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# Effects of Machining Parameters of C45 Steel Applying Vegetable Lubricant with Minimum Quantity Cooling Lubrication (MQCL)

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**Abstract:** One of the most significant performance indicators for measuring the machinability of materials is tool wear and surface roughness. Choosing the best combination of cutting parameters can help reduce production costs, which is what the manufacturing industry is interested in. At the same time, industries are always looking for an alternative to conventional flood cooling since its use creates an environmental burden and health concerns for the operators. Therefore, vegetable oil-based minimum quantity cooling lubrication (MQCL) is considered a cutting environment. Sunflower oil is utilized as base fluid in MQCL and applied to the cutting zone through a nozzle. The turning experiments are conducted on C45 material which is widely used in various industrial applications, including numerous automotive components. Since flood cooling is widely utilized in machining C45, it is the present-day need to assess alternative cooling and lubricating approaches to avoid the adverse effects of flood cooling. The Taguchi method was used in the present work to minimize surface roughness and tool wear. $L_9$ orthogonal array was constructed, and experiments were performed on C45 steel using coated carbide cutting tools. The statistical approach is utilized to evaluate the effect of cutting parameters on output responses. The optimal cutting settings for cutting speed, feed, and depth of cut to minimize surface roughness are 100 m/min, 0.18 mm/rev, 0.150 mm, and 80 m/min, 0.18 mm/rev, and 0.150 mm for tool wear. According to the findings, cutting speed, feed rate, and depth of cut varied surface roughness by 1.9%, 78.3%, and 14.04%, and tool wear by around 43.8%, 37.9%, and 6.3%, respectively. The outcomes can be useful to metal-cutting industries to identify the combination of machining parameters with vegetable oil-based MQCL.

**Keywords:** machining; vegetable oil; MQCL; tool wear; surface roughness

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## 1. Introduction

In the metal-mechanical industry, machining processes applied to a workpiece on a lathe or a milling machine are the most frequent processes used in manufacturing. The primary factor influencing competition in the machining sector is the surface quality, dimensional precision, and tool wear produced. One of the key determinants of a product's quality is surface roughness. Process variables include the type of lubricant applied, tool shape, cutting conditions, feed rate, cutting speed, and depth of cut affect surface roughness [1–3]. Achieving a good surface finish increases production costs as well as processing time. Therefore, improving surface quality and minimizing manufacturing costs are emerging as the two most important elements to consider for production. The efficiency and quality of machining are frequently impacted by tool deflection caused by excessive cutting forces during manufacturing operations [4]. In reality, choosing the right machining parameters is frequently accomplished by trial-and-error experimentation, which is an expensive and time-consuming process [5], especially when high-precision machining is necessary.

The strength, hardness, and wear resistance of medium carbon steel compositions have led to significant growth in their applications. The automotive, agriculture, and aerospace industries employ hardened carbon steel raw materials for their products. At the same time, machining hardened steels is difficult due to the higher amount of heat generated. Machining these materials is becoming challenging because of the tool wear associated with it and the energy input applied. During dry machining, the tool wear is caused by friction generated due to a high temperature developed at the tool-chip-workpiece contact. Hence, tool wear is the characteristic that affects cutting performance, production rate, and cost [5]. To increase productivity, the industry is more concerned about longer tool productivity (useful life). Rapid-cutting tool wear shortens the life of the tool and impacts the quality of the machined surface [6]. Productivity and quality can therefore be increased by reducing tool wear. Khare et al. [7] assessed the roughness of AISI 4340 steel by optimizing factors such as cutting speed, feed rate, depth of cut, and rake angle to obtain low surface roughness.

The Taguchi technique has emerged as the most well-known optimization strategy for increased productivity. However, many investigations discovered that the Taguchi approach could only improve one response at a time [7–10]. Akkus et al. [11] investigated the effect of cutting parameters during dry turning on hardened AISI 4140 steel using coated carbide cutting tools. The experiments were designed using the Taguchi method. The surface roughness (Ra) was negatively affected by the feed rate, according to the optimized cutting settings. The response surface method (RSM) was utilized by Singh et al. [12] to machine EN24 steel. A numerical illustration of tool life and surface roughness (Ra) was developed. The predicted value obtained for surface roughness (Ra) was 79.8236 ru, and tool life was 24.8688 min at a 95% confidence level. Çelik et al. [13] analyzed the effect of machining parameters on tool wear during machining Ti-6Al-4V alloy. Utilizing multiple regression and genetic expression programming techniques, it was established that the cutting speed and feed rate significantly affected the tool wear. Moreover, it was concluded that cutting speed had more effect than feed rate.

Employing analysis of variance (ANOVA), Jahanbakhsh et al. [14] evaluated ceramic tools for turning operations with Inconel 625. To measure material removal and tool wear, the cutting parameters cutting speed, feed, and depth of cut were changed from 65.91 to 234.09 m/min, 0.07 to 0.23 mm/rev, and 0.46 to 1.64 mm, respectively. The study showed that the amount of flank wear decreased with an increase in feed rate; however, an increase in the depth of cut significantly affected the rate of tool wear [14]. Lalwani et al. [15] investigated cutting forces and surface roughness while hard-tuning maraging steel 250 defense (MDN250) steel manufacturing. They concluded that cutting speed does not represent a critical affectation on surface roughness.

Surface roughness is caused by workpiece hardness, tool geometry, and cutting speed, according to Nalbalt et al. [16]. They performed research about the surface roughness effect of coated cemented carbide tooling on AISI 1030 steel by using feed rate, tool geometry, workpiece hardness, and cutting speed as process factors during turning manufacturing. The uncoated tooling was analyzed and compared with two Physical vapor deposition (PVD) AlTiN (Aluminium Titanium nitride) and TiAlN (Titanium aluminium nitride) coated components and two Chemical vapor deposition (CVD) TiN (nitride) coated tooling with multilayer materials (TiN, $Al_2O_3$, TiC). It was observed that the coating tools improved the workpiece surface finish, in the range of 16–22%, particularly with high cutting speeds (300 m/min). Aslan et al. [17] performed experimental studies to optimize the machining parameters of $Al_2O_3$-based ceramic cutting tools for machining hardened steels. Using an orthogonal array and analysis of variance (ANOVA), the effects of cutting speed, feed rate, and depth of cut on two performance measures, flank wear (VB), and surface roughness (Ra), were investigated.

