30 degrees from the cross-feed direction, while for the dual-nozzle system, the first nozzle position is the same as that of the single-nozzle MQL system, while the second nozzle position was kept vertical to the interface zone of the tool and workpiece, as shown in Figure 1. The distance between the test specimen from the spray nozzle (single and dual nozzles) outlet point is maintained at 25 ± 5 mm. Many researchers have preferred this nozzle distance while performing experimental trials [32–34]. Additionally, trial experiments are accomplished to find out the optimum air pressure to spray the lubricant in mist form into the cutting zone. The authors have used 4 bar, 5 bar, 6 bar, 7 bar, and 8 bar air pressure to deliver the mist lubricant into the cutting zone; the 6 bar air pressure was found to be the best among all the considered air pressure to minimize tool wear, improve the surface quality and reduce the cutting temperature in the turning process. Hence, 6 bar air pressure was used for all of the experiments under both nozzle conditions of MQL. The MQL oil flow rate for double-nozzle MQL is twice that of single-nozzle MQL. In double-nozzle MQL, both nozzles will deliver lubricant with the same flow rate. With 6 bar air pressure, the flow rate of a single nozzle was 50 mL/h for 1 s pulse time, 33 mL/h for 3 s pulse time, and 20 mL/h for 5 s. Therefore, it can be clearly seen that as the pulse time increases, the lubricant consumption decreases. The design of the experiment was utilized as a Taguchi L_9 design for both single- and double-nozzle MQL-assisted experiments. The main aim of this research is to compare the machinability performance of super duplex stainless steel under single and dual-nozzle MQL systems. Therefore, it is essential to take the different combinations of input terms to fulfill the above-stated aim. The Taguchi design (orthogonal array) provides a set of different combinations of input terms to carry out the experiments. Taguchi provides the experimental design, which can be less than the full factorial design. For example, in the current research, we have used 3 factors and their 3 levels. For this, the total number of experiments required is 27, which is practically time consuming, and more resources are required. Therefore, the authors used Taguchi L_9 DOE only to save time and resources to fulfill the aim of the current research. Also, many researchers have used L_9 DOE for accomplishing their experimental work and found satisfactory results [19–22]. Based on this discussion, the authors have used Taguchi L_9 DOE. Three different turning inputs such as the feed rate, depth of cut, and pulse time are used to study its effect on surface roughness, tool-flank wear, tool-flank temperature, power consumption, and material removal rate. Pulse time is a control factor used in MQL to govern the spraying of mist lubrication from the nozzle into the cutting zone. The pulse time is the period between spraying the mist lubrication and halting it. For example, if the pulse time is 3 s, the mist lubrication will spray for 3 s and then stop spraying for the following 3 s. This is a periodic phenomenon observed in a pulse mode MQL system. The cutting speed was maintained constant at 100 m/mm for the entire experimental trails. It is well known that the cutting speed has the largest effect on machinability factors; therefore, the effects of other parameters, especially pulse time effects, were not assessed properly when cutting speed was considered as a variable. Therefore, in this study, the cutting speed was kept fixed. The cutting speed was selected based on super duplex stainless steel turning research papers. Krolczyk et al. [5] tested the machinability of super duplex stainless steel by turning it at three different cutting speeds (50, 100, and 150 m/min). Similarly, for machining UNS S32750 super duplex stainless steel, Parsi et al. [35] used two cutting speeds (100 m/min and 140 m/min). The cutting speed ranges mentioned above in the literature correspond to the cutting speed ranges advised by the tool's manufacturer. Based on the above findings, the authors used a cutting speed of 100 m/min for this study. The levels of feed and depth of cut were also considered based on the literature and the manufacturer's recommendations for steel materials. Pulse time (1 s, 3 s, and 5 s) was taken based on the author's previous research article [36]. Each input variable has three different levels, and all of the experimental details of the machining conditions are listed in Table 2. Tool-flank wear analysis is performed considering the average of numerical values of principal flank wear width. The surface quality of the workpiece is determined by considering the average value of the surface roughness. Measurement of tool-flank wear (VB) and surface roughness (Ra) were accomplished using an Olympus STM6 Optical Microscope (Made in Tokyo, Japan) and Taylor Hobson roughness tester (Manufactured by AMETEk Inc., Berwyn, PA, USA), respectively. For the measurement of machining temperature, a portable-type infrared thermometer (Model TB-1350 and manufactured by Tashika Co. Ltd., Ashiya City, Japan) was used. It has a measuring range of −18 to 1350 °C and measuring accuracy of ±1.5 °C. It has a response time of 500 milliseconds, and the distance of the camera from the hot spot is maintained at 30 cm from the tool-tip. The temperature data were recorded at different instants for each and every experimental trial, and the maximum temperature was analyzed. The power consumption during the turning operation was recorded by a 3-phase multi-function power cum energy meter (RISH Delta Energy, EMT 34). Digital weighing equipment (provided by National Pvt. Ltd., Vajdi, India) was used to measure the weight of the workpiece before and after machining. MRR was estimated by dividing the differential weight amount (initial weight–final weight) by the machining time for each operation. The experimental setup and measuring instruments are displayed in Figure 1.

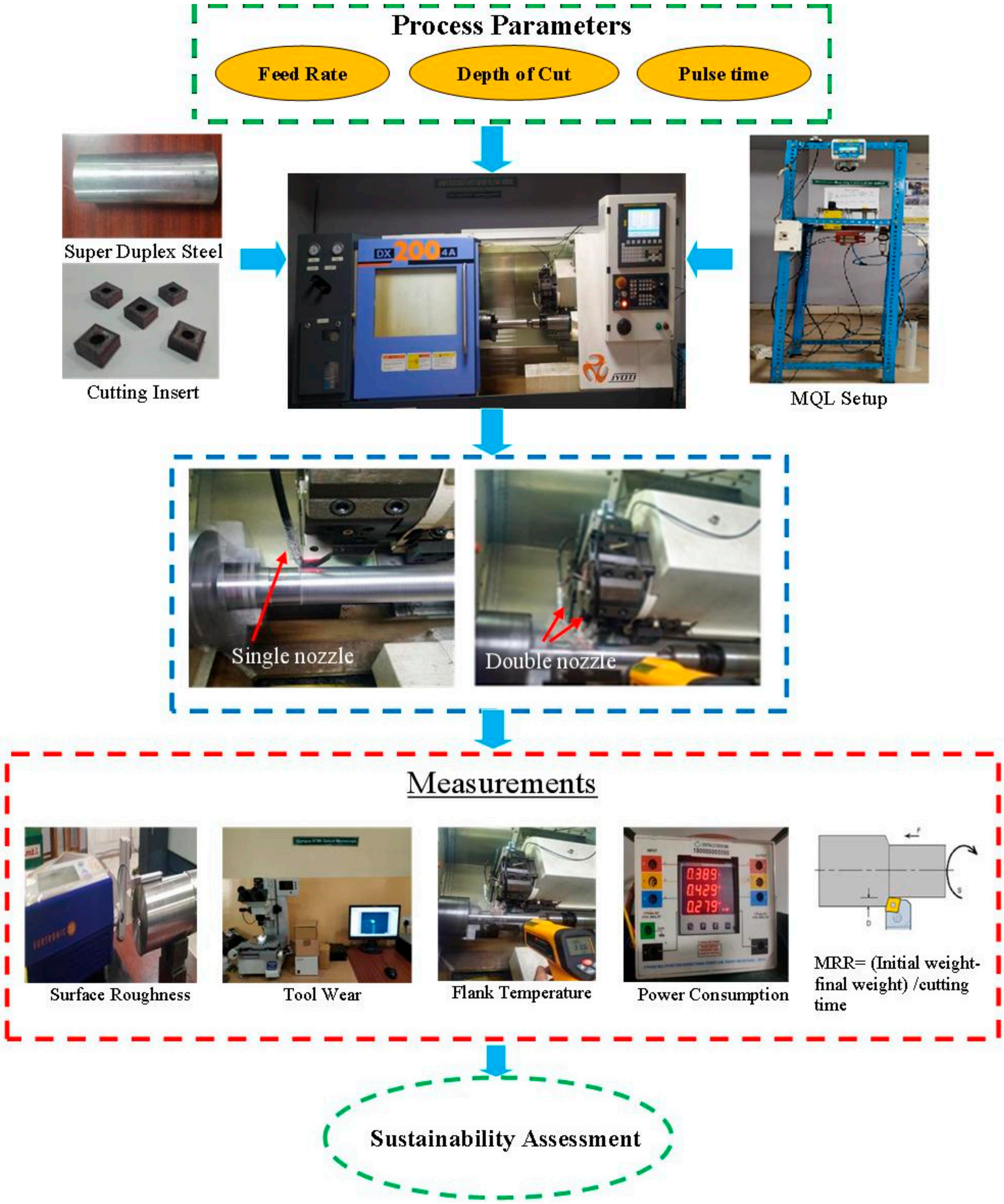


Figure 1. Overall details of research methodology.

Table 2. Summary of experimental details.

