Optimization of Cutting Parameters using the RSM-Desirability Approach in the MQL-Assisted Turning of AISI 4130

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ABSTRACT: In this study, the main task is to identify the best cutting parameters to improve the machining performance during MQL-turning with various cutting fluids like coconut oil, ground nut oil, sunflower oil, soyabean oil, and blassocut oil. Cutting temperature and surface roughness were used as performance metrics, with the goal of minimizing these responses. To construct an experimental plan for turning AISI4130 with uncoated brazed carbide, full factorial design for three levels and three factors (3^3) design of experiments was used. The optimal cutting parameter was identified using the response surface approach. Aiming to discover the optimum possible cutting settings, the desirability function method was utilized. It was discovered that the best cutting speed, depth of cut, and feed rate for minimizing the temperature and surface roughness are 72.38 m/min, 0.5 mm, and 0.35 mm/rev respectively. According to the ANOVA findings, the feed and depth of cut have a substantial impact on the tool temperature for MQL-soyabean oil.

KEYWORDS: Optimization, Desirability, Vegetable oil, Minimum quantity lubrication, Temperature, Surface roughness

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NOMENCLATURE

MQL	Minimum Quantity Lubrication
v	Cutting speed
dp	Depth of cut
f	feed
Ra	Surface roughness

I. INTRODUCTION

Increased machining productivity and efficiency are critical for technological growth. This ensures a high rate of material removal and extended tool life. However, high material removal rates are associated with significant heat generation and elevated temperatures. This temperature increase degrades the tool's performance and reduces its lifespan. The expense of replacing and maintaining cutting tools is significant (Ghuge and Mahalle, 2018).

Cutting fluids are used to alleviate the negative effects of temperature and friction. Mineral-based cutting fluids are employed in the majority of industries. A cutting fluid's principal roles are cooling and lubrication. By absorbing heat from the workpiece, chip, and tool, the coolant reduces heat from the cutting zone. Reduced temperature results in decreased thermal distortion, extended tool life and improved dimensional accuracy. Cutting fluids reduce friction by lubricating the interface between the tool's cutting edge and the chip (Iowa Waste reduction Centre, 2003), (Bankar, Shelke and Irfan, 2019**).**

Due of the cutting fluid's inability to reach the contact, its impact of cutting fluid is limited at high speeds. The cost and hazardous impact on human beings are the main limitations. The cost of cutting fluid has major share in the entire production cost (Khanna *et al*, 2022).

Cutting fluids are extensively utilized in production units. It is necessary to dispose of around 60%-70 % of the used cutting fluid. From an environmental perspective, cutting fluid waste management is a dominant issue. Mineral oils are a nonrenewable energy source that emits greenhouse gases which contribute to global warming. The ecological system's equilibrium has been disturbed by petroleum oil-based lubricating oil. The waste cutting fluid recycling cost is expensive since it necessitates a separate setup and maintenance (Krolczyk *et al*, 2019). The operator's health is the key concern. Cutting fluids could potentially expose millions of operators to adverse toxic implications. The operator could get skin or respiratory problems, which could lead to cancer (Ni *et al*, 2020).

Nowadays, any rising ecological issue is viewed as a severe threat to society's survival. One of the primary sources of environmental pollution is the industrial sector. It is critical for every organization to comply with ISO 9000, ISO-14000 standards, and the occupational health and safety assessment series. Ecological degradation is increasingly being considered on a global scale, and each country is required to keep pollution levels below a specific threshold. The pollution control board,

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occupational safety and health organization, environmental protection agency are some of the regulatory authorities that determine the limit for metalworking fluid exposure levels. In order to dispose of hazardous and toxic product wastes, several developed countries have established strict environmental protection requirements (Costello *et al*, 2020).

Mineral-based cutting fluids are being phased out due to poor surface quality, operator health, environmental concerns, and government regulations. Due to the absence of cutting fluid, dry cutting drew a lot of attention at first. Dry cutting is ineffective when it comes to improving machining performance, improving surface properties, or dealing with extreme cutting conditions. Increased wear rate, as well as high temperatures, are important concerns. As a result, dry cutting has not been proven to be a superior option to flood cutting. Due to environmental and budgetary concerns, manufacturers are seeking new ways to cut down the quantity of cutting fluids used in machining. Dry machining and flood cutting are being replaced with near-dry machining, micro lubrication, or minimum quantity lubrication (Goindi and Sarkar, 2017).