In machining operations, metalworking fluids are used to flush out debris, cool the workpiece and tolling, and minimize friction. However, these fluids can have negative environmental impacts, including water and air pollution [18–20]. The work discussed sustainable alternatives to traditional metalworking fluids, including vegetable lubricants, water-based fluids, and nanofluids. The properties and performance of these alternative fluids are critical to investigate as potential environmental benefits [18,21]. Vila et al. [22] studied how different cutting techniques affected the long-term machining of hardened steels. According to the experimental findings, utilizing coated cutting tools at faster cutting and slower feed rates can greatly lengthen tool life, lessen cutting forces, and keep material removal rates high. Diverse studies have also examined the viability of using minimal quantity lubrication (MQL) as a long-term cooling method in machining operations [23–26]. MQL is a method used to lower heat and friction in the machining zone during metal-cutting operations [24]. MQL only lubricates the cutting tool in a very small amount, generally 100 mL per hour [26]. Zhang et al. [27] analyzed tool life and workpiece surface quality while machining Ni-based super-alloys in dry and MQL cutting regimes. Researchers discovered that MQL produced superior surface shape and 150% longer tool lifespan than dry machining. Lower friction caused by the fine, pressurized mist penetrating the tool chip intermediate surface is related to longer tool wear. Similarly, Tamang et al. [28] studied the tool wear and cutting power during the dry and MQL machining of Inconel-825 while taking sustainability into consideration. Different feed rates, cutting speeds, and cut depths were used when turning. Results showed that MQL machining reduced 10.4% surface roughness, 8.5% cutting power, and 16.5% tool wear when compared to dry machining. Xavior et al. [2] conducted an experimental examination to evaluate the lubricating capability of diverse green lubricants to process AISI 304 steel with a carbide tool. According to their observations, coconut oil considerably decreased the rate of tool wear and the roughness of the machined surfaces. To machine hardened steel, Mia et al. [29] used a small amount of green, biodegradable coolant based on olive oil. They evaluated machining effectiveness based on the tool's temperature and the cutting zone's surface condition.

Vegetable and recycled oils' potential as MQL cutting fluids for Inconel 718 end milling was evaluated. Rheological and tribological tests were conducted to describe four environmentally friendly oils. Specifically, commercial canola oil was compared to high oleic sunflower, sunflower, castor, and ECO-350 recycled oils. The outcomes revealed the efficacy of sunflower oil with about 15% improvement in tool life compared to other oils [30]. Khanna et al. [31] evaluated the performance of flood, MQL, and cryogenic machining during turning Ti-6Al-4V alloy. Around 60% higher cutting force was reported under flood cooling than MQL due to a lack of proper lubricating effect. The life cycle analysis showcased the unsuitability of flood cooling with almost 50% higher total impact on ecology than MQL and cryogenic cooling. Pereira et al. [32] investigated the effectiveness of MQL and cryogenic cooling while machining AISI304. Tool wear was reduced by around 40% under MQL and cryogenic cooling due to enhanced lubrication and cooling. Further, the life cycle analysis showcased these techniques as eco-friendlier than flood cooling. Computational fluid dynamics (CFD) and experimental investigations were conducted to compare the performance of MQL with emulsion cooling. It was established through simulation that the MQL flow effectively penetrated in cutting zone and provided lubrication, and helped in carrying away the chips produced [33].

The literature review demonstrates that developing optimum cutting parameters using traditional experimental design methods would be tedious and time-consuming. This method would require verifying the results every time, increasing the cost. The experiment number would also increase with increasing cutting parameters, leading to slow production. Many research issues persist despite extensive research efforts, such as the optimization of machining parameters under MQCL. It is observed that the previous study has not explored the study of performance characteristics of the turning parameters with vegetable-based lubricant with minimum quantity cooling lubrication (MQCL). Additionally, little research is reported evaluating how machining parameters affect tool wear and surface roughness under MQCL based on vegetable-based lubricants. The Taguchi methodology is followed in this investigation to evaluate the impact of the machining conditions. Analysis of variance (ANOVA) and correlations between the parameters using multiple linear regressions are used in this method to examine the impact of cutting parameters. Validation experiments are used to evaluate how well the developed models work. Therefore, the aim is to minimize tool wear and enhance the surface quality of C45 steel in an MQCL environment based on vegetable oil. A flow chart of the methodology adopted for the experiments is presented in Figure 1.