Equipment/Items	Details
Turning Machine	CNC lathe machine model DX 200 4A
Work Specimen	UNS S32750 Super duplex stainless steel
Work Specimen Hardness	27.2 HRC
Work Specimen Dimension	200 mm in length and 60 mm in diameter

Table 2. *Cont.*

Equipment/Items	Details
Cutting Length	160 mm
Cutting Insert	CVD-coated carbide ISO Geometry: CNMG120404FF, tool geometry specification: clearance angle: 7°, rake angle: −6°, inclination angle: −6°, approach angle: 95°, nose radius: 0.4 mm Coating layers: TiN/TiCN/Al_2O_3/ZrCN
Cutting Insert Holder	PCLNR2525M12
Machining Temperature Measurement Instrument	Portable infrared thermometer manufactured by Tashika Co., Ltd., Japan (Model TB-1350)
Design of the Experiment	Taguchi L_9 orthogonal array
Machining Speed (V)	100 m/min (Constant)
Feed Rate (f)	0.08, 0.16, 0.24 mm/rev
Depth of Cut (ap)	0.1, 0.2, 0.3 mm
Pulse Time (Pt)	1, 3, 5 s
Spraying Nozzle Type	CH10 5/16
MQL Lubricant Discharge Pressure	6 bar
MQL Lubricant and Its Properties	LRT 30 oil Viscosity @ 30 °C = 47.6 cP Thermal conductivity @ 30 °C = 0.166 W/mK

3. Results and Discussions

The CNC turning experiments under single- and double-nozzle MQL were conducted using Taguchi L_9 (three factors and their three levels) design of experiments. According to the plan of experiments, the input details and corresponding five measured outputs results (surface roughness—Ra, tool flank wear—VB, tool-flank temperature—Tf, power consumption—Pc, and material removal rate—MRR) were displayed in Table 3. The measurement of responses was repeated five times to estimate the measurement error. The average standard error for Ra, VB, Tf, Pc, and MRR were estimated as ±1.12%, ±1.53%, ±2.56%, ±1.32% and ±1.04%, respectively.

Table 3. Machining results for single-nozzle and double-nozzle MQL.

Exp No.	Input Values			Output Results				
	ap (mm)	f (mm/rev)	Pt (s)	Ra (µm)	VB (mm)	Tf (°C)	Pc (kW)	MRR (g/min)
Single-Nozzle MQL								
1	0.1	0.08	1	0.81	0.105	76.3	0.756	7.10
2	0.1	0.16	3	1.56	0.154	86.2	0.803	13.93
3	0.1	0.24	5	2.28	0.209	94.9	0.891	28.81
4	0.2	0.08	5	1.49	0.178	89.7	0.867	14.11
5	0.2	0.16	1	1.57	0.161	85.6	0.889	32.74
6	0.2	0.24	3	2.26	0.174	100.3	0.924	46.51
7	0.3	0.08	3	1.67	0.182	91.5	0.872	26.06
8	0.3	0.16	5	2.23	0.290	98.2	0.967	40.10
9	0.3	0.24	1	2.26	0.218	95.7	1.012	66.15

Table 3. *Cont.*

Exp No.	Input Values			Output Results				
	ap (mm)	f (mm/rev)	Pt (s)	Ra (μm)	VB (mm)	Tf (°C)	Pc (kW)	MRR (g/min)
				Double-Nozzle MQL				
1	0.1	0.08	1	0.68	0.092	67.6	0.734	8.78
2	0.1	0.16	3	1.47	0.131	74.4	0.778	18.87
3	0.1	0.24	5	1.92	0.194	89.5	0.856	31.49
4	0.2	0.08	5	1.08	0.166	88.4	0.842	16.18
5	0.2	0.16	1	1.37	0.107	79.5	0.873	41.35
6	0.2	0.24	3	2.01	0.147	92.3	0.897	50.67
7	0.3	0.08	3	1.56	0.124	88.6	0.849	33.49
8	0.3	0.16	5	2.10	0.206	93.3	0.929	51.25
9	0.3	0.24	1	2.14	0.149	86.9	0.971	74.04

3.1. Surface Quality Analysis

Surface roughness (Ra) is one of the important scientific indexes to estimate the surface quality of the finished product. Ra plays a vital role during any machining operation, and it is very closely related to tool wear [37]. With the increase in flank wear, the nose radius was reduced, and as a result, the surface roughness was improved [38]. In the modern competitive market, demands of high surface quality are very essential to meet the user's desires. Therefore, this research investigates the influence of three different parameters (ap, f and Pt) on Ra using single-nozzle and double-nozzle MQL environments. The Ra values for single-nozzle and double-nozzle techniques are shown in Table 3. The surface quality with a double nozzle was greatly improved in comparison to a single nozzle. The least surface roughness in the double nozzle was identified as 0.68 μm (run 1), which was about 16.05% lower than the roughness (run 1) obtained in the single nozzle. Similarly, considering an average of nine experiment results, the Ra in the double nozzle was found to be 11.16% lower in comparison to the single nozzle. The reason behind obtaining a better surface finish under a dual nozzle is as follows: under dual nozzle MQL circumstances, the oil mist is simultaneously sprayed to the rake face and flank face, lubricating the surfaces to reduce surface roughness and preventing chip adhesion at lower temperatures. Also, in machining, frictional forces between mating surfaces (tool-workpiece) are retarded by the pulse mode of a lubricant delivered across interfacing surfaces; as a result, the surface quality was improved. Many other researchers observed similar findings [39–41].

Statistically, the results obtained under both cooling conditions followed the normal probability curve as their respective *p*-values were higher than 0.05 (Figure 2a,b). Moreover, the effect of different input factors on Ra was investigated by statistical plots (main effects plots and 3D surface plots) and ANOVA. According to the main effect plots (Figure 2c,d), for both conditions, the roughness was sharply rising with the leading feed [42]. A similar trend for depth of cut was seen for both cooling conditions. Pulse time has seemed to have more influence on the single nozzle, as the curve sharply enhanced in comparison to the double nozzle. In the study conducted by Rajan et al. [43], when turning was performed at faster feed rates and deeper depths of cut, the dynamic instability in cutting increased, and this led to non-uniform engagement between the tool and workpiece, resulting in the higher surface roughness. The 3D surface plots (Figure 2e,f) for both cooling conditions also show the growing slope of the curve in diagonal directions, which confirmed that the roughness was leading with simultaneous increments in feed and depth of cut. Kulshreshtha [44] also found a similar effect of feed and cutting depth on surface roughness in turning EN 36-grade steel. ANOVA (Table 4) informed the contribution of each input term on Ra. It also indicated whether the input term has a significant effect or not on Ra. Results for both cooling conditions confirmed that all the input terms have significant consequences on Ra. The contribution of feed was traced to be highest for both conditions (65.39% and 63.70%, respectively), which was followed by depth of cut (18.69% and 27.45%, respectively) and pulse time (15.41% and 8.64%, respectively). According to Raykar et al. [45], the feed rate and depth of cut were the dominant factors that directly controlled the surface finishing of EN 8 alloy. Considering the above discussion, it can be summarized that the Ra values decrease drastically during dual-nozzle MQL operation due to improved lubrication and superior heat dissipation, and the feed rate was the topmost influencing term for Ra.

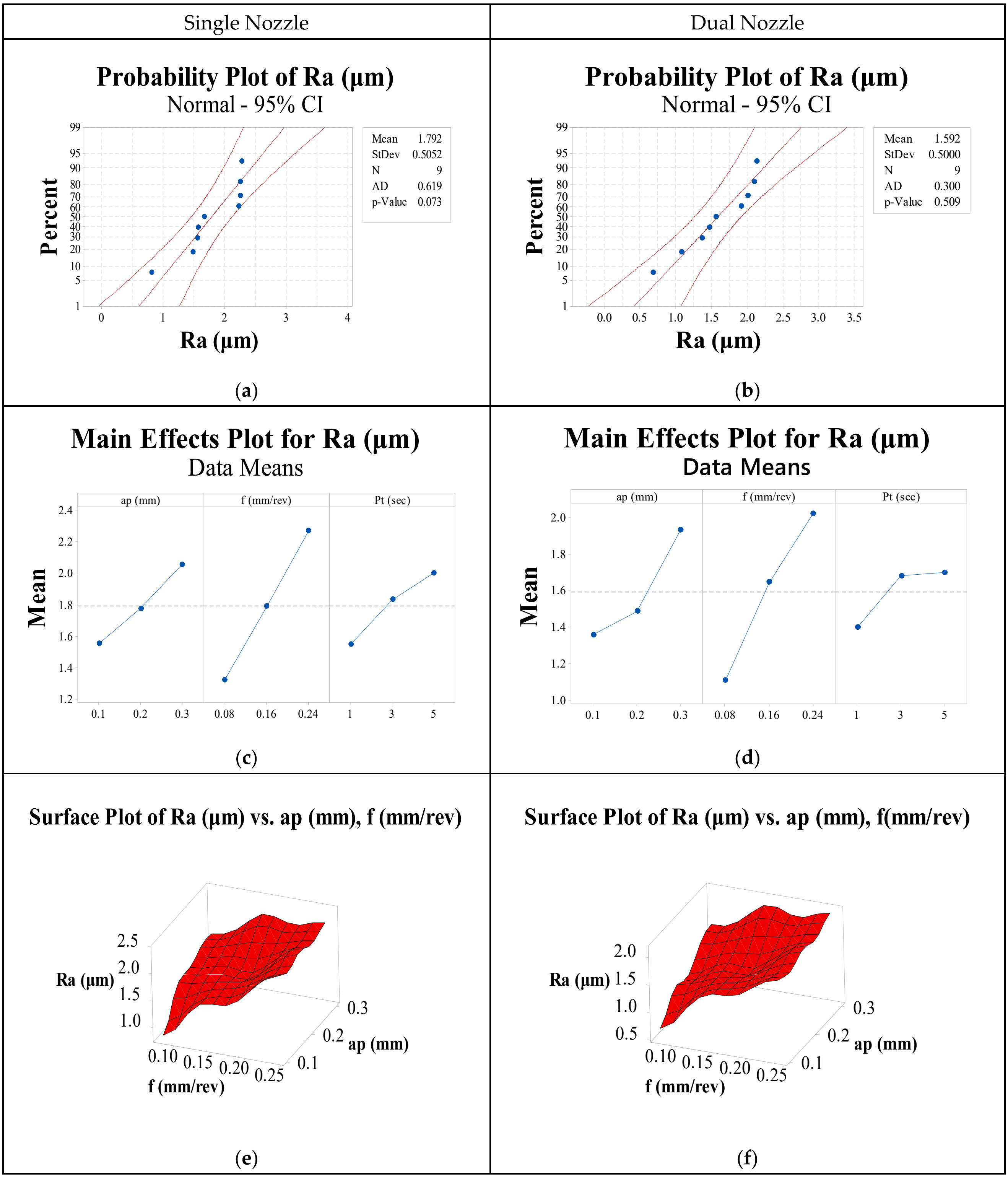


Figure 2. Assessment of surface roughness results using (**a**,**b**) probability plot (**c**,**d**) main effect plot (**e**,**f**) 3D surface plot.

