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OPTIMISATION OF A NEEM OIL BASED MINIMUM QUANTITY LUBRICATING (MQL) SYSTEM PARAMETERS FOR THE ORTHOGONAL MACHINING OF MILD STEEL

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ABSTRACT

Cutting tools experience early failure and dimensional variation due to the high temperature developed during machining. Conventional cutting fluid applications do not successfully remove heat because they do not reach the chip-tool contact. Operators on the work floor may experience the adverse side effects of cutting fluids, such as skin and respiratory issues. As a result, a different lubricating method is necessary for machining without harming the tool-workpiece, which would also be advantageous for health and the economy. This research aims to develop and evaluate the efficiency and optimization of minimal use of Neem seed oils as lubrication for the Taguchi L_9 array-based design for machining of mild steel. The Taguchi optimization technique was used to examine the impact of the neem oil based Minimum quantity lubrication (MQL) system (with flow rate, air pressure and nozzle diameter as factors) on the workpiece temperature and chip thickness ratio at cutting speeds of 260 rpm and 470 rpm. The outcome demonstrated that optimal settings at 260 rpm were a flow rate of 50 ml/hr, air pressure of 1.5 bars, and nozzle diameter of 0.8 mm for workpiece temperature, and a flow rate of 100 ml/hr, air pressure of 1 bar, and nozzle diameter of 0.8 mm for chip thickness ratio. At 470 rpm, optimal settings for workpiece temperature were a flow rate of 50 ml/hr, air pressure of 1.5 bars, and nozzle diameter of 0.5 mm, while chip thickness ratio optimization indicated a flow rate of 100 ml/hr, air pressure of 1 bar, and nozzle diameter of 0.5 mm.

Keywords: *Minimum quantity lubrication (MQL); Taguchi; Analysis of Variance (ANOVA); workpiece, mild steel; Optimization.*

1.0 INTRODUCTION

Minimum quantity lubrication (MQL) refers to the use of cutting fluids of only a minute amount – typically of a flow rate of 50 to 500 ml/hour – which is about three to four orders of magnitude lower than the amount commonly used in flood cooling conditions, where, for example, up to 10 litres of fluid can be dispensed per minute. Minimum quantity lubrication, which uses a fine spray of the cooling medium, is, therefore, being followed as an alternative for conventional coolants.

The concept of MQL sometimes referred to as near-dry lubrication or micro-lubrication, has been suggested for over two decades as a means of addressing the issues of environmental intrusiveness and occupational hazards with airborne cutting fluid particles. Furthermore, minimising cutting fluid leads to economic benefits by saving lubricant costs and workpiece/tool/ machine cleaning cycle time. However, there has been little investigation into the use of vegetable oil based cutting fluids in MQL machining.

Vegetable oil lubricants are biodegradable and non-toxic, unlike conventional mineral-based oils [1]. They have low volatility due to high molecular weight of the triglyceride molecule and have a narrow range of viscosity changes with temperature. Polar ester groups are able to adhere to metal surfaces and therefore, possess good boundary lubrication properties. In addition, vegetable oils have high solubilizing power for polar contaminants and additive molecules. As the demand for vegetable oils for food has increased in recent years, it is impossible to justify the use of these oils for cutting fluid, hence, the present focus on production and utilization of oil from non-edible oil seeds (neem seed oil) [2].

Machining of steel inherently generates high cutting zone temperatures. Such high temperature causes dimensional deviation and premature failure of cutting tools. It also impairs the surface integrity of the product by inducing tensile residual stresses and surface and subsurface microcracks in addition to rapid oxidation and corrosion. In machining, conventional cutting fluid application do not adequately penetrate the chip-tool interface and thus cannot remove heat effectively. Furthermore, the addition of extreme pressure additives in the cutting fluids does not ensure penetration of coolant at the chip-tool interface to provide lubrication and cooling [3].

However, the advantages caused by cutting fluids have been questioned lately due to the several adverse effects they cause. On the shop floor, the operators may be affected by the bad effects of cutting fluids, such as skin and breathing problems. For companies, the costs related to cutting fluids represent much of the total machining costs. Several researchers have stated that the costs of cutting fluids are frequently higher than those of cutting tools [4]. Consequently, eliminating cutting fluids, if possible, can be a significant economic incentive. Considering the high cost associated with cutting fluids and projected escalating costs when stricter environmental laws are enforced, the choice seems obvious. Enormous efforts to reduce or eliminate the use of lubricant in metal cutting are, therefore, being made from the viewpoint of cost, ecological and human health issues.

Also, machining by MQL is a relatively new technology and certainly still new to Nigerian machinists. Because of the expensive nature of the MQL metering system, it has limited the full-scale application of MQL, which has the potential to save cost on a very large scale.

2.0 MATERIALS AND METHODS

2.1 Materials and equipment

Mild steel, HSS, Neem seem oil, Compressor, fuel pump, oil tank, steel plates, nozzles, pressure gauge, connecting pipes, valves, lathe machine, thermocouples, a digital weighing balance, an MQL cooling system, micrometer screw gauge, vernier caliper, electric cutting machine, drilling machine and welding machine.

2.2 Experimental procedure

2.2.1 Design of Experiment

The Minitab statistical software and Taguchi design with an L_9 orthogonal array composed of three factors and three levels were employed to optimise the input parameters. The selected input parameters for this study were flow rate (ml/hr), air pressure (bars), and nozzle diameter (mm) (as shown in Table 1). This was employed for two cutting speeds (260 rpm and 470 rpm) at a depth of cut of 1.0mm. The Taguchi method was applied to the experimental data, and the signal-to-noise ratio (S/N) for each level of process parameters was measured based on the S/N analysis. Regardless of the quality characteristic category, a higher S/N ratio corresponds to a better quality characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. A detailed Analysis of Variance (ANOVA) framework for assessing the statistical significance of the process parameters was provided. The optimal combination of the process parameters can then be predicted. Finally, a design expert offers a model based on the input parameters.