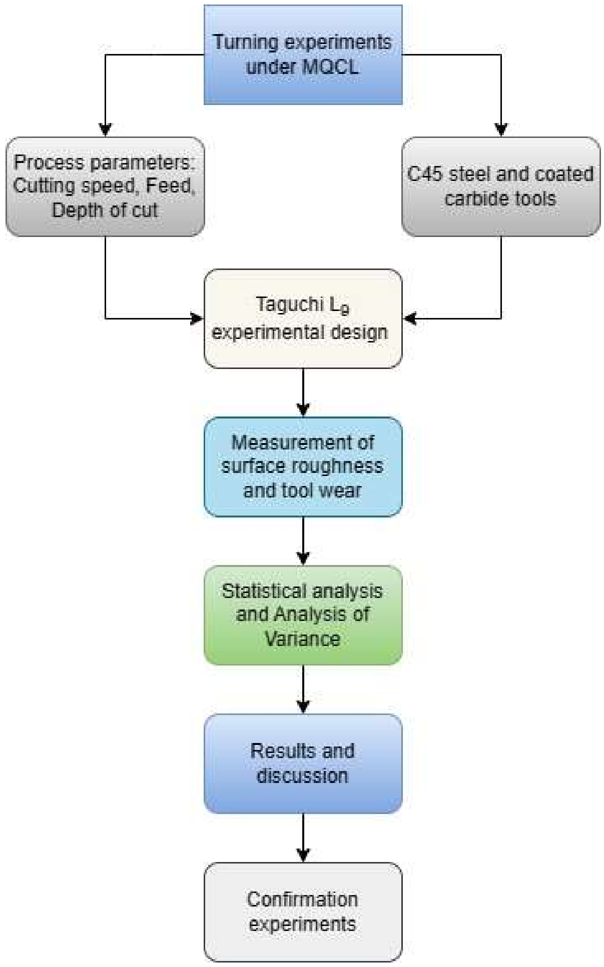


**Figure 1.** Experimental setup with MQCL system.

## 2. Material and Processes

### *2.1. Materials*

C45 steel is employed for this research. Numerous automobile parts and components are manufactured from C45 steel, including connecting rods, crankshafts, shafts, and spindles, among others. The chemical composition of C45 is C (0.45%), Si (0.24%), Ti (0.01%), Cr (0.09%), Ni (0.06%), Mn (0.72%), and Fe as balance. C45 steel hardness is 20 HRC when measured on the Rockwell hardness tester (Make: Metlab Equipments & Engineering Systems, Gujarat, India). The turning is performed by using cemented carbide cutting tool.

### *2.2. Experimental Method*

The evaluations are performed on a Kirloskar Turnmaster 35 lathe with a maximum spindle speed of 1120 rpm and a maximum power of 2.2 kW. The MQCL system mounted on the machine is used to deliver the lubricant mixture to the cutting zone while machining.

It comprises a lubricant reservoir, inlet valve, pressure regulator, outlet valve, flow control knob, and pipes connected to the nozzle. Figure 2 depicts the experimental setup. Each experiment is repeated three times, and an average value is considered for further analysis to ensure the accuracy of the experimental results. Tool wear is analyzed on the flank face of the cutting tool. The flank wear formed along the flank face is measured using a toolmaker's microscope. The turning is performed by using cemented carbide cutting tool with a TiN coating (CNMG120408-5) with the following insert geometry angles: nominal rake angle of 6°, rear rake angle of 6°, clearance angle of 6°, approach angle of 80°- and 0.8-mm nose radius. The tool holder, with the ISO designation PSBNR2525M12 was utilized. A Surftest SJ-210 (Make: Mitutoyo, Japan) a surface roughness tester, is used to measure average surface roughness (Ra). The resolution of the employed surface roughness tester is 0.02 μm. The roughness values are measured at three different locations along the machining length to avoid any measurement error. Fatty acids and triglycerides make up the majority of vegetable oil. Vegetable oil molecules include many polar groups, such as -COOH and -COOR, because of these substances. The extraordinary lubricating capability of vegetable oils is attributed to these polar groups [34]. The sunflower oil is utilized as a lubricant under the MQCL environment. Sunflower oil exhibits a strong oxidative stability resistance because of the more than 90% molecular weight of saturated fatty acids that were present. The greater oxidative and thermal stability of sunflower oil, in contrast to other commonly used vegetable oils in machining, encourages one to use it as a coolant/lubricant. It has higher flash and pour points and biodegradability than conventional cutting fluids. According to available literature, the sunflower is suitable for turning materials ranging from steel to super-alloys [35]. Vegetable oil, including sunflower oil, was used as the MQL base fluid in turning experiments by various researchers [36–38]. The findings revealed that MQL-assisted machining exhibited much superior machining behavior than dry and wet machining. The flow rate of the lubricant mixture is 100 mL/h, applied through a nozzle at an angle of 45° and 25 mm from the tool surface. Figure 3 shows the methodology of the work.