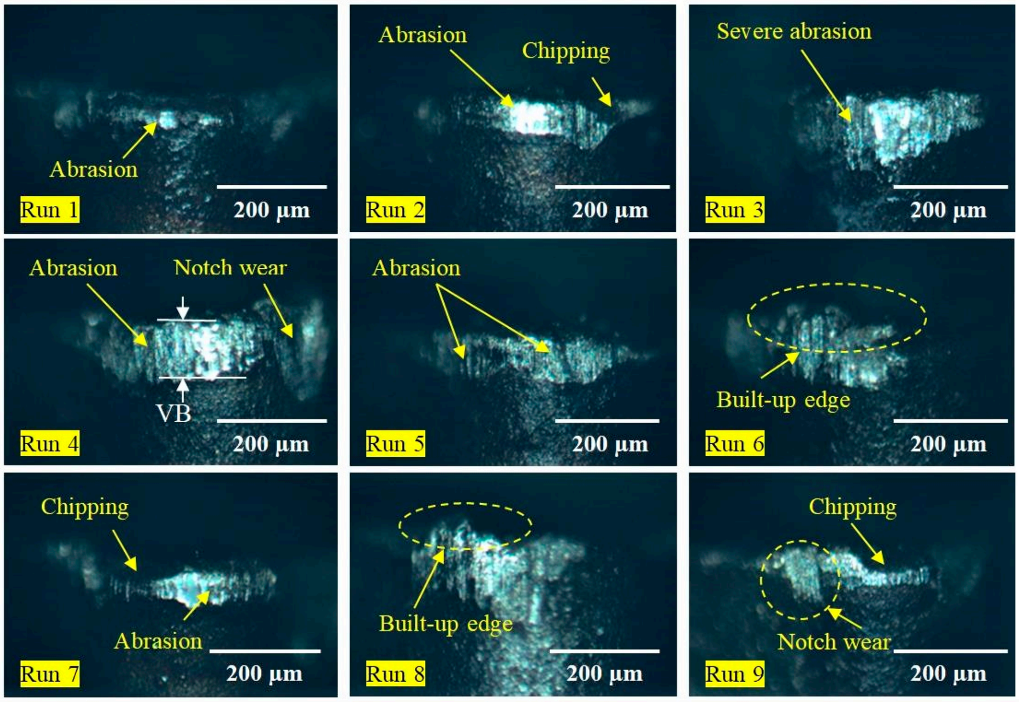
Table 4. ANOVA for Ra.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	% Contribution	Significant
Single Nozzle							
ap	2	0.38162	0.190811	37.09	0.026	18.69	Yes
f	2	1.33496	0.667478	129.75	0.008	65.39	Yes
Pt	2	0.31469	0.157344	30.59	0.032	15.41	Yes
Error	2	0.01029	0.005144				
Total	8	2.0415					
Summary: R^2 = 99.50%; R^2 (adjacent) = 97.98%; R^2 (prediction) = 89.79%.							
Double Nozzle							
ap	2	0.54896	0.274478	126.04	0.008	27.45	Yes
f	2	1.27376	0.636878	292.44	0.003	63.70	Yes
Pt	2	0.17269	0.086344	39.65	0.025	8.64	Yes
Error	2	0.00436	0.002178				
Total	8	1.99976					
Summary: R^2 = 99.78%; R^2 (adjacent) = 99.13%; R^2 (prediction) = 95.59%.							

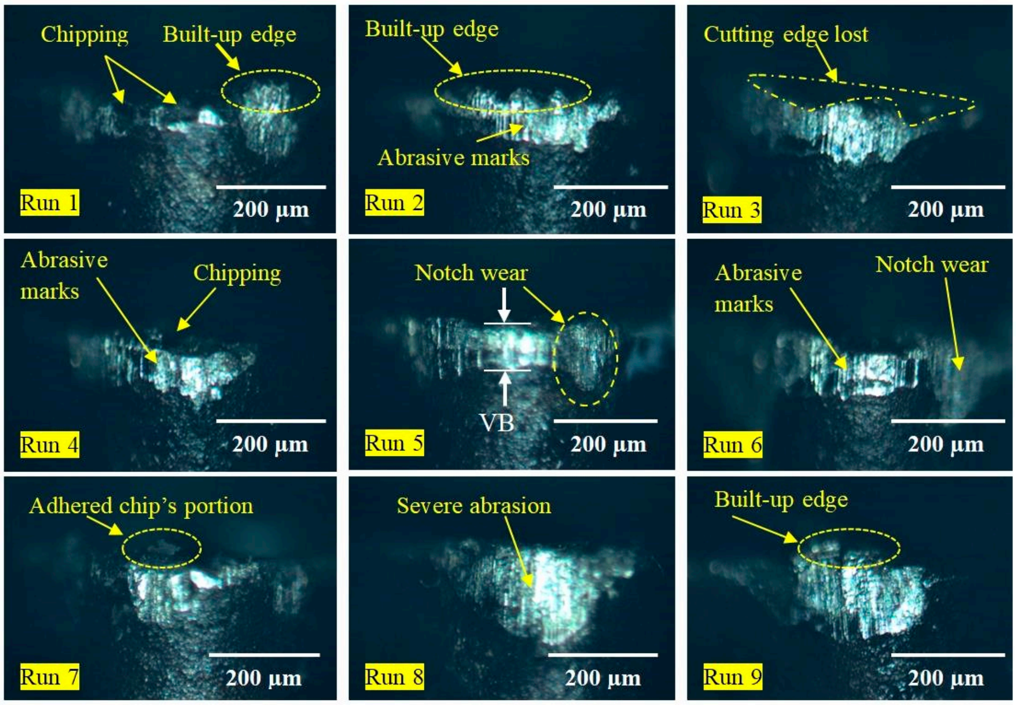
3.2. Tool-Flank Wear Analysis

Tool-flank wear is a gradual wear that occurs on the flank face of the cutting insert during the machining operation [46]. This type of wear cannot be eliminated, and the only way to reduce its occurrence is by selecting suitable machining parameters and implementing advanced cooling techniques. Higher wear results in poor surface finish and a lower dimensional accuracy of the final product. Moreover, leading wear also causes an increase in cutting force and power consumption as well as shorter tool life and higher tooling cost. Therefore, to control these worthy issues, an investigation must be conducted on the machining parameters and cooling strategies that have relevant effects on the wear during machining. Keeping this context, in the present study, the wear at the tool-flank surface was measured by varying the cutting feed, depth of cut, and pulse time. For every experiment, a new edge-cutting tool tip was used. After machining, wear width was measured at different portions of wear locations, and the average value was noted in Table 3.

The wear image for each run is shown in Figure 3. From the wear results value, it can be stated that the double-nozzle cooling strategy was beneficial over a single nozzle. Considering the average of nine experiment results, the tool-flank wear was 21.24% lower in double-nozzle machining in comparison to the single nozzle. Moreover, the growth in wear was leading with pulse time, and for both cooling conditions, the least wear was obtained at the lowest value of feed, depth of cut and pulse time. Considering tool failure criteria VB = 0.3 mm (based on ISO 3685 standard) [47], both cooling conditions are suitable for single-pass turning, but the double nozzle outperformed the single nozzle. For both cooling strategies, the abrasion phenomenon was the leading cause of generating flank wear on the tool's tip. Abrasion is the outcome of the dynamic rubbing of the hard ferrite phase of super duplex steel and tool-flank surface [46]. Moreover, the built-up edge on the tool's tip was also noticed in some runs under both cooling scenarios, as displayed in Figure 3. The adhesion of the workpiece and or chip materials on the tool's tip was also noticed under both conditions. Notch wear was also found in some runs under both conditions, as shown in Figure 3. The chances of diffusion wear were very rare, as the temperature found on the tool's tip was below 101 °C. In each test run, the coating of the insert was removed from the tool's tip. At the highest depth of cut condition, the delamination of the coating was higher, as more cutting load was acted on the tool's tip. The chipping of the tool's tip shown in Figure 3 clearly indicates the loss of coatings from the tool tip.



(**a**)

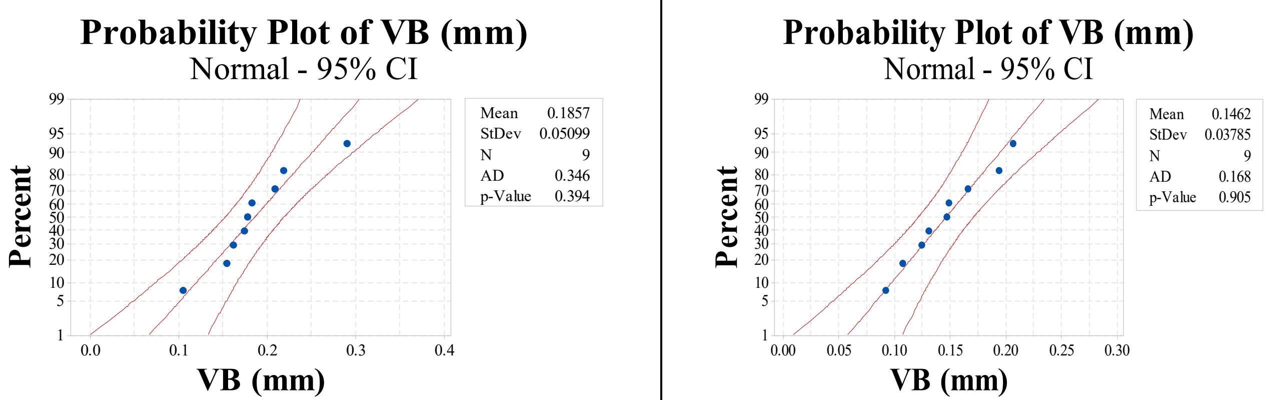


(**b**)

Figure 3. Tool-flank wear images obtained under (**a**) single nozzle and (**b**) double nozzle.