Table 1: Factors and levels in Taguchi L_9 experimental design plan

Factors	Levels		
	1	2	3
(A) Flow rate (ml/hr)	50	100	150
(B) Air pressure (bars)	1	1.5	2
(C) Nozzle diameter (mm)	0.5	0.8	1.0

Table 2: Experimental design and runs

S/N	Flow rate (ml/hr)	Air pressure (bars)	Nozzle diameter (mm)
1	50	1.0	0.5
2	50	1.5	0.8
3	50	2.0	1.0
4	100	1.0	0.8
5	100	1.5	1.0
6	100	2.0	0.5
7	150	1.0	1.0
8	150	1.5	0.5
9	150	2.0	0.8

The experimental runs with the input factor mix are displayed in Table 2. The output for this study are temperature (^{o}C) and chip thickness ratio (mm).

2.2.2 Machining of MILD steel and MQL application system

The samples with original lengths of 100mm and 30mm rod diameter was placed into the lathe machine mounted firmly on the vice: the tendency of the cutting tool to walk was pre-empted by establishing a centering mark or centre punching before machining with a high-speed steel tool.

The MQL is supplied at a flow rate of 50ml/hr to 150ml/hr at a certain distance in the direction of the feed. The system was also designed to align the nozzle in tool-workpiece engagement points relative to the spindle axis. In addition, the design of the movable nozzle clamps allows the nozzle discharge tips to be relocated away from the machining zone. The cutting parameters were then measured and evaluated against dry and wet machining processes using a thermocouple, micro-meter screw gauge and vernier calipers.

ANOVA was used to determine the importance of MQL parameters and quantitative impact on individual response optimisation. The ANOVA analysis was used to ascertain how much the MQL parameters affect the studied outcomes. If the P-value is less than 0.05 at a 95% degree of confidence, the MQL parameters and interactions are reported to be significant. Furthermore, a very high P-value indicates that the MQL parameter significantly affects the performance characteristic.

Using Minitab 16 software, regression analysis was used to simulate the temperature and chip thickness ratio values. The flow rate represents A, the air pressure represents B, and the calculated mathematical model represents C. The interaction investigated how the MQL settings affected the machining operation. This was done to comprehensively understand how MQL parameters might be tuned for various desired outcomes.

3.0 Results and Discussion

3.1 Results

3.1.1 Data Inspection Analysis

Data inspection may be used to optimise unique performance qualities, and in this study, Tables 3 and 4 display an L_9 orthogonal array of the experimental data attributes under various MQL settings. For 260 rpm cutting speed, the second experimental run, which used a flow rate of 50 ml/hr, air pressure of 1.5 bar, and nozzle diameter of 0.8 mm, produced the lowest workpiece temperature of 56.7 ^oC. In contrast, the ninth experimental run with a flow rate of 150 ml/hr, air pressure of 2 bars, and nozzle diameter of 0.8 mm had the lowest chip thickness of 0.72 mm. For 470 rpm cutting speed, the second experimental run, which used a flow rate of 50 ml/hr, air pressure of 1.5 bars, and nozzle diameter of 0.8mm, produced the lowest workpiece temperature of 83.7 ^oC. In contrast, the first experimental run with a flow rate of 50 ml/hr, air pressure of 1 bar, and nozzle diameter of 0.5 mm had the lowest chip thickness of 0.6 mm.

Table 3: Experimental data at 260 rpm cutting speed

Factors			**Responses**	
Flow rate (ml/hr)	Air Pressure (bars)	Nozzle diameter (mm)	Temperature (^oC)	Chip Thickness (mm)
50	1.0	0.5	61.3	0.73
50	1.5	0.8	56.7	0.83
50	2.0	1.0	66.4	0.87
100	1.0	0.8	70.4	0.76
100	1.5	1.0	68.7	0.78
100	2.0	0.5	70.5	0.86
150	1.0	1.0	72.0	0.92
150	1.5	0.5	71.6	0.85
150	2.0	0.8	74.2	0.72

Table 4: Experimental data at 470 rpm cutting speed

Factors			**Responses**	
Flow rate (ml/hr)	Air Pressure (bars)	Nozzle diameter (mm)	Temperature (^oC)	Chip Thickness (mm)
50	1.0	0.5	87.7	0.60
50	1.5	0.8	83.7	0.77
50	2.0	1.0	84.7	0.64
100	1.0	0.8	101.4	0.73
100	1.5	1.0	93.7	0.62
100	2.0	0.5	84.5	0.64
150	1.0	1.0	100.4	0.64
150	1.5	0.5	84.3	0.61
150	2.0	0.8	107.2	0.85

The results showed that the workpiece temperature and chip thickness ratio do not exist in the same region or even within the same range, in conformity with the findings of [5]. This similar result trend, was as also obtained by [6] for EN24 steel alloy, the limitation of data inspection analysis is seen; hence, additional optimisation analysis is required to determine the MQL settings for the smallest feasible temperature and chip thickness ratio aside from data inspection.

3.1.2 Workpiece Temperature

To enhance the quality of the machining operation, achieving minimal workpiece temperature is crucial for achieving a smoother and improved surface finish, as [7] stated. The response means corresponding to various machining parameters are presented in Tables 5 and 6 for 260 rpm and 470 rpm, respectively. Optimal settings were determined based on the smallest data within each of the three levels for every machining parameter.