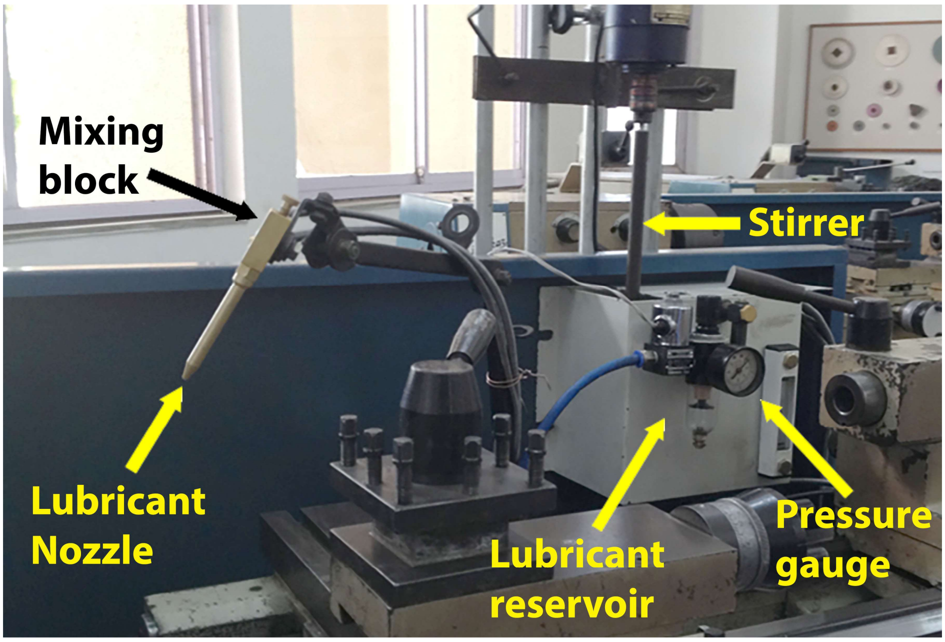


**Figure 2.** Experimental setup with MQCL system.

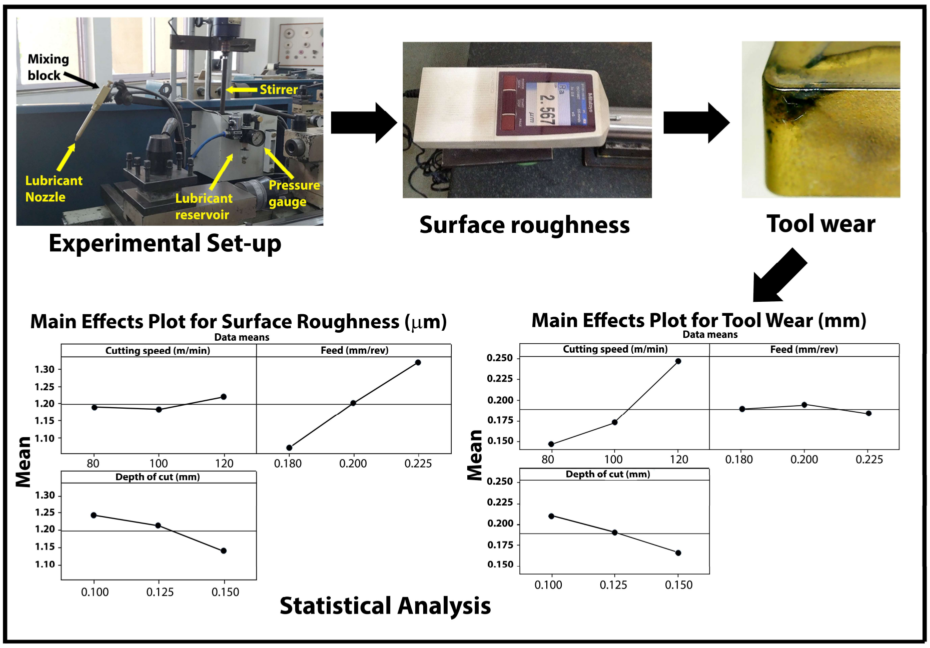


**Figure 3.** Schematic representation of methodology.

The range of the machining parameters is selected based on the recommendation of the tool manufacturer, preliminary experiments, and a review of the available literature [32,39]. The considered levels of the cutting parameters are shown in Table 1.

**Table 1.** Machining parameters and range.

| Parameters | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Cutting speed (m/min) | 80 | 100 | 120 |
| Feed rate (mm/rev) | 0.180 | 0.200 | 0.225 |
| Depth of cut (mm) | 0.100 | 0.125 | 0.150 |

### *2.3. Experimental Design Using the Taguchi Method*

The conventional experimental design approaches are overly intricate and challenging to apply. Additionally, several trials must be conducted as the number of machining parameters rises. As a result, it is essential to identify and test the variables under controlled laboratory circumstances. The Taguchi method's biggest benefits include a shorter experimental duration, lower costs, and the ability to identify important components quickly.

Creating products that are resistant to all noise influences is the goal of quality engineering. The most important step in the design of an experiment is the selection of the control variables. To quickly identify non-significant factors, including as many variables as possible is essential [12]. Taguchi created a standard orthogonal array to address this demand. Taguchi selected the signal-to-noise (S/N) ratio as the preferable quality criterion. Since the standard deviation increases when the mean decreases and vice versa, the standard deviation is not used as a quantitative value. To put it in less scientific terms, the signal-to-noise ratio contrasts the level of a desired signal, such as music, with the volume of background noise. The background noise is less intrusive as the ratio increases. The phrase "signal-to-noise ratio" can be used colloquially to describe the proportion of true or relevant information to misleading information in a conversation or engagement. In other words, the mean cannot be brought to the objective without minimizing the standard deviation [12,13,40].

As the process is being built, the target mean value may change. The notion of the S/N ratio has two applications: improving measurement and raising quality by lowering variability. By considering "the smaller the better" signal-to-noise ratio, the Taguchi approach was able to determine the ideal cutting parameters necessary for the optimal surface roughness.

## 3. Results and Discussions

### *3.1. Analysis Using the Taguchi Methods*

When analyzing experimental data with the Taguchi technique, the signal-to-noise ratio is the most important consideration. The S/N ratio in this study should have a maximum value in accordance with the Taguchi technique to generate optimal cutting conditions. In Table 2, it was discovered that −0.11219 S/N ratios and 17.0774 S/N ratios, respectively, were the best cutting conditions for Ra and tool wear. The cutting parameters of 100 m/min cutting speed, 0.18 mm/rev feed rate, and 0.15 mm depth of cut (2 1 3 orthogonal array) produced the best Ra. Similarly, the lowest tool wear was achieved by combining a cutting speed of 80 m/min, a feed rate of 0.18 mm/rev, and a depth of cut of 0.125 mm (1 1 2 orthogonal array). Therefore, in calculating the ideal cutting settings for experiments to be carried out under the same circumstances, interpretations may be made following the level values of X, Y, and Z factors.

**Table 2.** Experimental results.

| | Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Surface Roughness (Ra) (µm) | S/N Ratio for Ra | Tool Wear (mm) | S/N Ratio for Tool Wear |
|---|---|---|---|---|---|---|---|
| 1 | 120 | 0.180 | 0.100 | 1.15967 | −1.28669 | 0.28 | 11.0568 |
| 2 | 120 | 0.200 | 0.125 | 1.25633 | −1.98207 | 0.25 | 12.0412 |
| 3 | 120 | 0.225 | 0.150 | 1.24533 | −1.90569 | 0.21 | 13.5556 |
| 4 | 100 | 0.200 | 0.100 | 1.19400 | −1.54009 | 0.19 | 14.4249 |
| 5 | 100 | 0.225 | 0.125 | 1.34467 | −2.57231 | 0.18 | 14.8945 |
| 6 | 100 | 0.180 | 0.150 | 1.01300 | −0.11219 | 0.15 | 16.4782 |
| 7 | 80 | 0.225 | 0.100 | 1.37467 | −2.76397 | 0.16 | 15.9176 |
| 8 | 80 | 0.180 | 0.125 | 1.03700 | −0.31558 | 0.14 | 17.0774 |
| 9 | 80 | 0.200 | 0.150 | 1.15900 | −1.28167 | 0.14 | 17.0774 |