When compared to standard flood lubrication (1-10 liters per min), minimal quantity lubrication uses less cutting fluid (50-500 ml/h). This lubrication method atomizes fluid droplets using high-pressure air. Consequently, temperature and frictional forces are decreased. Reducing the amount of cutting fluid saves money. It also minimizes the length of time the operator is required to engage with the cutting fluid (Sultana *et al*, 2019). However, because of the health dangers and environmental concerns, stringent regulation has been enacted to restrict the use of mineral oil based cutting fluids. The elimination of chemical-based cutting fluids is a current priority. Cultivating and biologically modifiable nature of vegetable oils makes them regenerative and biodegradable. The vegetable oil's triglyceride structure provides desirable boundary lubrication and high viscosity (Wickramasinghe *et al*, 2019). Vegetable oil molecules form a strong, uniform coating. The high boiling point and molecular weight of vegetable oil significantly reduces the evaporation loss. As a result, vegetable oils have emerged as a feasible alternative to petroleum-based cutting fluids (Shaikh *et al*, 2020).

In machining, manufacturers strive for a low cost of production or a high rate of production. These two metrics are linked to cutting variables like speed, feed, and cut depth. To achieve the intended result, proper input parameter selection is required. Experimenting and determining the best values based on the results takes a lot of talent, effort, and money. For experimental analysis and prediction, various statistical analysis software like response surface methods, taguchi analysis and artificial neural networks are used (Montgomery, 2017).

According to the literature, mineral-based cutting fluids must be replaced because they are expensive and hazardous to the operator. Vegetable based oil is supposed to be the best alternative to the mineral based cutting fluid. Temperature and surface roughness are the important factors which mostly affect the efficacy of the machining process. It is also observed that machining with an optimum cutting parameter gives the best performance.

This research deals with the performance evaluation of the various vegetable oils based on temperature and surface roughness. Coconut oil, sunflower oil, groundnut oil and soyabean oil are inexpensive and widely available, hence considered as a cutting fluid. A low cost MQL system is used for experimentation. RSM-desirability approach is used for optimizing the parameters for the best performing cutting fluid.

II. METHODOLOGY

Based on prior research, it was decided to analyze minimum quantity lubrication to evaluate cutting fluid performance. Experiments were conducted using a 60 mm diameter and 120 mm long AISI 4130 steel bar. An uncoated brazed carbide tool was used for turning purposes. The cutting tool was fixed on a dynamometer. Medium duty Lathe machine is used for experimentation. Speed, depth of cut, and feed were selected inline with industry practice**,** lathe machine capacity and constraints. During the experiment, tool height and tool geometry were kept constant.

The cutting speed was calculated from the workpiece diameter and the machine spindle speed. The feed rate was increased from 0.35 to 0.45 mm/rev. The depth of cut varied from 0.5 mm to 1.5 mm. The practice of delivering very small quantities (50-500 ml/hr) of cutting fluid blended with air at the point of exact contact between both the tool and the workpiece is termed minimum quantity lubrication (MQL). A simple MQL setup is constructed for this investigation. Relative to other MQL units on the market, the setup cost is quite reasonable, not exceeding 15000 rupees. Figure 1 (a) shows the experimental setup, which includes a medium-duty lathe machine and the MQL system while Figure 1(b) shows cutting tool and workpiece. The MQL System includes components such as a compressor, nozzle, oil storage, air filter, airflow valve, siphon tube, and air pressure valve. The oil tank is the oil reservoir with a refilling plug capacity of 5 liters. A nozzle is a varied cross-sectional area tube that can be used to direct the flow of a fluid. It is used to regulate the flow rate, velocity, direction, and pressure of the stream that emerges from it. The coolant is sprayed through the nozzle at the application. The air compressor is used to compress the air, and compressed air can be supplied to the pipe at the required pressure.

The MQL system works on the siphonage principle. Compressed air and oil are mixed, and a high jet of oil is sprayed through a nozzle. Highly compressed air with a typical air pressure of two bar is supplied to the air filter. The air filter removes any impurity or contamination to keep the equipment clean and dirt free. A high-velocity jet passes through the spray unit. Oil in the reservoir is sucked up due to the pressure difference and mixed with the air. The high-velocity air pushes the oil breaking it into small droplets. The oil then passes through the nozzle to form a spray of oil.

In Maharashtra (India), soyabean, groundnut, and sunflower are cultivated on large scale; hence, oils from these seeds can be easily available. Blassocut is a petroleum-based high-performance cutting fluid that is highly soluble in water and shows good properties and performance.