In Table 5, Level 1 for the flow rate yielded the lowest workpiece temperature, Level 2 for the air pressure exhibited the lowest workpiece temperature, and Level 2 for the nozzle diameter resulted in the lowest workpiece temperature for 260 rpm. Table 5 provides the machining parameters associated with the identified optimal levels, indicating that a flow rate of 50 ml/hr, air pressure of 1.5 bars, and nozzle diameter of 0.8 mm (second experimental run) represent the best settings for achieving the lowest workpiece temperature.

Similarly, as shown in Table 6, Level 1 for the flow rate yielded the lowest workpiece temperature, Level 2 for the air pressure exhibited the lowest workpiece temperature, and Level 1 for the nozzle diameter resulted in the lowest workpiece temperature for 470 rpm. However, the identified optimal levels, indicating a 50 ml/hr flow rate, air pressure of 1.5 bars, and nozzle diameter of 0.5 mm, are not part of the experimental runs shown in Table 6.

Furthermore, it is essential to recognize the significance of each MQL parameter in influencing the resultant workpiece temperature. Statistical analysis, reflecting delta as the range of workpiece temperature values for each MQL parameter, revealed that for 260 rpm, the flow rate exhibited the highest delta value, followed by air pressure and nozzle diameter. These characteristics are ranked in descending order, underscoring the importance of the flow rate as the most influential MQL parameter. This aligns with the findings of [8] and [9], who used flow rate to determine MQL efficiency over air pressure for MQL of AISI 4140 steel.

On the other hand, the delta statistical analysis showed that with an increase in the rotating speed of the workpiece to 470 rpm, the nozzle diameter exhibited the highest delta value, closely followed by flow rate, while the air pressure had the least impact on the workpiece temperature. This result aligns with the findings of [10], whose analysis demonstrated that the most influential factor for an optimum response was nozzle diameter, followed by air pressure. The significance of MQL parameters in influencing workpiece temperature differs at 260 rpm and 470 rpm due to the dynamic nature of machining processes, varying cutting conditions, and the interplay of factors such as fluid dynamics and material properties[11].

3.1.3 Effect of MQL Parameters on Workpiece Temperature

Figures 1 and 2 show how the MQL settings affected the workpiece temperature during machining at 260 rpm and 470 rpm, respectively. As demonstrated in this study and the previous studies, such as that of [12], workpiece temperature increases as the flow rate increases, which could be due to the increase in chip thickness and friction with an increase in flow rate. As the flow rate increases, the chip is thicker, and the larger thickness-to-surface area of the chip is cut per revolution, which means there is less opportunity for the heat to be dissipated; hence, temperature increases. In contrast, increased air pressure from 1 bar to 1.5 bar, as observed by [13) and [14], decreases the workpiece temperature. This is because the high-pressure condition prevents chip accumulation, thus reducing the total heat flux.

Table 5: Workpiece temperature response based on the smaller-is-better optimisation for 260 rpm

Level	**Flow rate**	**Air Pressure**	**Nozzle Diameter**
1	61.47	67.90	67.80
2	69.87	65.67	67.10
3	72.60	70.37	69.03
Delta	11.13	4.70	1.93
Rank	1	2	3

Table 6: Workpiece temperature response based on the smaller-is-better optimisation for 470 rpm

Level	**Flow rate**	**Air Pressure**	**Nozzle Diameter**
1	85.37	96.50	85.50
2	93.20	87.23	97.43
3	97.30	92.13	92.93
Delta	11.93	9.27	11.93
Rank	2	3	1

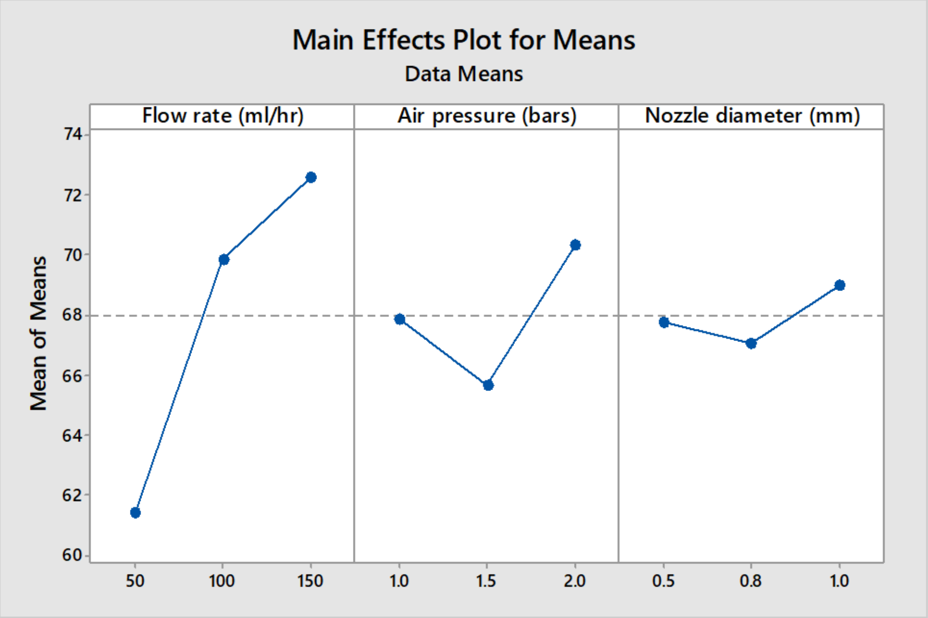

Figure 1: Effect of MQL parameters on workpiece temperature at 260 rpm cutting speed