### *3.2. S/N Ratio Analysis for Surface Roughness (Ra)*

Table 3 lists the different S/N ratio values between the maximum and minimum, and Figure 4 shows the main effect plot for the S/N ratio. The feed rate and the depth of cut (1.8425 and 0.7637, respectively) are the two variables with the largest differences in values. Increasing the feed rate and depth of cut has had a major impact on Ra. As can be seen in Figure 3 and Table 3, the second level of the A factor (cutting speed), the first level of the B factor (feed rate), and the third level of the C factor (depth of cut) are higher as a result. As a result, the optimal cutting settings are 100 m/min for cutting speed, 0.18 mm/rev for feed rate, and 0.150 mm for cut depth.

**Table 3.** S/N response table for surface roughness (Ra).

| Level | Cutting Speed (m/min) | Feed (mm/rev) | Depth of Cut (mm) |
|---|---|---|---|
| 1 | −1.4537 | −0.5715 | −1.8636 |
| 2 | −1.4082 | −1.6013 | −1.6233 |
| 3 | −1.7248 | −2.4140 | −1.0998 |
| Delta | 0.3166 | 1.8425 | 0.7637 |
| Rank | 3 | 1 | 2 |

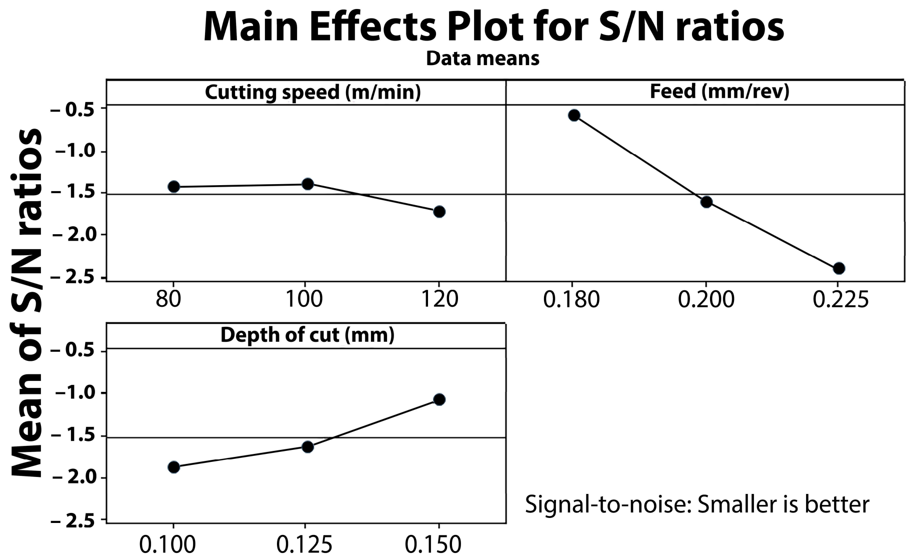


**Figure 4.** The mean of S/N ratios versus factor levels surface roughness (Ra).

### 3.3. Regression Analysis for Surface Roughness

The regression equation obtained for surface roughness is presented as Equation (1) below. This equation can be used to predict the value of surface roughness under the selected machining environment.

$$Surfaceroughness = 0.261 + 0.000755 Cuttingspeed + 5.56 Feed - 2.07 Depthofcut \quad (1)$$

Tables 4 and 5 present an analysis of variance for surface roughness. It is observed that the value of the predicted-$R^2$ is 91.9%, and the value of the adjusted-$R^2$ is 87.1%. The difference in these values is very low, indicating that this optimization model accurately predicts surface roughness. From the main effect plots shown in Figure 5a, an increase in feed rate led to a sharp rise in surface roughness. Not only would the peak heights be reduced with a low feed rate, but less cutting force would also be produced. Ra will be lower because of the modest plastic deformation and barely perceptible feed marks resulting from this. Higher feed rates would increase the cutting forces, which would cause more chatter, which would be registered as a higher surface roughness [41]. Additionally, the area would be hotter. Overall, this will result in a rougher surface because it causes rapid tool wear. The rough surface could result from increased mechanical vibrations brought on by higher feed. Additionally, obtaining low surface roughness at 100 m/min results in a smaller influence of increasing cutting speed on surface roughness. It has been seen from the probability plot presented in Figure 5b that the residuals are equally distributed along the mean line proving the accuracy of the proposed model for predicting surface roughness. It is also clear from the normal probability plots in Figure 4b that the chosen machining settings impact the surface roughness because each plot is close to the standard residual line. Additionally, MQCL has a different role from dry machining in that it helps to regulate how machining parameters affect machining responses such as tool wear and surface roughness. The presence of a lubricant mixture at the tool-work and chip-tool interfaces reduced friction and helped the tool keep its cutting edge for longer, improving surface quality. It can be further concluded that the effective cooling provided by the compressed air helped in taking away chips and debris from the cutting zone and helped in improving the surface finish. The improved lubrication provided by vegetable oil resulted in a smaller contact area between the tool and chips, which contributed to a reduction in surface roughness.

**Table 4.** Analysis of variance for surface roughness.

| Predictor | Coef. | SE Coef. | T | P |
|---|---|---|---|---|
| Constant | 0.2610 | 0.2069 | 1.26 | 0.263 |
| Cutting speed (m/min) | 0.0007555 | 0.0009048 | 0.83 | 0.442 |
| Feed (mm/rev) | 5.5576 | 0.8026 | 6.92 | 0.001 |
| Depth of cut (mm) | −2.0734 | 0.7238 | −2.86 | 0.035 |

S = 0.0443257, R-Sq = 91.9%, R-Sq(adj) = 87.1%.