Statistically, the wear results obtained under both cooling strategies followed the normal probability curve as their respective p values were higher than 0.05 (Figure 4a,b). Furthermore, the influence of three different parameters (ap, f and Pt) on VB are studied using main effects graphs, surface plots and ANOVA. For the single nozzle, the tool-flank wear was growing greatly with the depth of cutting and pulse rate (Figure 4c), while for the double nozzle, it was greatly increasing with leading pulse time (Figure 4d). In addition, with leading feed from 0.08 to 0.16 mm/rev, the wear growth is very high for the single nozzle but beyond 0.16 mm/rev feed, there was a negligible change in wear. Similarly, for the double nozzle, there was an increasing trend in wear when the feed was leading, while the depth of cut had a marginal effect on wear. Moreover, the surface plot (Figure 4e) for the single nozzle indicated that the highest wear was achieved when a moderate feed (0.16 mm/rev) and the highest depth of cut (0.3 mm) was used. A similar trend for the double nozzle (Figure 4f) was also seen. From another surface plot (Figure 4g), it can be illustrated that with the increase in pulse rate and depth of cut simultaneously, the slope of the surface was leading diagonally, which ensures the growing trend in tool-flank wear. Similarly, for the double nozzle, the slope of the surface was uneven, and the moderate feed with the largest pulse time exhibited the largest growth in wear (Figure 4h). From ANOVA (Table 5), depth of cut has the greatest effect (44.14%) on tool-flank wear when a single nozzle was used, while for the double nozzle, pulse rate has the dominant effect (74.98%) on tool-flank wear. For the single nozzle, all the input terms were significant, while for the double nozzle, the pulse rate and feed were significant, while the depth of cut was insignificant. Typically, the depth of cut in the turning process can affect tool wear, but its significance is dependent on a variety of criteria such as the material being machined and the cutting variables, particularly the cutting speed and the lubricant employed. The frictions between the tool and workpiece are reduced under double-nozzle MQL conditions by providing lubricant in the cutting zone in two distinct directions, making shearing phenomena at constant cutting speed simpler and putting less strain on tool wear. Because feed and pulse duration both had a substantial effect, the effect of depth of cut was determined to be insignificant. In certain cases, it appears that the depth of cut does not affect tool wear. When the ideal cutting speed was selected for machining, Viktor P. Astakhov [48] discovered that the depth of cut had no influence on tool wear. Singh et al. [49] also found that the depth of cut had no influence on tool wear while machining Inconel 718 superalloy. Suresh et al. [50] discovered that the depth of cut had the least influence (4.96%) in hard turning on AISI 4340 steel.

Single Nozzle	Double Nozzle



(**a**) (**b**)

Figure 4. *Cont.*

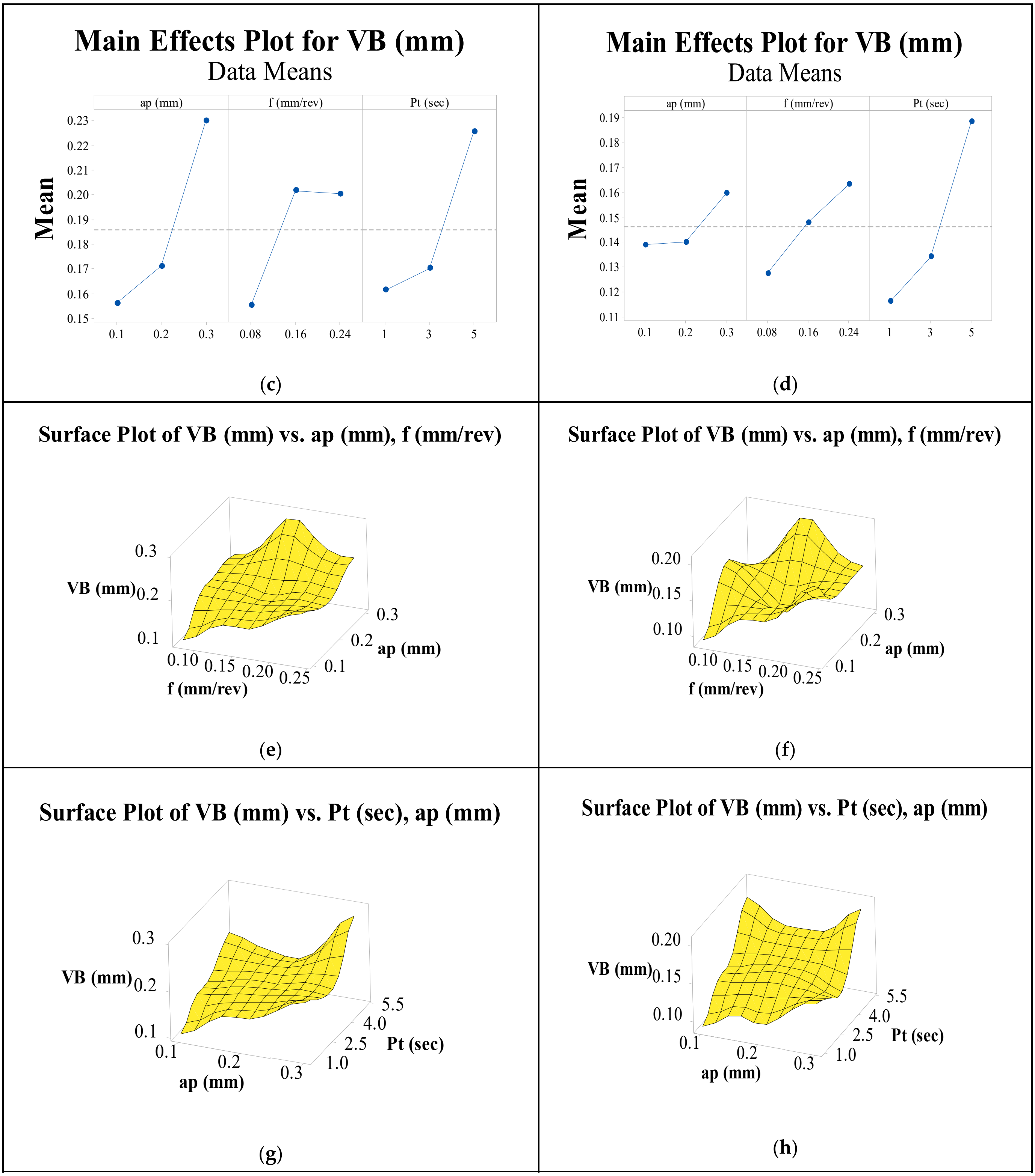


Figure 4. Assessment of tool-flank wear using (**a**,**b**) probability plot, (**c**,**d**) main effect plot, and (**e**–**h**) 3D surface plot.

Table 5. ANOVA for VB.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	% Contribution	Significant
Single Nozzle							
ap	2	0.009182	0.004591	126.36	0.008	44.14	Yes
f	2	0.004235	0.002117	58.28	0.017	20.35	Yes
Pt	2	0.007313	0.003656	100.63	0.010	35.16	Yes
Error	2	0.000073	0.000036				
Total	8	0.020802					
Summary: R^2 = 99.65%; R^2 (adjacent) = 98.60%; R^2 (prediction) = 92.93%.							
Double Nozzle							
ap	2	0.000815	0.000407	8.71	0.103	7.11	No
f	2	0.001958	0.000979	20.93	0.046	17.09	Yes
Pt	2	0.008593	0.004296	91.85	0.011	74.98	Yes
Error	2	0.000094	0.000047				
Total	8	0.011460					
Summary: R^2 = 99.18%; R^2 (adjacent) = 96.73%; R^2 (prediction) = 83.47%.							

3.3. Tool-Flank Temperature Analysis

The high temperature generated during turning operation has an adverse effect on the overall machining performance. This leads to deterioration in the surface quality of the final product and generates severe tool wear, which greatly reduces the life of the cutting insert. To cope with the above problems, the proper selection of machining parameter combinations and cooling techniques becomes noteworthy. This research paper implemented a novel cooling technique known as double-nozzle MQL to increase the heat dissipation at the machining zone to control the flank temperature. For both cooling strategies, the tool-flank temperature (Tf) of each test was measured, and the maximum temperature is shown in Table 3.

For the single nozzle, the tool-flank temperature varied from 76.3 °C (lowest) to 100.3 °C (highest), while for the double nozzle, it varied from 67.6 °C (lowest) to 93.3 °C (largest). From these results, it can be said that the double-nozzle MQL provided a lower temperature in comparison to the single nozzle. Moreover, considering the average of nine results, the tool-flank temperature was found to be lower (7.07%) under the double nozzle in comparison to the single nozzle. With a double-nozzle setup, two separate streams of lubricant can be directed toward the cutting zone; thus, the spraying surface area was enhanced. As a result, the convective and evaporative heat transfer rate was also enhanced and a better cooling effect occurred, which reduced the cutting temperature. Furthermore, in MQL, a higher frequency of lubricant impingement into the cutting zone allows for a greater rise in Nusselt number, which improves heat transmission and lowers tool-flank temperature [51]. Also, with dual-nozzle application, the friction as well as heat generation during machining processes was reduced due to the better penetration of atomized mist lubricant into the cutting zone. According to Hong and Ding [52], the simultaneous cooling of the rake and flank faces is the most effective choice for decreasing cutting temperatures.