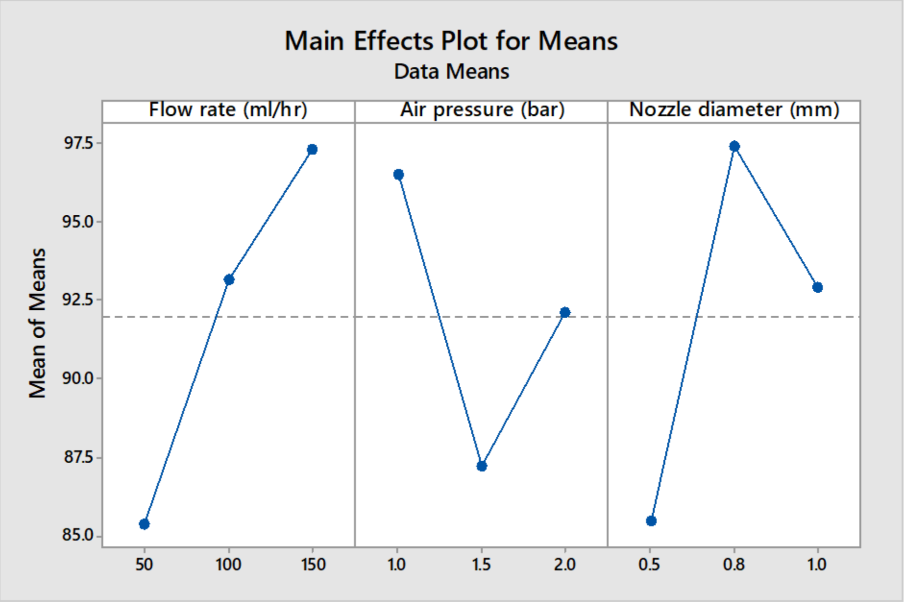

Figure 2: Effect of MQL parameters on workpiece temperature at 470 rpm cutting speed

On the other hand, when the pressure becomes too much, it prevents the lubricant from the MQL from having contact with the workpiece, thereby increasing the temperature [15]. This is because the temperature around the machining region increases rapidly when the chips accumulate, causing high heat flux on the workpiece surface [16]. This explains the increase in the workpiece temperature with increased pressure up to 2 bars. From the results, nozzle diameter has little influence on the workpiece temperature at 260 rpm and massive influence at 470 rpm. At 260 rpm, the increase in nozzle diameter initially enhances cooling, reducing the workpiece temperature, but excessive fluid may impede effective heat dissipation, leading to a subsequent temperature increase, as [17] reported. Conversely, at 470 rpm (higher speed), a larger nozzle diameter initially provides insufficient fluid for cooling, increasing temperature until increased fluid flow effectively cools the workpiece, causing a subsequent temperature decrease, aligning with the findings of [10].

The examination of optimal MQL parameter settings on the workpiece temperature for 260 rpm and 470 rpm cutting speeds, respectively, is shown by the variance analysis (ANOVA) in Tables 7 and 8. These results reaffirm these MQL parameters' noteworthy impact, with a distinctive numerical effect on the workpiece temperature. Specifically, at 260rpm, the flow rate emerges as the most influential parameter, contributing 84.99%, followed by air pressure at 11.92%, while the nozzle diameter consistently demonstrates insignificance with a mere 1.19% contribution. The residual error holding lesser significance underscores the importance of a meticulously designed experiment to minimize its impact on workpiece temperature.

Table 7: ANOVA analysis of the MQL Parameters for optimum workpiece temperature at 260 rpm cutting speed

Factors	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**Contribution**	**Remark**
Flow rate (ml/hr)	2	201.982	100.991	14.28	84.99%	Most significant
Air Pressure (bar)	2	33.162	16.581	2.34	11.92%	Significant
Nozzle diameter (mm)	2	5.749	2.874	0.41	1.90%	Less significant
Error	2	14.142	7.071		1.19%	Insignificant
Total	8	255.036	R^2 = 94.45%		R^2_{adj} = 77.82%	

Table 8: ANOVA analysis of the MQL Parameters for optimum workpiece temperature at 470 rpm cutting speed

Factors	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**Contribution**	**Remark**
Flow rate (ml/hr)	2	220.58	110.29	2.70	33.05%	Most significant
Air Pressure (bar)	2	128.95	64.47	1.58	21.65%	Less significant
Nozzle diameter (mm)	2	217.91	108.95	2.67	31.67%	Significant
Error	2	81.61	40.80		13.67%	Insignificant
Total	8	649.04	R^2 = 87.43%		R^2_{adj} = 49.71%	

Furthermore, at 470 rpm, as shown in Table 8, the MQL parameters have relatively close significance, with flow rate being the most impactful parameter, making a substantial contribution of 33.05%, followed by nozzle diameter at 31.62%, and the air pressure at 21.65%.

3.1.4 Workpiece Temperature Modelling

Regression analysis mathematically describes workpiece temperature using the MQL factors, as shown in Equations (1) and (2) for 260 rpm and 470 rpm cutting speeds, respectively.

$$T = 51.54 + 0.1113A + 2.47B + 2.09C \quad (1)$$

$$T = 73.7 + 0.1193A - 4.37B + 16.8C \quad (2)$$

Workpiece temperature may be calculated at any point of MQL parameters outside these equations' three separate levels since it allows for unaccounted MQL parameters. If the machinist has a restricted MQL capacity, this aids in navigating the available MQL parameter settings. The machinist can choose the ideal MQL settings for optimal workpiece temperature.