**Table 5.** Analysis of variance.

| Source | DoF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 3 | 0.111695 | 0.037232 | 18.95 | 0.004 |
| Residual Error | 5 | 0.009824 | 0.001965 | | |
| Total | 8 | 0.121519 | | | |

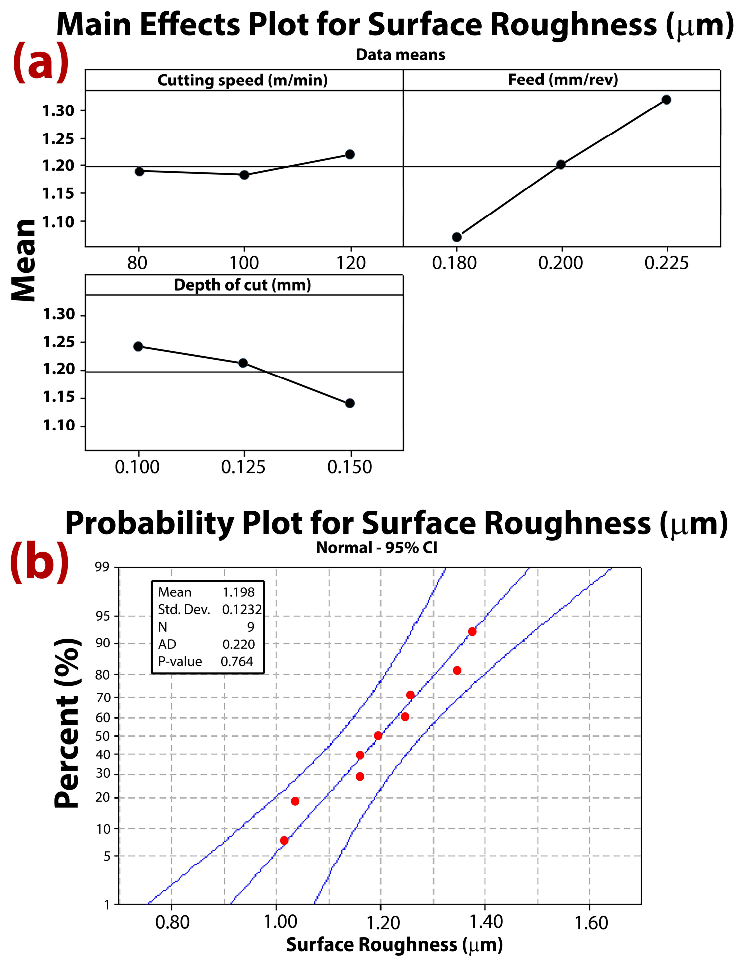


**Figure 5.** (**a**) Main effect plot for surface roughness, in µm (**b**) probability plot for surface roughness, in percentage.

### *3.4. S/N Ratio Analysis for Tool Wear*

To determine tool wear values, the Taguchi design method was employed. As indicated in Figure 6 and Table 6, the first level of the A factor (cutting speed), the first level of the B factor (feed rate), and the third level of the C factor (depth of cut) are higher. The best cutting conditions for the experiments to be conducted are (1 1 3) 80 m/min for cutting speed, 0.18 mm/rev for feed rate, and 0.150 mm for depth of cut.

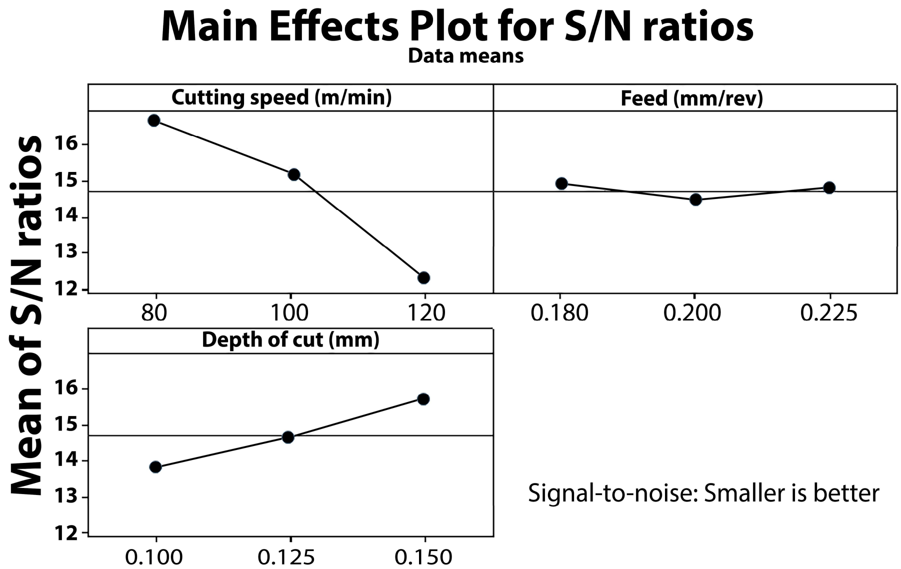


**Figure 6.** The mean of S/N ratios versus factor levels tool wear.

**Table 6.** S/N response table for tool wear factor.

| Level | Cutting Speed (m/min) | Feed (mm/rev) | Depth of Cut (mm) |
|---|---|---|---|
| 1 | 16.69 | 14.87 | 13.80 |
| 2 | 15.27 | 14.51 | 14.67 |
| 3 | 12.22 | 14.79 | 15.70 |
| Delta | 4.47 | 0.36 | 1.90 |
| Rank | 1 | 3 | 2 |

*3.5. Regression Analysis for Tool Wear*

The regression equation employed for tool wear is presented as Equation (2). This equation can be used to predict the amount of tool wear under the selected machining environment.

$$Toolwear = 0.0792 + 0.0025Cuttingspeed - 0.158Feed - 0.867Depthofcut \quad (2)$$