Figure 1(a): Experimental Setup.

Figure 1 (b): Cutting tool with work piece.

To assess the performance of the vegetable oil variables like surface roughness and temperature are measured. The surface roughness (Ra) was determined using a portable TR110 surface roughness tester. Temperature is measured by using a non-contact type infrared thermometer. Kusum-Meco make IRL-550 infrared thermometer used for the measurement of temperature.

III. DESIGN OF EXPERIMENTS

In the present work, Minitab-17 is used to plan the design of experiments. Full Factorial design for three levels and three factors (3^3) with single replication is used as shown in Table 1. For each cutting fluid; twenty-seven trials were performed.

Table 2 demonstrates the design matrix and the combination of the independent variables as per full factorial design. A, B, C signifies the cutting parameters. These are represented as v, f and dp respectively. The run order shows the sequence of the experiment. The standard order, run order, center point indicator, block assignment are all located in columns in Minitab. Each row in the worksheet contains data that corresponds to one run of the experiment (Minitab Manual, 2020).

Table 1: Machining parameters and their levels.

Level	V, Speed (m/min)	f, Feed (mm/rev)	d, Depth of cut (mm)
1	34.27	0.30	0.50
2	53.00	0.35	1.00
3	79.73	0.40	1.50

IV. OPTIMIZATION OF MACHINING PARAMETERS

The choice of optimal machining parameters for each machining operation is a significant step in ensuring product quality, lowering machining costs, and increasing production rate. Cutting conditions established by manufacturers are sometimes too far from ideal. Therefore, different mathematical techniques are used for obtaining optimized parameters in machining (Abas *et al*, 2020).

The Composite desirability D is calculated using individual desirability. The geometric mean of individual desirability gives composite desirability.

The composite desirability is given by,

$$D = (d1\ (y1) * d2\ (y2) * d3\ (y3) * \ldots * dk\ (yk))\ \hat{}\ (1/k) \quad (1)$$

where, k is the total number of responses.

Table 2: Design Matrix and Observation Results (Soyabean oil).

Std Order	Run Order	Blocks	A	B	C	V (m/min)	f (mm/rev)	dp (mm)	Ra µm	T °C
1	1	1	1	1	1	34.27	0.35	0.50	1.98	63.00
2	2	1	1	1	2	34.27	0.35	1.00	2.11	74.30
3	3	1	1	1	3	34.27	0.35	1.50	2.47	82.40
4	4	1	1	2	1	34.27	0.40	0.50	2.67	72.90
5	5	1	1	2	2	34.27	0.40	1.00	2.81	84.60
6	6	1	1	2	3	34.27	0.40	1.50	2.97	97.00
7	7	1	1	3	1	34.27	0.45	0.50	3.01	82.40
8	8	1	1	3	2	34.27	0.45	1.00	3.12	95.00
9	9	1	1	3	3	34.27	0.45	1.50	3.21	102.00
10	10	1	2	1	1	53.00	0.35	0.50	1.54	52.80
11	11	1	2	1	2	53.00	0.35	1.00	1.61	66.80
12	12	1	2	1	3	53.00	0.35	1.50	1.71	80.20
13	13	1	2	2	1	53.00	0.40	0.50	1.88	67.10
14	14	1	2	2	2	53.00	0.40	1.00	1.96	82.40
15	15	1	2	2	3	53,00	0.40	1.50	2.01	83.70
16	16	1	2	3	1	53.00	0.45	0.50	2.11	86.40
17	17	1	2	3	2	53.00	0.45	1.00	2.29	84.20
18	18	1	2	3	3	53.00	0.45	1.50	2.48	100.00
19	19	1	3	1	1	79.73	0.35	0.50	1.46	52.60
20	20	1	3	1	2	79.73	0.35	1.00	1.58	74.40
21	21	1	3	1	3	79.73	0.35	1.50	1.69	80.40
22	22	1	3	2	1	79.73	0.40	0.50	1.78	64.20
23	23	1	3	2	2	79.73	0.40	1.00	1.93	79.70
24	24	1	3	2	3	79.73	0.40	1.50	2.04	98.60
25	25	1	3	3	1	79.73	0.45	0.50	2.19	66.40
26	26	1	3	3	2	79.73	0.45	1.00	2.31	82.40
27	27	1	3	3	3	79.73	0.45	1.50	2.40	102.00

Often, machining parameters are optimized by considering a single objective function, such as surface finish, tool-work temperature, cutting force, tool wear, and tool life. Response surface optimizer is used to optimize multi-objective responses. In this study, optimization is carried out to minimize surface roughness, and temperature. Desirability evaluates optimization feasibility. When desirability nears 1, optimization is realistic and practical. Individual desirability (d) evaluates one response. Composite desirability (D) analyzes multiple responses simultaneously. Desirability is measured on a scale of zero to one.