Figures 3 show the MQL settings' interaction modelling on the workpiece temperature evaluation at 260 rpm. The interaction between the MQL settings indicated a low workpiece temperature at a low flow rate, low air pressure, and nozzle diameter between 0.6 and 0.9mm, as indicated by the light green hues. On the other hand, Figure 4 shows the MQL parameter interactions for the workpiece temperature at 470rpm. At this workpiece speed, low temperatures are obtained at an air pressure of 1.4 to 1.8 bars, low flow rate and nozzle diameter.

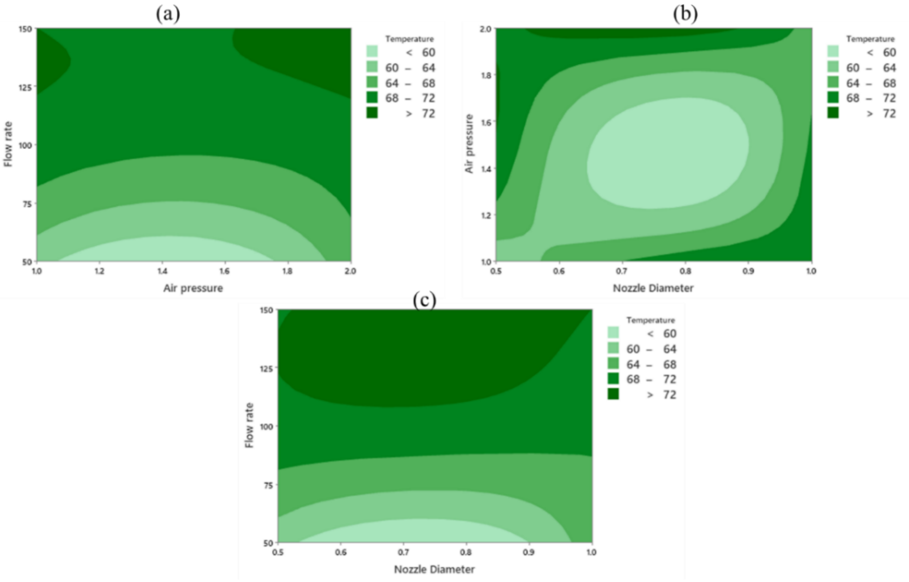

Figure 3: Interaction of the MQL parameters on workpiece temperature at 260 rpm cutting speed (a) Flow rate versus air pressure, (b) air pressure versus nozzle diameter, and (c) flow rate versus nozzle diameter

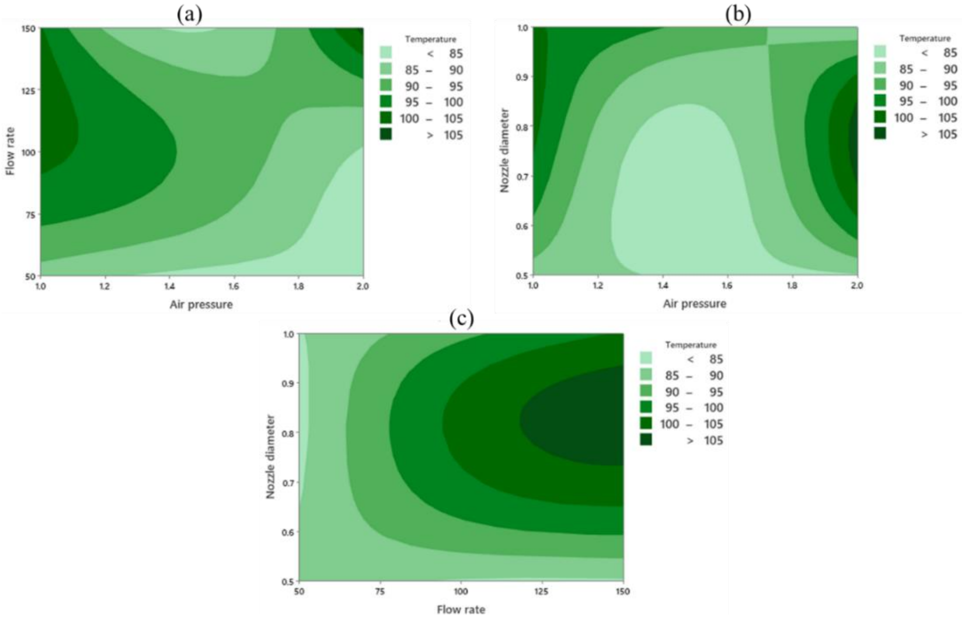

Figure 4: Interaction of the MQL parameters on workpiece temperature at 470 rpm cutting speed (a) Flow rate versus air pressure, (b) nozzle diameter versus air pressure, and (c) nozzle diameter versus flow rate

3.1.5 Chip thickness ratio

As indicated in the study of [18], a machine product must have a low chip thickness ratio for smoother, better surface finishing. A low chip thickness ratio is attributed to a low approach angle and increased effective cutting edge, favouring low surface roughness [7]. The response means in relation to the MQL parameters are displayed in Tables 9 and 10. The best settings are determined based on the smallest data from the three levels shown under each MQL parameter in the tables.

According to Table 9, at 260 rpm cutting speed, Level 2 for the flow rate yielded the lowest chip thickness ratio, Level 1 for the air pressure exhibited the lowest chip thickness ratio, and Level 2 for the nozzle diameter resulted in the lowest chip thickness ratio for 260 rpm. Flow rate of 100 ml/hr, air pressure of 1 bar, and nozzle diameter of 0.8 mm (fourth experimental run) represent the best settings for achieving the lowest chip thickness ratio.