The analysis of variance for tool wear is presented in Tables 7 and 8. The value of predicted-$R^2$ is 90.9%, and the value of adjusted-$R^2$ is 85.4%. The difference in these values is very low, indicating that this optimization model accurately predicts surface roughness. As presented in Figure 7a, tool wear is significantly affected by an increase in cutting speed from 80 to 120 m/min. The increase in tool wear at higher speeds is attributed to the generation of a higher amount of heat in the cutting zone, resulting in rapid wear at the cutting edge of the tool. The residual plot is close to the standard residual line (Figure 6b), which shows the effect of machining parameters on tool wear under the MQCL environment. As can be seen from Figure 7b, the residuals are normally distributed over the mean line, which presents the significance of the proposed model for predicting tool wear. The continuous supply of lubricant in mist form to the cutting zone helps in retaining the fluid for a longer time by creating a thin layer of lubricant, which provides effective lubrication and prevents the rubbing action of a tool against a workpiece. Furthermore, the pressurized air supply carried away the heat produced and prevented the early wear of the tool, helping in minimizing the tool wear.

**Table 7.** Analysis of variance for tool wear.

| Predictor | Coef. | SE Coef. | T | P |
|---|---|---|---|---|
| Constant | 0.07918 | 0.08844 | 0.90 | 0.412 |
| Cutting speed (m/min) | 0.0025000 | 0.0003868 | 6.46 | 0.001 |
| Feed (mm/rev) | −0.1585 | 0.3431 | −0.46 | 0.664 |
| Depth of cut (mm) | −0.8667 | 0.3095 | −2.80 | 0.038 |

S = 0.0189506, R-Sq = 90.9%, R-Sq(adj) = 85.4%.

**Table 8.** Analysis of variance.

| Source | DoF | SS | MS | F | P |
|---|---|---|---|---|---|
| Regression | 3 | 0.0178933 | 0.0059644 | 16.61 | 0.005 |
| Residual Error | 5 | 0.0017956 | 0.0003591 | | |
| Total | 8 | 0.0196889 | | | |

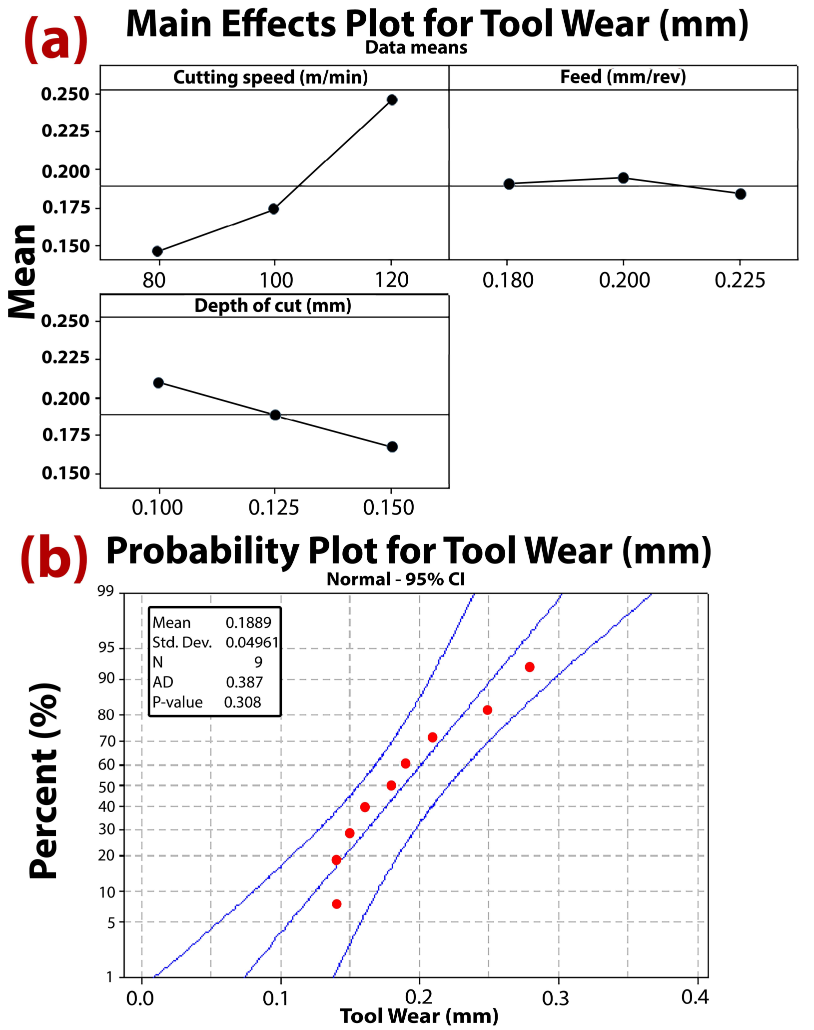


**Figure 7.** (**a**) Main effect plot for tool wear in mm. (**b**) Probability plot for tool wear in percentage.

### *3.6. Confirmation Tests*

The models for surface roughness and tool wear should be confirmed through experimentation. Four confirmation experiments were done for selected cutting environments—and the responses are measured as indicated in Table 9 to evaluate the suitability of the model. The two test conditions for confirmation experiments are among the experimental settings that are part of the design of the experiment for each cutting environment. The remaining two sets of parameters are selected within the range of selected parameters.

**Table 9.** Results of confirmation experiments under MQCL.

| | Cutting Speed (m/min) | Feed (mm/rev) | Depth of Cut (mm) | Surface Roughness (µm) | | Tool Wear (mm) | |
|---|---|---|---|---|---|---|---|
| | | | | Exp. | Pred. | Exp. | Pred. |
| 1 | 120 | 0.200 | 0.125 | 1.25633 | 1.20485 | 0.25 | 0.23 |
| 2 | 80 | 0.225 | 0.100 | 1.37467 | 1.36540 | 0.16 | 0.15 |
| 3 | 90 | 0.190 | 0.130 | 1.32120 | 1.11625 | 0.17 | 0.16 |
| 4 | 110 | 0.195 | 0.140 | 1.17210 | 1.15915 | 0.22 | 0.20 |

The results of the confirmation trials indicate that Equations (1) and (2) can be used to predict the surface roughness and tool wear value under chosen machining environments because the measured error between the predicted value and the experimental test is within acceptable ranges.