First step in determining desirability is to transform each response yi into a unique desire function di. The desirability function varies from 0 to 1. If the response achieves the target value, di equals 1, but if it exceeds the permissible limit, di equals 0. The second phase is to choose the input parameter combination that maximizes overall appeal. The overall desirability is zero if any reaction is completely unacceptable (D=0). If desirability is higher than 0.9, the parameter combinations are deemed to be the best for achieving maximum performance (Minitab, 2020).

V. RESULTS AND DISCUSSION

Multivariate radar charts are used to represent the variation of responses as shown in Figures 2 and 3. Points 1–27 in the Figure represent the number of experiments observed.

A. *Temperature Variation*

During machining, heat is produced due to shear and plastic distortion at the primary deformation zone. Heat is generated at the tool chip contact due to secondary deformation. Figure 2 shows that if the depth of cut and feed rate increase, the temperature goes up. Due to friction between the tool and the job, the temperature is raised. Lubricant particles are transformed into a vaporised phase in MQL.

The smaller the individual particle size, the greater the surface area, which leads to improved evaporative heat transfer and lower cutting temperature for a given volume. When compared to soyabean oil, Blassocut showed about 7% higher temperature. In comparison to other oils, soyabean oil has the lowest temperature (52.6°C). Soybean oil is 7% cooler than sunflower oil. Soybean oil (220) and sunflower oil (218) have a higher viscosity index than oil derived from minerals (100-150). High viscosity index is a sign of superior performance at elevated temperatures (Fasina. *et al*, 2008). Vegetable oil viscosity decreases more gradually than petroleum based oil, as the cutting temperature rises. Vegetable oil, on the other hand, remains more fluid when the temperature drops, allowing faster discharge of chips. Higher temperatures have little effect on the lubricity of soybean and other vegetable oils.

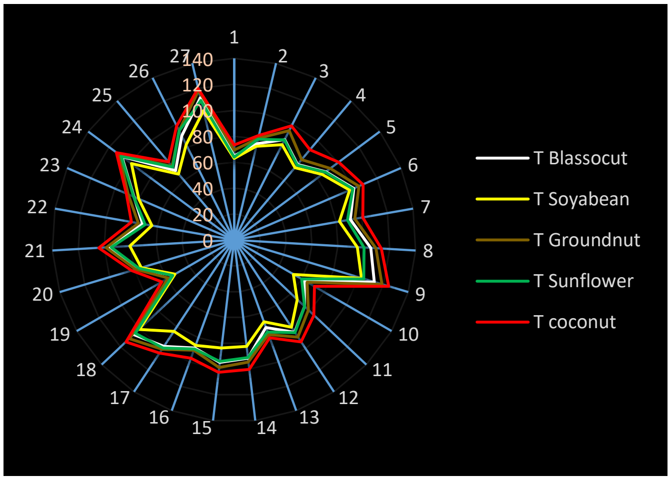

Figure 2: Variations of temperature for different cutting fluid.

A. Surface Roughness Variation.

Surface finish is an important part of machinability because it affects how well the product is made and how long it will last. When the MQL-vegetable system is utilized, the surface roughness is drastically lowered. The MQL - turning process with soyabean oil resulted in a 16 percent decline in roughness value in comparison to blassocut. This is owing to the fact that soyabean oil has lower cutting forces. The lubricating effect of soyabean oil's dipolar molecule lowers frictional force. The molecular weight of soybean oil is greater than that of mineral oil. It reduces the probability of cutting fluid evaporation. Reduced temperature is responsible for a reduction in tool wear. The surface quality of the work piece is improved due to a decrease in tool wear. When machining with soyabean oil, roughness values are reduced by 4%, 8%, and 15%, respectively, as compared to sunflower oil, groundnut oil, and coconut oil. Figure 3 shows that changing the speed from 53 m/min to 79.72 m/min results in a significant drop in roughness value. The chip-tool engagement duration decreases when cutting speed increases, leading to a decreased friction coefficient.