On the other hand, according to Table 10, at 470 rpm cutting speed, Level 2 for the flow rate yielded the lowest chip thickness ratio, Level 1 for the air pressure exhibited the lowest chip thickness ratio, and Level 1 for the nozzle diameter resulted in the lowest chip thickness ratio for 470 rpm. This indicates that a flow rate of 100 ml/hr, air pressure of 1 bar, and nozzle diameter of 0.5 mm represent the best settings for achieving the lowest chip thickness ratio, which is not part of the initial run.

Table 9: Chip thickness ratio response based on the smaller-is-better optimisation for 260 rpm

Level	Flow rate	Air Pressure	Nozzle Diameter
1	0.8100	0.8033	0.8133
2	0.8000	0.8200	0.7700
3	0.8300	0.8167	0.8567
Delta	0.0300	0.0167	0.0867
Rank	2	3	1

Table 10: Chip thickness ratio response based on the smaller-is-better optimisation for 470 rpm

Level	Flow rate	Air Pressure	Nozzle Diameter
1	0.6700	0.6567	0.6167
2	0.6633	0.6667	0.7833
3	0.7000	0.7100	0.6333
Delta	0.0367	0.0533	0.1667
Rank	3	2	1

It is also crucial to understand the impact of each MQL parameter on the chip thickness ratio. At 260 rpm, the nozzle diameter exhibited the highest delta value, closely followed by the flow rate, while the air pressure had the least impact on the workpiece temperature. This result aligns with the findings of [10], whose analysis demonstrated that the most influential factor that affects chip thickness for an optimum response was nozzle diameter, followed by air pressure. Similar to the 260 rpm, at 470 rpm, the most significant effect was the nozzle diameter. However, this is followed by air pressure and then flow rate. As seen in the workpiece temperature, the disparities in MQL parameters for chip thickness at different speeds, of 260 rpm and 470 rpm, stem from the dynamic nature of machining processes and the interplay of factors like fluid dynamics and material properties [11].

3.1.6 Effect of MQL Parameters on Chip Thickness Ratio

Figures 5 and 6 show how the MQL settings affected the chip thickness ratio during machining at 260 rpm and 470 rpm, respectively. It has been demonstrated that the chip thickness ratio increases as the flow rate increases above 100 ml/hr for both 260 rpm and 470 rpm, which could be due to the increase in friction with an increase in flow rate. This result is consistent with the research of [12], who evaluated the chip thickness ratio during drilling and the effect of cutting parameters and spray mist applications. In contrast, increasing air pressure from 1 bar to 1.5 bar at 260 rpm increases the chip thickness ratio and decreases when moved to 2 bar which indicate that beyond a specific pressure, increasing the air pressure results in decreased chip size, which can lead back to the increasing jet force of the coolant with an increasing dynamic coolant supply pressure.

On the other hand, when the pressure becomes too much, it prevents the lubricant from the MQL from having contact with the workpiece, thereby increasing the chip thickness ratio, which is the case of a part machined with 470 rpm cutting speed. From the results, nozzle diameter has a significant influence on the chip thickness ratio. For 260 rpm, the 0.8mm diameter nozzle produced the least chip thickness ratio. Increasing the nozzle diameter from 0.5mm kept the air velocity constant and decreased the average temperature drop on the workpiece, thereby decreasing the chip thickness ratio. However, when the nozzle diameter was further increased, air-cooling efficiency was reduced, and air velocity decreased, increasing the chip thickness ratio, as was observed by [19]. For 470 rpm, a reduction in air-cooling efficiency was not observed with an increase in nozzle diameter.

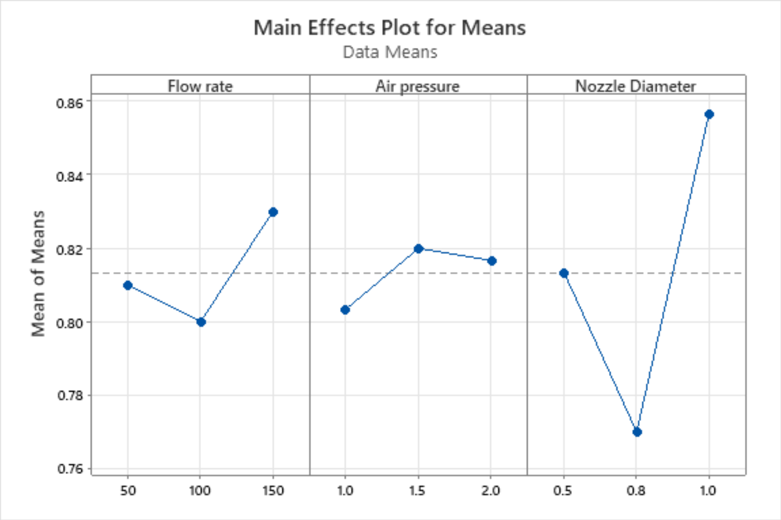

Figure 5: Effect of MQL parameters on chip thickness ratio at 260 rpm cutting spee