Moreover, the influence of three different parameters (ap, f, and Pt) on Tf was studied using the main effects plots, surface plots, and ANOVA. Statistically, the temperature results obtained under both cooling strategies followed the normal probability curve, as their respective p values were higher than 0.05 (Figure 5a,b). The tool-flank temperature for both cooling methods led to higher values with increasing levels of ap, f, and Pt. In the case of the single nozzle (Figure 5c), Tf was greatly improved with higher feed rates, while for the double nozzle (Figure 5d), it was largely improved with a greater depth of cut. From Figure 5e,f, it was observed that the surface slope increased at moderate feed rates with the largest depth of cut conditions. This observation indicated that when using a moderate feed rate and the largest depth of cut, the tool-flank temperature was found to be the highest. Also, these plots confirmed the lowest temperature values at the lowest levels of feed and depth of cut. In the other plots (Figure 5g,h), the temperature showed a trend of increasing with simultaneous increments in the depth of cut and pulse time. The rate of temperature increment was enhanced with moderate levels of depth of cut and pulse time. The ANOVA results (Table 6) revealed that the tool-flank temperature under the single-nozzle configuration was significantly influenced by all input terms (ap, f, and Pt), while for the double-nozzle configuration, it was significantly affected by ap and Pt. The feed rate was found to be insignificant. The friction between the tool and the workpiece is greatly decreased when using dual-nozzle MQL-aided machining. This reduction in friction can help reduce the temperature rise produced by greater feed rates. However, because other cutting factors such as depth of cut and pulse time have a large impact on temperature, the effects of increasing feed on tool-flank temperature were shown to be minor. Many investigations discovered that the feed rate has little influence on the cutting temperature in hard machining [53,54]. In the case of the single nozzle, the contribution of feed rate (42.58%) was observed to be the largest, which was followed by the depth of cut (30.18%) and pulse time (26.77%). Similarly, for the double-nozzle configuration, the contribution of depth of cut (41.44%) was the largest, which was followed by the pulse time (37.85%).

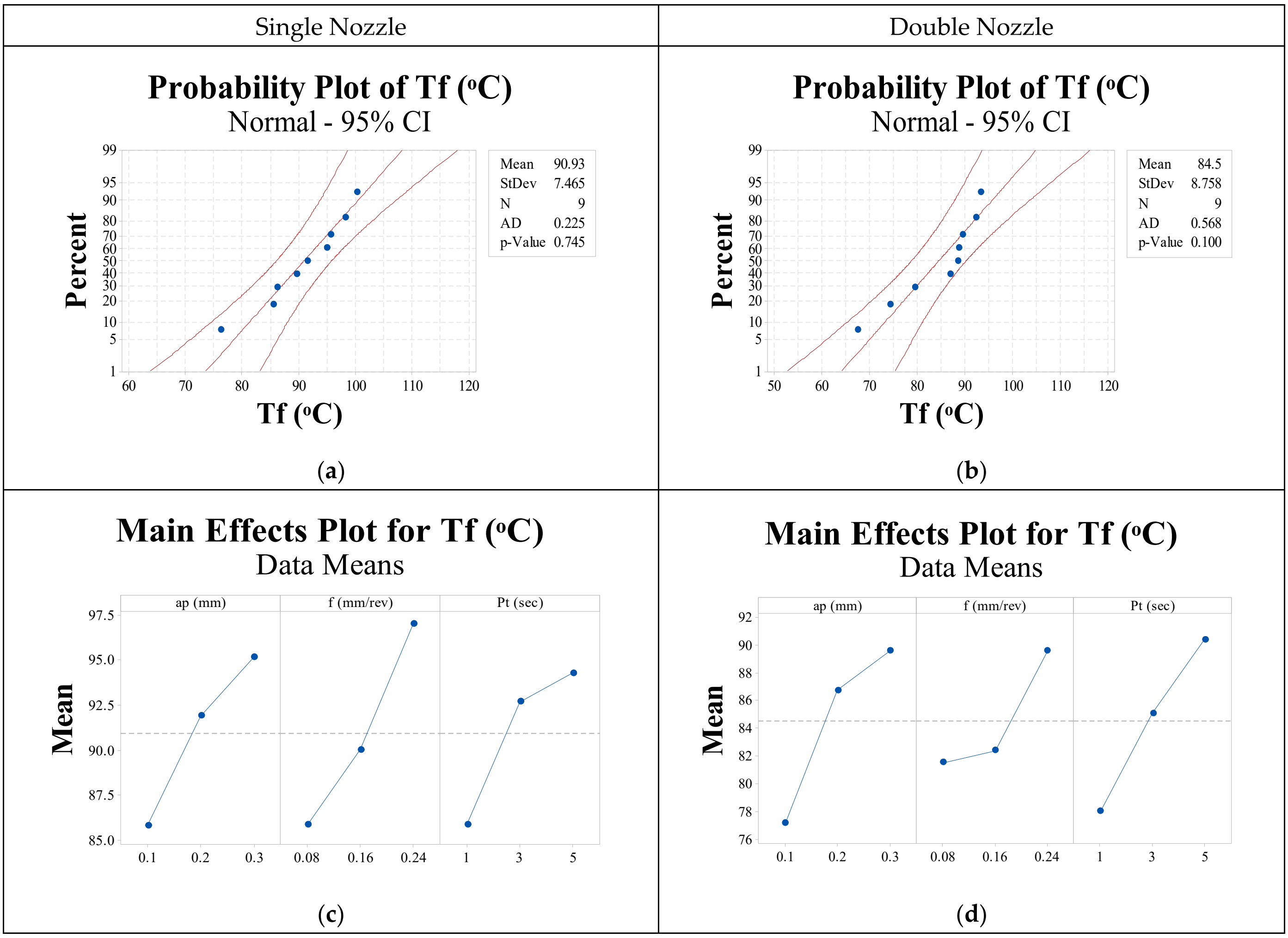


Figure 5. *Cont.*

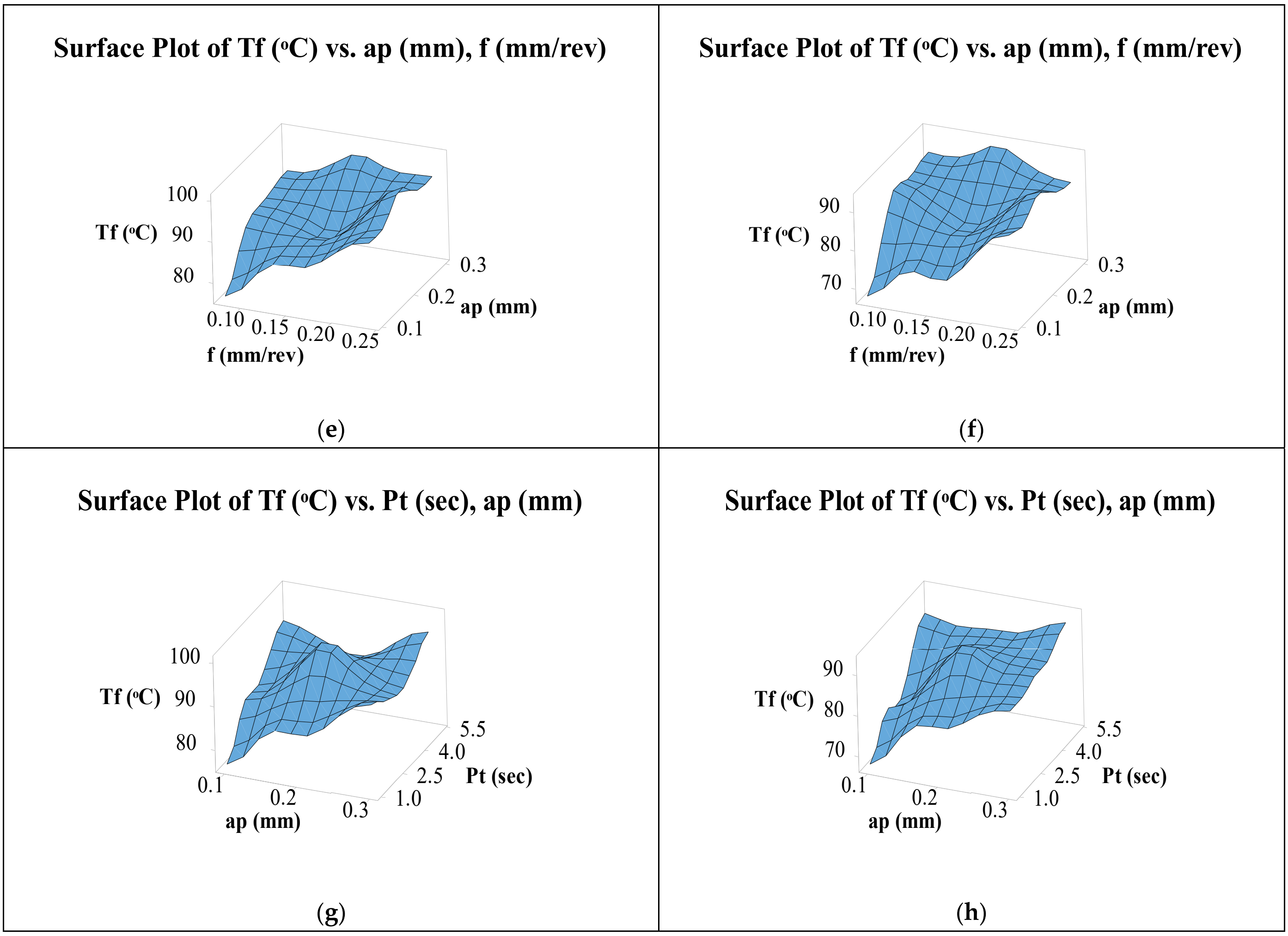


Figure 5. Assessment of tool-flank temperature using (**a**,**b**) probability plot (**c**,**d**) main effect plot (**e**–**h**) 3D surface plot.