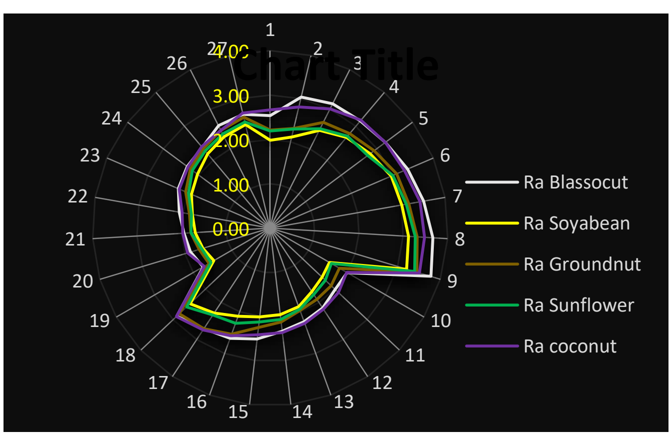

Figure 3: Variation of surface roughness at different cutting conditions.

B. Influence of Machining Parameters on Temperature (Soyabean Oil).

From experimentation, it is seen that soyabean oil gives good results as compared to other cutting fluids. ANOVA testing is used to determine the impact of input parameters on output parameters. The ANOVA Table 3 gives the contribution percentage (C %) of each term. The contribution will assist in determining the most crucial component. Surface graphs are plotted to decide the significant parameters. 3-D surface plots can be used to estimate the performance parameter at any fitting combination of the input parameters.

The temperature of the tool for MQL-soyabean oil is significantly influenced by the depth of cut and feed. Speed has an insignificant effect on the temperature. The increase in feed increases the temperature. Figure 4 illustrates how the temperature rises significantly as the depth of cut increases. Temperature can reach up to 100ºC at a maximum depth of cut (1.5mm) and feed value (0.45 mm/rev).

Table 3: F-Value and % contribution for MQL-Soyabean oil.

Factor	Temperature		Surface Roughness	
	F	% C	F	% C
Model	28.18	--	99.91	--
V	8.26	3.23	370.6	39.67
f	88.76	34.67	363.6	38.92
dp	146.8	57.37	41.55	4.45
v*v	3.19	1.25	152.2	16.29
f*f	1	0.39	1.75	0.19
dp*dp	0.15	0.06	0.07	0.01
v*f	1.52	0.59	3.51	0.38
v*dp	6.15	2.40	0.82	0.09
f*dp	0.1	0.04	0.14	0.01

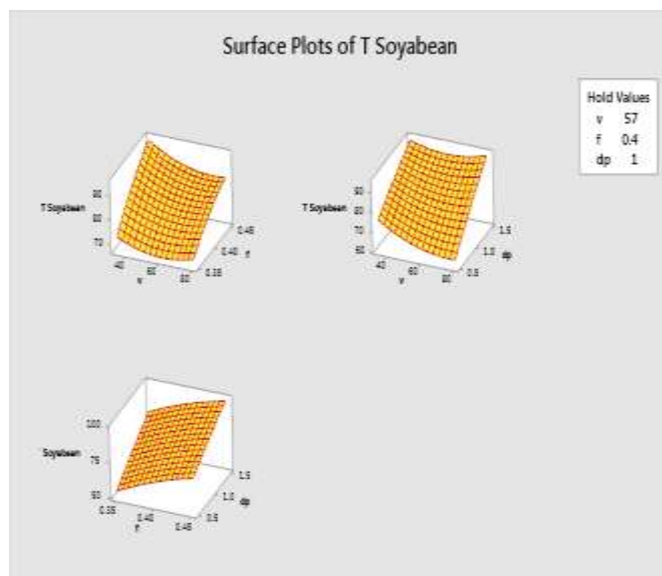

Figure 4: Surface plots of temperature for soyabean oil.

D. Influence of Machining Parameters on Surface Roughness (Soyabean Oil.)

Surface roughness is affected equally by cutting speed and feed. The surface roughness is less affected by the depth of cut. At lower feed rates and faster speeds, an excellent surface superiority is obtained. Figure 5 shows how surface roughness reduces as speed rises. Increasing the feed rate also enhances the surface's roughness. It also shows that cutting speed is more sensitive than the other parameters. The variation of cutting speed causes more changes in surface roughness. Surface roughness is lowest when cutting speed and depth of cut are both high, and feed rate is low.