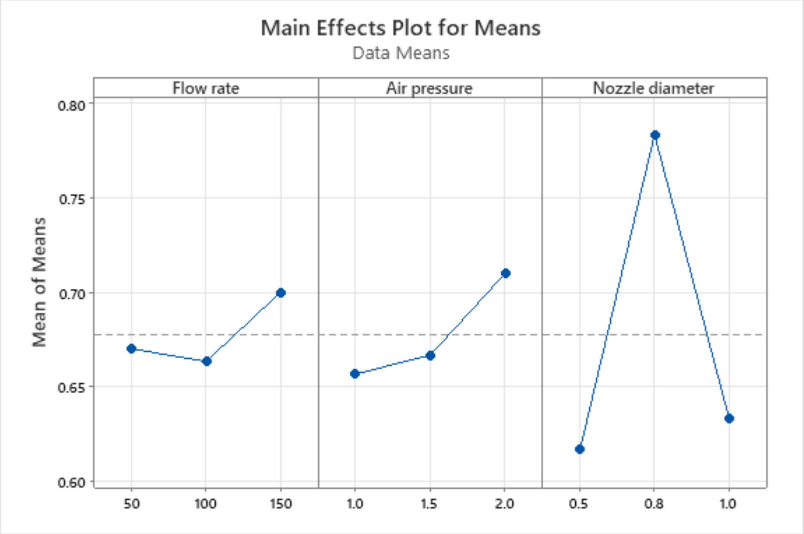

Figure 6: Effect of MQL parameters on chip thickness ratio at 470 rpm cutting speed

The variance analysis (ANOVA) in Tables 11 and 12 showed the importance of each MQL parameter on the chip thickness ratio for 260 rpm and 470 rpm cutting speeds, respectively. Specifically, at 260rpm, the nozzle diameter emerges as the most influential parameter, contributing 30.71%, followed by flow rate at 5.38%, while the air pressure consistently demonstrates insignificance with a mere 0.49% contribution. The residual error holding high significance underscores that a substantial portion of the variability in the response variable remains unexplained.

Similarly, at 470 rpm, as shown in Table 12, the nozzle diameter MQL parameter had the most significant contribution of 89.47%, followed by air pressure at 7.00% and flow rate at 1.86%. The relatively low contribution of the residual error (1.67%) denotes the carefully planned experiment's accuracy to denote the factors' effect on the chip thickness ratio. In the linear fit model, the R^2 value was obtained as 97.48% and R^2_{adj} as 89.93%, indicating a precise experimental design.

Table 11: ANOVA analysis of the MQL Parameters for optimum chip thickness ratio at 260 rpm cutting speed

Factors	DF	Adj SS	Adj MS	F-Value	Contribution	Remark
Flow rate (ml/hr)	2	0.001400	0.000700	0.06	5.38%	Less significant
Air Pressure (bar)	2	0.000467	0.000233	0.02	0.49%	Insignificant
Nozzle diameter (mm)	2	0.011267	0.005633	0.45	30.71%	Significant
Error	2	0.024867	0.012433		63.42%	
Total	8	0.038000	R^2 = 34.56%		R^2_{adj} = 0%	

Table 12: ANOVA analysis of the MQL Parameters for optimum chip thickness ratio at 470 rpm cutting speed

Factors	DF	Adj SS	Adj MS	F-Value	Contribution	Remark
Flow rate (ml/hr)	2	0.002289	0.001144	1.54	1.86%	Insignificant
Air Pressure (bar)	2	0.004822	0.002411	3.24	7.00%	Significant
Nozzle diameter (mm)	2	0.050556	0.025278	33.96	89.47%	Most significant
Error	2	0.001489	0.000744		1.67%	Less significant
Total	8	0.059156	R^2 = 97.48%		R^2_{adj} = 89.93%	

3.1.7 Chip Thickness Ratio Modelling

Regression analysis was also used to mathematically describe chip thickness ratio using the taken-into-account MQL factors, as shown in Equations (4.3) and (4.4) for 260 rpm and 470 rpm cutting speeds, respectively.

$$CTR = 0.721 + 0.0002A + 0.0133B + 0.068C \quad (4.3)$$

$$CTR = 0.511 + 0.0003A + 0.0533B + 0.075C \quad (4.4)$$

Since it allows for unaccounted-for MQL factors, the chip thickness ratio may be determined at any point of MQL parameters outside of the three distinct level points investigated by these equations. This helps the machinist navigate the available MQL parameter settings if they have limited MQL capacity. The machinist selects the perfect MQL parameters for the best chip thickness ratio.

All three interaction graphs illustrate the desired chip thickness ratio range in light green hues for 260 rpm in Figure 5 and dark blue hues for 470 rpm in Figure 6. The interaction between the MQL settings indicated a low chip thickness ratio at a low air pressure of 1 bar, low flow rate, and nozzle diameter between 0.5 and 0.55mm, as indicated by the light green hues. On the other hand, Figure 8 shows that at 470 rpm, a low chip thickness ratio is obtained within the air pressure of 1.4 and 1.6 bars, low flow rate and extreme nozzle diamaters.