Table 6. ANOVA for Tf.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	% Contribution	Significant
Single Nozzle							
Ap	2	134.587	67.293	66.41	0.015	30.19	Yes
f	2	189.847	94.923	93.67	0.011	42.58	Yes
Pt	2	119.360	59.680	58.89	0.017	26.77	Yes
Error	2	2.027	1.013				
Total	8	445.820					
Summary: R^2 = 99.55%; R^2 (adjacent) = 98.18%; R^2 (prediction) = 90.79%.							
Double Nozzle							
ap	2	254.33	127.163	24.35	0.039	41.44	Yes
f	2	116.65	58.323	11.17	0.082	19.01	No
Pt	2	232.26	116.130	22.23	0.043	37.85	Yes
Error	2	10.45	5.223				
Total	8	613.68					
Summary: R^2 = 98.30%; R^2 (adjacent) = 93.19%; R^2 (prediction) = 65.53%.							

3.4. Power Consumption Analysis

The amount of electricity consumed during the machining operation is referred to as its power consumption. The power consumed during operations in the manufacturing plant contributes to the total machining cost. To attain the optimum cost of production and pass the sustainability test, the proper management of power consumption is very important. In today's manufacturing industries, there is an increasing demand for more and more electricity consumption. As per the International Energy Agency, electricity consumption is increasing by 1.5% every year from 2007, and this trend is expected to continue until 2030. The USA itself will be accountable for 50% of the electricity consumption by the year 2030. As per this report, India and China will become the greatest power consumers by 2030 [55]. So, the present manufacturing sectors face the challenge of minimizing the electric power utilization during production processes to overcome the global electricity shortages in the near future. Thus, considering all these factors, the current paper provided a brief experimental comparison of power consumption between the single-nozzle and proposed dual-nozzle MQL turning operation. The power consumption (Pc) for each run under both single-nozzle and dual-nozzle MQL has been recorded during machining, and the data are displayed in Table 3. The power consumption was found to be highest when the feed rate and depth of cut were highest (Run 9). At this condition, the double-nozzle system produced 4.05% less power consumption than the single-nozzle system. Considering the average of nine test results, the power consumption was traced to be less (3.16%) under the double nozzle in comparison to the single nozzle. Statistically, the power consumption results obtained under both cooling strategies followed the normal probability curve, as their respective p values were higher than 0.05 (Figure 6a,b). Moreover, the influence of three different parameters (ap, f and Pt) on Pc was studied using the main effects plot, surface plot and ANOVA. For both cooling conditions (Figure 6c,d), the power consumption was leading with the depth of cut and feed rate, while the effect of pulse time was minor or irrelevant. Many other studies have observed similar findings, such as a considerable influence of feed and depth of cut on power consumption in machining [56,57]. Valeraa and Bhavsara [58] also concluded that the power consumption was gradually improved when the tool feed was improved in turning EN 31 grade steel. In another study in the literature [59], the power consumption increased dramatically when the cutting depth was increased from 0.25 to 0.35 mm, which might be attributed to the greater force necessary to cut out high-depth stock from the workpiece. As the curve slope is higher for the depth of cut, therefore, the effects of the depth of cut were traced to be higher than the feed. Sahinoglu and Rafighi [60] also observed that the depth of cut (64.83%) had the biggest significant influence on Pc in comparison to feed (11.80%) in hard turning. The surface plots (Figure 6e,f) also confirmed the leading trend of power consumption with a simultaneous increment in the depth of cut and feed. ANOVA (Table 7) also reported the highest contribution of depth of cut (55.94% for single nozzle and 59.59% for double nozzle) succeeded by feed on power consumption (38.07% for single nozzle and 35.78% for double nozzle), while a negligible effect of pulse time was found for both cooling scenarios. In pulse mode MQL, the pulse time regulates the volume of lubricant flow through the nozzle; raising the pulse duration reduces the lubricant flow volume. A higher volume of lubricant flow allows for more efficient friction management between the tool and the workpiece, allowing for less cutting force and power consumption during machining. Because the machining length in this study was modest (160 mm), the power usage varied only minimally with altering pulse time; as a result, it was determined to be insignificant in the ANOVA report.

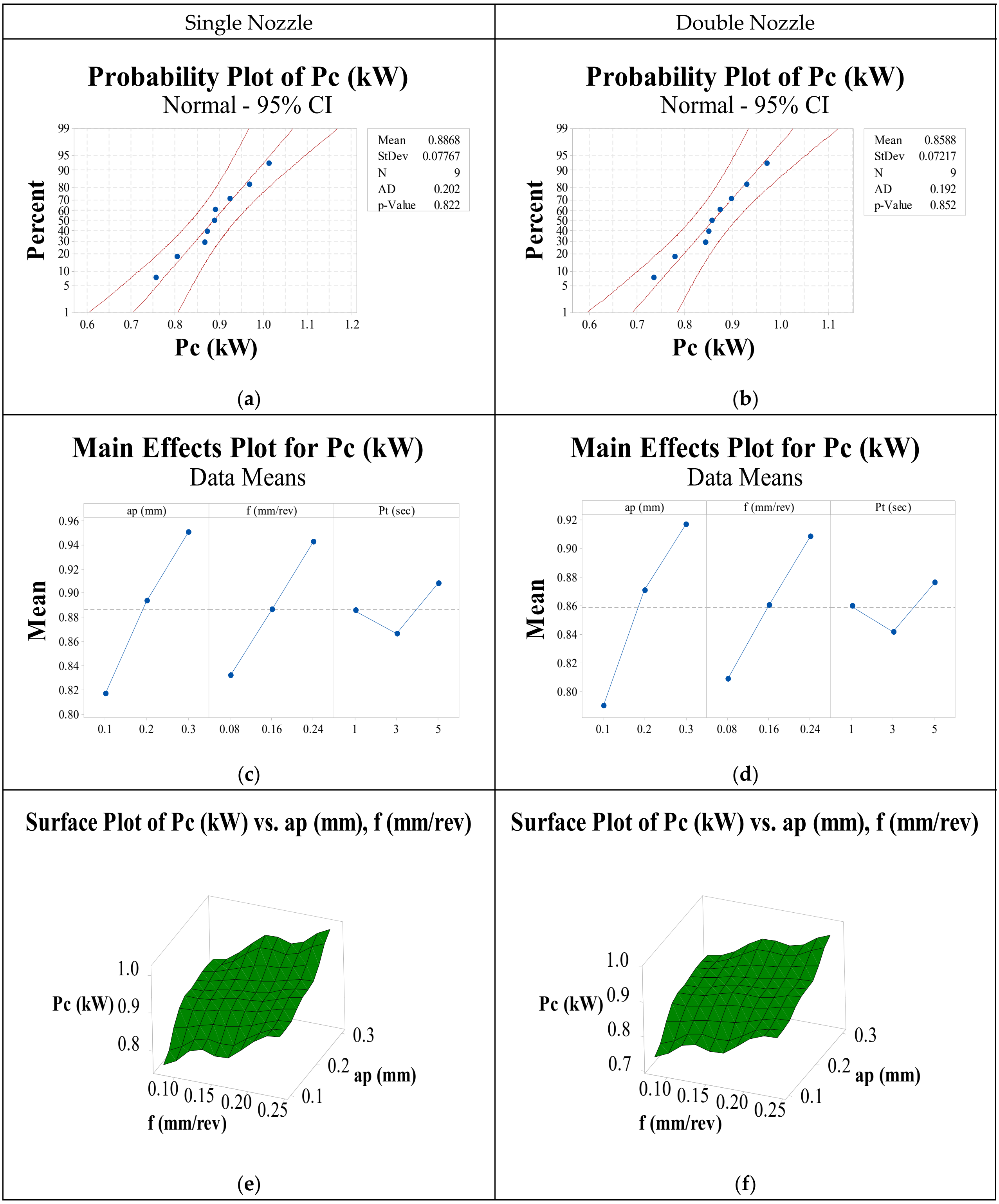


Figure 6. Assessment of power consumption using (**a**,**b**) probability plot, (**c**,**d**) main effect plot, (**e**,**f**) 3D surface plot.

Table 7. ANOVA for Pc.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	% Contribution	Significant
Single Nozzle							
ap	2	0.026994	0.013497	113.00	0.009	55.94	Yes
f	2	0.018372	0.009186	76.90	0.013	38.07	Yes
Pt	2	0.002652	0.001326	11.10	0.083	0.5	No
Error	2	0.000239	0.000119				
Total	8	0.048256					
Summary: R^2 = 99.50%; R^2 (adjacent) = 98.02%; R^2 (prediction) = 89.98%.							
Double Nozzle							
ap	2	0.024830	0.012415	153.69	0.006	59.59	Yes
f	2	0.014907	0.007453	92.27	0.011	35.78	Yes
Pt	2	0.001770	0.000885	10.95	0.084	0.39	No
Error	2	0.000162	0.000081				
Total	8	0.041668					
Summary: R^2 = 99.6%; R^2 (adjacent) = 98.45%; R^2 (prediction) = 92.15%.							

3.5. Material Removal Rate Analysis

The amount of material removed per unit of time is referred to as the material removal rate (MRR) in machining [61]. It can be measured in terms of volume or weight of material removed in unit time. The amount of time needed to create a machined item directly influences the part's production cost when manufacturing activities are designed. MRR is a time-dependent response. Nowadays, every manufacturing sector wants to achieve maximum productivity in a limited time, so this goal can only be achieved by achieving higher MRR. The general advantages of higher MRR are a reduction in cycle time per unit product, lower cost per part, improved tool life and surface finish by proper selection of cooling environments. Overall, a higher MRR can lead to increased productivity, lower costs and improved quality during turning operations. However, it is important to balance MRR with other factors such as tool life, surface finish and workpiece deformation to optimize the entire machining process. The MRR for each run under both single-nozzle and dual-nozzle MQL has been estimated, and their values in g/min are mentioned in Table 3.