### 3.7. Efficiency of Vegetable-Based Lubricant MQCL

As understood from the available literature, using traditional cutting fluid raises safety and environmental issues. Considering this, the study explored the application of vegetable oil-based MQCL with the aim of improving machining performance. The lubricant mixture is applied along with compressed air, leaving the nozzle in mist form and directed to the cutting zone. A thin hydrostatic tribo-film is believed to form on the surfaces with the application of MQCL and is retained there by the continual delivery of lubricant mixture in mist form through MQL [30,39]. Thus, the layer of long-chain fatty acid-rich sunflower oil assisted in retaining fluid in the machining interfaces for an extended time. Further, it helps in the reduction of friction in machining interfaces. Additionally, using compressed air contributes to effective cooling by removing the heat produced in the cutting zone.

Figure 8 demonstrates how employing cutting fluids with a vegetable oil-based coolant can reduce surface roughness and tool wear while providing only a small amount of lubrication. These fluids are free from mineral oil and chlorine. Because of the polar nature of the molecules, it is a very active lubricant. The fatty acid content in cutting fluid for vegetable bases causes a noticeable improvement in friction. The viscosity of this fluid also creates flow resistance, which results in more effective lubrication at the tool-chip interface and less friction between the cutting tool and the workpiece [42].

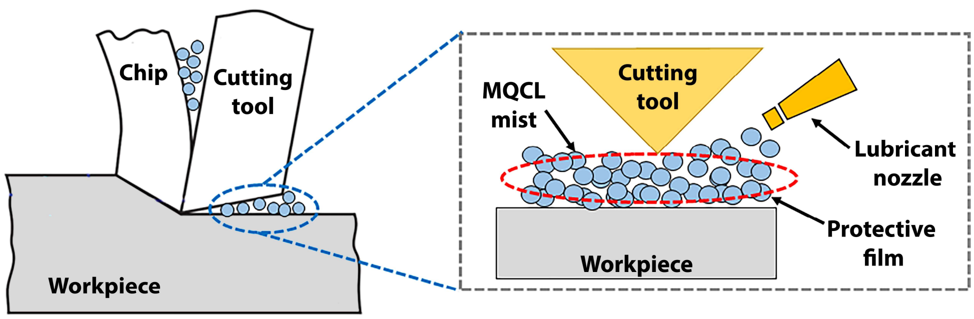


**Figure 8.** Fluid delivery and effect of vegetable-based MQCL.

There are further advantages in the form of improved cooling and lubrication with MQCL-assisted machining over flood cooling. This can be used to correlate tribological effects at the tool-chip interfaces (i.e., secondary and third deformation zones). Additionally, the mechanical behavior of the work material is a concern of this effect. The principal deformation zone is most affected by this behavior. The friction coefficient is lowered by using vegetable oil when turning C45. Certainly, the cooling of the cutting tool is influenced by the heat transfer coefficient. This is further correlated with the amount of tool wear resulting. Furthermore, there is a significant temperature difference between the heated cutting tool and the sunflower oil. This significantly impacts the heat transfer ability of sunflower oil and workpiece material. Therefore, when compared to traditional cutting fluids, the use of biodegradable vegetable oil-based MQCL can be a useful substitute for improved machining performance.

## 4. Conclusions

Under vegetable-based lubricant MQL machining (turning) of C45 steel, surface roughness, and tool wear experiments were carried out by changing the cutting parameters (cutting speed, feed rate, and depth of cut). Using Taguchi's experimental design, the output parameters (surface roughness and tool wear) were optimized. The main outcomes are:

1. Three distinct levels of cutting speed, feed rate, and depth of cut were used to build the $L_9$ orthogonal array. Results of studies corresponding to the $L_9$ orthogonal array were obtained for surface roughness, and tool wear S/N ratios. The highest S/N ratio value was chosen, which produced the ideal cutting settings;
2. The optimum cutting condition yielded a maximum S/N ratio of −0.11219 for surface roughness. The cutting parameters were 100 m/min for cutting speed, 0.180 mm/rev for the feed rate, and 0.150 mm for depth of cut (2-1-3 orthogonal array). Optimum cutting conditions for tool wear corresponding to a maximum 17.0774 S/N value were 80 m/min for cutting speed, 0.180 mm/rev for feed rate, and 0.125 mm for depth of cut (1-1-2 orthogonal array);
3. The effects of cutting parameters related to Ra and tool wear were also examined using the model summary. The results showed that cutting speed, feed rate, and depth of cut varied surface roughness by 1.9%, 78.3%, and 14.04%. For tool wear, the cutting speed, feed rate, and depth of cut have effects of 43.8%, 37.9%, and 6.3%, respectively;
4. The probability plots and main effect plots demonstrated the considerable impact of chosen machining parameters on tool wear and surface roughness in the MQCL environment;
5. Vegetable oil contains a significant number of nonpolar methyl groups in its fatty acid chain. Thus, between the molecules, a dispersion force exists. As a result, two molecules are drawn to one another. Vegetable oil droplets often have a high viscosity at higher cutting temperatures and remain in the cutting zone for a longer period, enabling a superior lubrication effect during machining. Considering the biodegradable nature of vegetable oil, the application of vegetable oil-based MQL can be considered a feasible alternative for improving machinability without affecting environmental resources.

## 5. Future Scope of Work

The work investigated the efficacy of vegetable oil-based MQCL during machining C45 steel. Future work in this direction can be focused on the characterization of the lubricant mixture and the life cycle analysis of the proposed approach. Further, the effectiveness of combined MQL and cryogenic cooling can be assessed along with sustainability analysis for different materials.

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