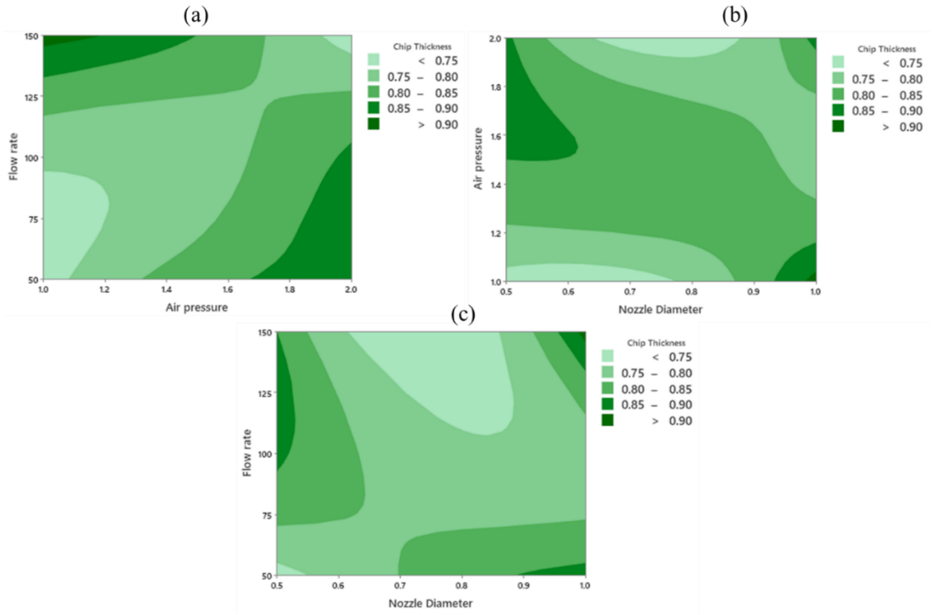

Figure 7: Interaction of the MQLparameters on chip thickness ratio at 260 rpm cutting speed (a) Flow rate versus air pressure, (b) air pressure versus nozzle diameter, and (c) flow rate versus nozzle diameter

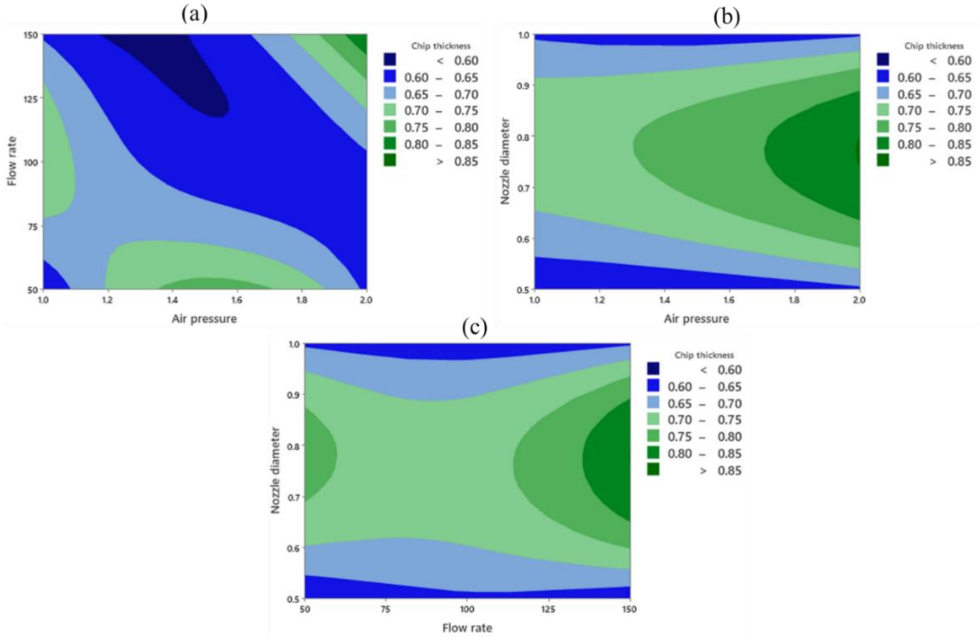

Figure.8: Interaction of the MQLparameters on chip thickness ratio at 470 rpm cutting speed (a) Flow rate versus air pressure, (b) nozzle diameter versus air pressure, and (c) nozzle diameter versus flow rate

3.1.8 Comparison of the Developed MQL System with Control samples and also Previously-developed MQL Systems

The control samples used for both flood coolant and dry machining gave workpiece temperatures of 76.2°C for flood coolant, thereby having a 25.6% decrease in workpiece temperature for the MQL and 84.5°C for dry machining, also having a 32.9% decrease in workpiece temperature for the MQL at 260rpm. A temperature of 107°Cfor flood coolant, thereby having a decreased workpiece temperature of 21.8% when MQL was used, and 118°C for dry machining, with a 29.1% decrease in workpieace temperature with MQL at 470rpm.

Also, control samples for both flood coolant and dry machining gave chip thickness ratio of 0.86 for flood coolant, thereby having a 16.3% decrease in chip thickness ratio for the MQL and 0.93 for dry machining, also having a 22.6% decrease in chip thickness ratio for the MQL at 260rpm. A chip thickness ratio of 0.79for flood coolant, thereby having a decreased chip thickness ratio of 24.1% when MQL was used, and 0.88 for dry machining, with a 31.8% decrease in chip thickness ratio with MQL at 470rpm.

These results underscore the superior thermal performance of the developed MQL system in machining mild steel.

4.0 CONCLUSIONS

At the end of this study on optimizing the potentials in the machining of mild steel under neem seed oil MQL conditions, the following conclusions were drawn:

At 260 rpm, optimal settings for workpiece temperature were identified as a flow rate of 50 ml/hr, air pressure of 1.5 bars, and nozzle diameter of 0.8 mm. For the same speed, chip thickness ratio optimization suggested a flow rate of 100 ml/hr, air pressure of 1 bar, and nozzle diameter of 0.8 mm as the most effective. At 470 rpm, optimal settings for workpiece temperature were a flow rate of 50 ml/hr, air pressure of 1.5 bars, and nozzle diameter of 0.5 mm. However, the optimal chip thickness ratio settings were a flow rate of 100 ml/hr, air pressure of 1 bar, and nozzle diameter of 0.5 mm. Statistical analyses revealed varying degrees of influence for each parameter on workpiece temperature and chip thickness ratio.

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