The highest MRR values under both cooling scenarios was found in run 9 (highest depth of cut, highest feed and lowest pulse time), while the lowest MRR values for both cooling conditions were observed at the lowest level of input parameters. Considering the average MRR of nine runs, the double-nozzle MQL provided 18.37% greater MRR over the single nozzle. According to the literature [62], with the application of lubricant during machining, the thermal stress on the tool and workpiece was reduced in comparison to dry cutting; thus, MRR was enhanced. In the double nozzle, mist lubricant works more effectively than in the single-nozzle MQL; hence, less thermal stress might develop on the tool and workpiece. As a result, MRR was improved with double-nozzle MQL. Statistically, the MRR results obtained under both cooling strategies followed the normal probability curve as their respective p values were higher than 0.05 (Figure 7a,b). Moreover, the influence of three different parameters (ap, f and Pt) on MRR was examined using the main effects plot, surface plot and ANOVA. From the graphs (Figure 7c,d), it was evident that the MRR was leading with the depth of cut and feed, while it was reducing with pulse time. Surface plots (Figure 7e,f) also ensured the increasing trend of MRR with together with an increment in depth of cut and feed. ANOVA (Table 8) also confirmed the dominance of feed and depth of cut toward MRR during both cooling conditions. Many researchers found similar effects of depth of cut and feed on MRR in the hard turning of bearing steel [62,63]. For the single nozzle, the feed rate was the largest contributor (54.49%), while for the double nozzle, the depth of cut was the largest one with 49.00% contribution. The effect of pulse time for MRR was marginal or insignificant in both cases.

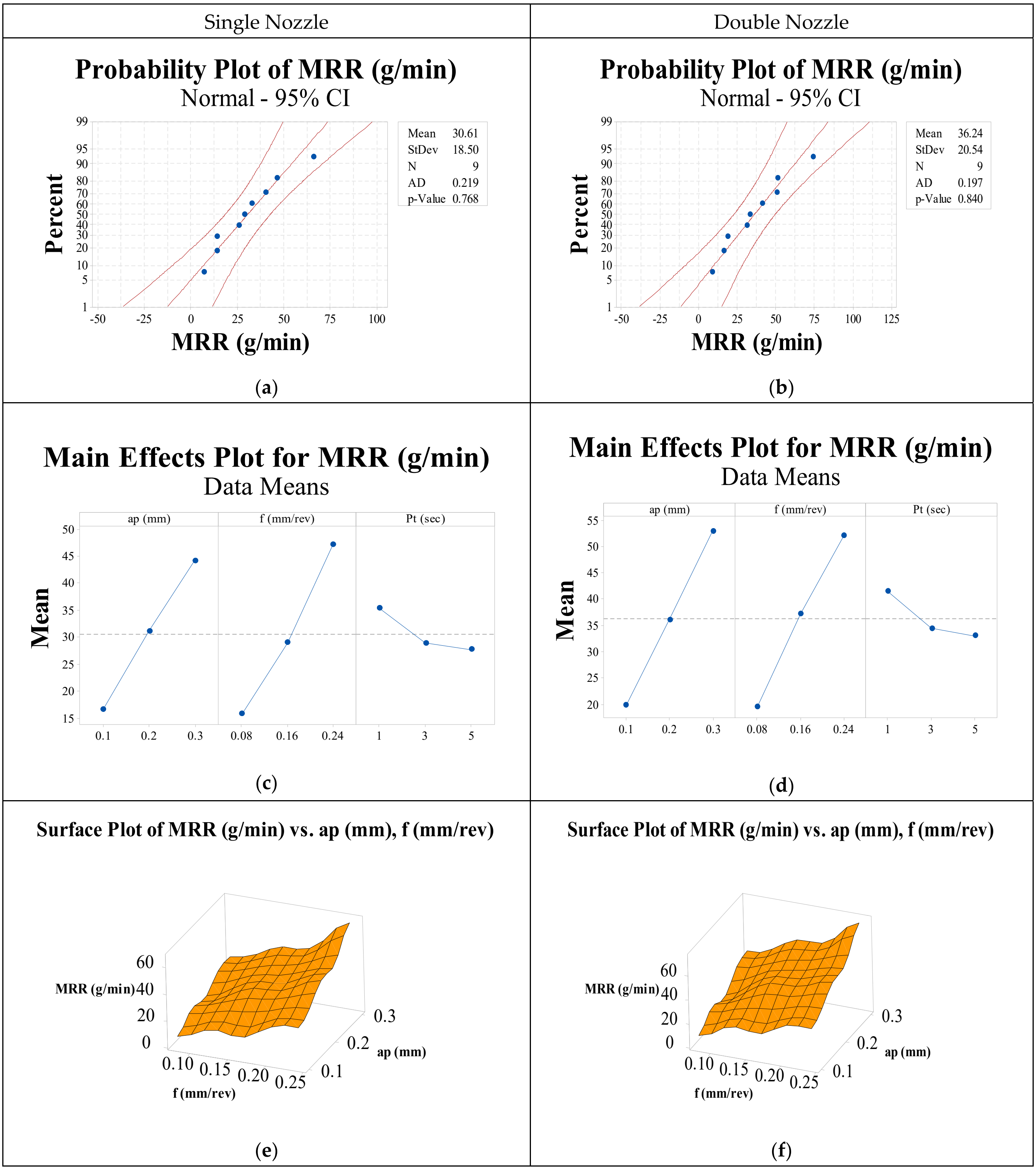


Figure 7. Assessment of MRR using (**a**,**b**) probability plot (**c**,**d**) main effect plot (**e**,**f**) 3D surface plot.

Table 8. ANOVA for MRR.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	% Contribution	Significant
Single Nozzle							
ap	2	1134.71	567.355	126.49	0.008	41.45	Yes
f	2	1491.78	745.888	166.29	0.006	54.49	Yes
Pt	2	102.18	51.088	11.39	0.081	3.73	Yes
Error	2	8.97	4.485				
Total	8	2737.63					
Summary: R^2 = 99.67%; R^2 (adjacent) = 98.69%; R^2 (prediction) = 93.36%.							
Double Nozzle							
ap	2	1654.82	827.408	508.19	0.002	49.00	Yes
f	2	1596.33	798.164	490.23	0.002	47.27	Yes
Pt	2	122.37	61.186	37.58	0.026	3.62	No
Error	2	3.26	1.628				
Total	8	3376.77					
Summary: R^2 = 99.90%; R^2 (adjacent) = 99.61%; R^2 (prediction) = 98.05%.							

4. Regression Modeling

Statistical regression modeling represents a methodological approach that is utilized to model and examine multiple variables, with the goal of establishing a functional relationship among one or more dependent and independent variables [64]. The linear regression model considers a linear relationship between independent and dependent variables. The analysis considers the impacts of the independent factors on the dependent variable. The accuracy of the regression model was ensured based on R^2 and R^2(Adj) results. If the R^2 and R^2(Adj) results are close to one, then the developed models are said to be fit to the experimental data [64,65]. In the current study, Minitab 17 software was used to generate the linear regression equations under both cooling scenarios as displayed in Equations (1)–(10). The estimated R^2 and R^2(Adj) results for each model are traced to be nearer to one; thus, all the generated models are fit to the experimental results.

4.1. Regression Equations for Single-Nozzle Results

$$Ra = 0.0056 + 2.517\,ap + 5.896\,f + 0.1133\,Pt \quad (1)$$

$$(R^2 = 99.10\%\ \&\ R^2\ (Adj) = 98.55\%)$$

$$VB = 0.0181 + 0.370\,ap + 0.283\,f + 0.01608\,Pt \quad (2)$$

$$(R^2 = 84.15\%\ \&\ R^2\ (Adj) = 74.64\%)$$

$$Tf = 64.17 + 46.67\,ap + 69.6\,f + 2.100\,Pt \quad (3)$$

$$(R^2 = 94.75\%\ \&\ R^2\ (Adj) = 91.61\%)$$

$$Pc = 0.6254 + 0.6683\,ap + 0.692\,f + 0.00567\,Pt \quad (4)$$

$$(R^2 = 95.20\%\ \&\ R^2\ (Adj) = 92.33\%)$$

$$MRR = -22.54 + 137.5\,ap + 196.3\,f - 1.914\,Pt \quad (5)$$

$$(R^2 = 98.64\% \; \& \; R^2 \text{ (Adj)} = 97.83\%)$$

4.2. Regression Equations for Double-Nozzle Results

$$Ra = -0.129 + 2.883 \text{ ap} + 5.729 \text{ f} + 0.0758 \text{ Pt} \tag{6}$$

$$(R^2 = 94.87\% \; \& \; R^2 \text{ (Adj)} = 91.80\%)$$

$$VB = 0.0351 + 0.1033 \text{ ap} + 0.2250 \text{ f} + 0.01817 \text{ Pt} \tag{7}$$

$$(R^2 = 91.67\% \; \& \; R^2 \text{ (Adj)} = 86.68\%)$$

$$Tf = 54.73 + 62.2 \text{ ap} + 50.2 \text{ f} + 3.100 \text{ Pt} \tag{8}$$

$$(R^2 = 91.14\% \; \& \; R^2 \text{ (Adj)} = 85.83\%)$$

$$Pc = 0.6199 + 0.6350 \text{ ap} + 0.623 \text{ f} + 0.00408 \text{ Pt} \tag{9}$$

$$(R^2 = 94.78\% \; \& \; R^2 \text{ (Adj)} = 91.65\%)$$

$$MRR = -23.25 + 166.07 \text{ ap} + 203.6 \text{ f} - 2.104 \text{ Pt} \tag{10}$$

$$(R^2 = 99.31\% \; \& \; R^2 \text{ (Adj)} = 98.90\%)$$

5. Sustainability Assessment

The present study uses the Pugh matrix sustainability assessment on single-nozzle and double-nozzle MQL techniques to decide the best among these two cooling environments during the turning operation of Duplex steel. To assess sustainability in manufacturing processes, the Pugh matrix decision-making sustainability assessment technique is preferred by many researchers [25,26]. This involves assigning specific scores to sustainable manufacturing parameters using mathematical numbers. Each quality parameter is allocated a score criteria ranging from −2 to +2 based on its level of importance. A score of −1 and +1 is assigned for the inferior and better results, respectively. A much superior result is assigned a score of +2 for the best and −2 for the worst results [66,67]. Apart from this, a separate weight factor is also added, which increases the efficiency of this sustainability assessment test. A total of 10 weight factors (10 W) are distributed among the seven selected sustainability assessment factors depending upon their importance in the present research experiment. The weight factor value is multiplied by the corresponding sustainability assessment factor values to achieve the final score. In this sustainability assessment, seven different sustainability assessment factors—surface finish quality, tool wear, machining temperature, power consumption, cutting force, operator's health and material removal rate—are selected for the sustainability calibration. It must be noted that among all the sustainability assessment factors, the surface finish quality, operator's health and MRR are framed as "high is better", whereas all the remaining factors are framed as "low is better".

Table 9 represents the Pugh matrix comparison values for single and double-nozzle MQL. As per the impact of the following sustainability assessment factors on both MQL techniques, the surface finish quality and tool wear are assigned two weight factors (2 W), and all the remaining sustainability assessment factors are assigned one weight factor (1 W). Now, scores for both MQL techniques are being allocated to each sustainability assessment factor. As per the work of many researchers, the worldwide desired Ra value during the turning operation is 1.6 μm [68,69]. The average Ra value of 1.792 μm is obtained in the case of the single nozzle, which exceeds the desired Ra value. The average Ra value of 1.592 μm is obtained in the case of the double nozzle, which is far better than that of the single nozzle. So, the surface finish quality for the single nozzle is assigned a score of −1, and for the double nozzle, the assigned score is +2.

Table 9. Pugh matrix comparison for single and double-nozzle MQL.

Sustainability Assessment Factors	Weight Factor	Single Nozzle MQL Score	Actual Score	Double Nozzle MQL Score	Actual Score
Surface Finish Quality	2 W	−1	−2	+2	+4
Tool Wear	2 W	+1	+2	+2	+4
Machining Temperature	1 W	+1	+1	+2	+2
Power Consumption	1 W	+2	+2	+2	+2
Material Removal Rate	1 W	+1	+1	+2	+2
Cutting Force	1 W	+1	+1	+2	+2
Operator's Health	1 W	+2	+2	−1	−1
Lubricant Consumption	1 W	+2	+2	−1	−1
Total +		+10	+11	+12	+16
Total −		−1	−2	−2	−2
Total Score		+9	+9	+10	+14

The average tool wear values in the cases of single- and double-nozzle MQL are 0.1857 mm and 0.1462 mm, respectively. The average tool wear in the case of the double-nozzle technique is quite less than that of the single-nozzle technique. So, tool wear for the single nozzle is assigned a +1 score, and for the double nozzle, the assigned score is +2. With the single- and double-nozzle MQL, respectively, the average machining temperature is 90.93 °C and 84.5 °C. As the average machining temperature of the double nozzle is less than that of the single nozzle, the score of +2 is assigned to the double nozzle and +1 is assigned to the single nozzle. In the case of single- and double-nozzle MQL, the average power consumption is 0.8868 kW and 0.8588 kW, respectively. As both the values are very close to each other when we consider the cases, we assigned a score of +2 to both the cases, as the consumption is quite less than the preferred power consumption values during the turning operation. The average material removal rate for single- and double-nozzle MQL is 30.61 g/min and 36.24 g/min, respectively. MRR during double-nozzle MQL is quite more than single-nozzle MQL, so a score of +2 is assigned for double nozzle and a score of +1 is assigned for single nozzle. From experimental analysis, it was observed that the cutting force under the double nozzle is quite less than that of machining under the single nozzle. Thus, a score of +2 is assigned to the double nozzle and a score of +1 is assigned to the single nozzle. The lubricant consumption comes under the economical factor, whereas the operator's health comes under the social factor. But both these factors are interconnected during machining operation under the MQL environment. The increase in lubricant consumption is directly proportional to adverse effects on the operator's health, as more lubricant means more carbon emission to the environment. As the lubricant consumption is more during double-nozzle MQL, the adverse effect on the operator's health also increases. So, a −1 score is being assigned to the double nozzle and a +2 score is assigned for the single nozzle for both these sustainability assessment factors. It must be noted that the lubricant consumption in both the MQL techniques is significantly less, so they possess negligible adverse effects on the environment. Now, after assigning the scores, the scores of both the MQL techniques under each of their Sustainability Assessment Factors are being multiplied by their respective weight factors. Thus, we achieve the actual scores in terms of positive and negative for both the MQL techniques. Now, after the summation of positive and negative scores in both cases, the final scores are achieved. The single nozzle receives a final score of +9, and the double nozzle receives a final score of +14. This clearly indicates that the double-nozzle MQL technique is superior in terms of sustainability compared with the single-nozzle MQL. All these results are displayed in the Kiviat diagram in Figure 8. Many researchers have used the Kiviat diagram to show the sustainability results [27–30].

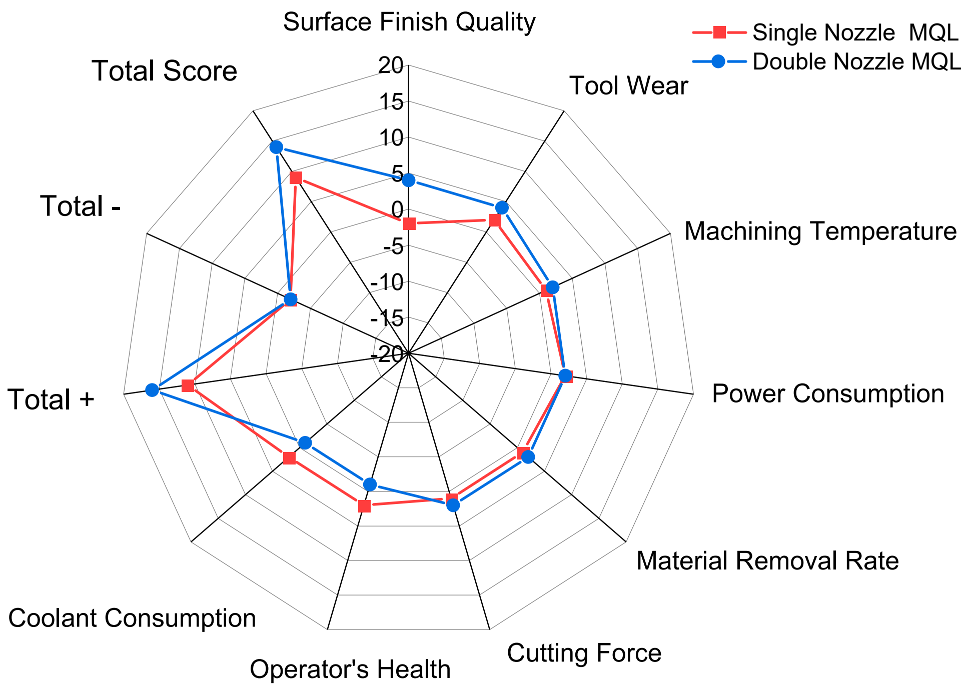


Figure 8. Sustainability assessment using Kiviat diagram.

6. Conclusions

This study aims to compare the single-nozzle and double-nozzle pulse mode MQL performance in turning UNS S32750 super duplex stainless steel. Also, the consequence of pulse time, cutting feed and depth of cut in both cooling scenarios was investigated at a constant cutting speed condition. The key findings are summarized as follows:

1. Double-nozzle MQL offered significant advantages over single-nozzle MQL systems by lowering Ra, VB, Pc, and Tf. The MRR is significantly improved with the use of the double nozzle. Considering the average results of nine experiments, in comparison to the single nozzle, Ra, VB, Tf, and Pc were found to be decreased by 11.16%, 21.24%, 7.07%, and 3.16% with the double nozzle, respectively, whereas MRR was found to be 18.37% higher with the double nozzle.
2. In both cooling strategies, the lowest Ra was found as 0.68 µm with double-nozzle MQL. The recommended feed, pulse time and depth of cutting for machining super duplex steel is 0.08 mm/rev, 1 s and 0.1 mm. For both machining strategies, feed had the largest impact on Ra, while the depth of cut and pulse time also significantly altered the Ra.
3. The common wear mechanisms such as abrasion, built-up edge, adhesion, and notch wear were detected in both cooling strategies. In the entire experiments, the lowest wear of 0.092 mm was achieved when double-nozzle MQL was operated with 1 s pulse time. The impact of pulse time for double-nozzle MQL was found to be highest (74.98%) among all variables.
4. The tool-flank temperature under single-nozzle MQL was greatly affected by the feed rate, while the depth of cut was the most influencing term when machining was finished in double-nozzle MQL. In both cases, pulse time exhibited significance on tool-flank temperature with a contribution of 26.77% (single nozzle) and 37.85% (double nozzle).

5. A marginal improvement in power consumption was noticed when machining was executed under the double nozzle. The pulse rate has negligible effects on power consumption, while the depth of cut exhibited the largest effect for both cases.
6. The material removal rate was greatly improved in double-nozzle MQL-assisted turning. The consequence of depth of cutting as well as feed was found to be significant, while pulse time has insignificant effects on it.
7. According to the Pugh matrix sustainable evaluation, the single nozzle earns a final score of +9, while the double nozzle receives a final score of +14. This score clearly shows that the double-nozzle MQL technique was superior to the single-nozzle MQL strategy in terms of sustainability.

In summary, the double-nozzle MQL system proves superior to the single-nozzle counterpart, offering enhanced lubrication, cooling and process adaptability, leading to improved machining performance and productivity. The future study of the current research may involve the analysis of heat transfer in dual-nozzle MQL-assisted machining. Additionally, in the future, a sustainability assessment analysis using a quantitative calculation of the economic and environmental benefits of dual nozzles can be carried out. Moreover, industry-based different lubricants can be applied to investigate their performance using the Pugh matrix sustainability approach.

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