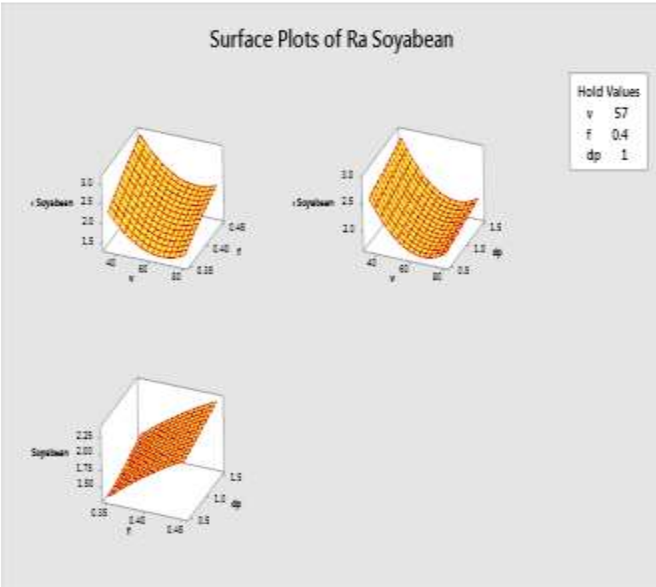

Figure 5: Surface plots of surface roughness for soyabean oil.

E. Optimization

RSM optimization results for temperature and surface roughness are revealed in Table 3. All the values of desirability are approaching one, which indicates that the optimization process is feasible. The optimum cutting speed is between 50 m/min-60 m/min. The depth of cut and feed are 0.5 mm and 0.35 mm/rev respectively. Figure 6 shows the optimum plot for soyabean oil.

Table 3: Optimum cutting conditions and desirability.

Cutting parameter/oil	V	f	dp	Ra	T	Desirability
	m/min	mm/rev	mm	µm	° C	
Blaso Cut	58.6	0.35	0.5	1.74	59.1	0.9114
Soyabean	50.8	0.35	0.5	1.456	55.8	0.9200
Sunflower	52.17	0.35	0.5	1.64	60.3	0.9146
Coconut	59.98	0.35	0.5	1.78	67.7	0.9013
Groundnut	55.85	0.35	0.5	1.61	63.1	0.9090

The influence of each element (columns) on the performance parameter and composite desirability is shown in Figure 6. The ideal factor settings are represented by the vertical red lines on the graph. The best factor values are shown by the red numbers at the top of each column. The dashed blue lines and numbers reflect the level of responses. It depicts how the required reaction changes as cutting speed, feed, and cut depth increase. The best setting is determined by the values that maximize desirability. For soyabean oil, the optimum conditions for maximum performance are 50.08 m/min, 0.35 mm/rev and 0.5 mm. The desirability value in all the cases is approaching 100. This indicates the success or feasibility of the optimization process.

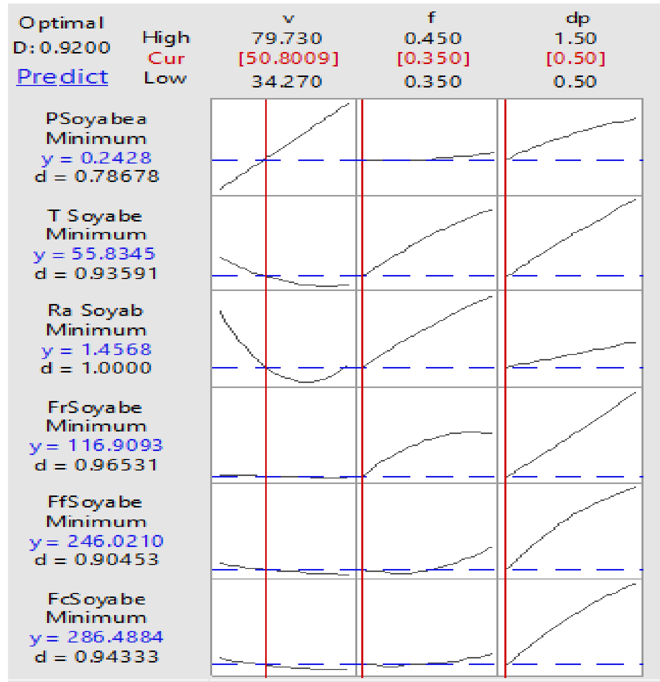

Figure 6: Optimum plot for soyabean oil.

F. Confirmation of Experiment to Validate Optimized Parameter

In order to validate the results obtained from the response optimizer, a confirmation experiment was conducted at the optimal process parameter. The percentage error was calculated after comparing the projected and experimental findings. The results of the confirmation experiments at different cutting conditions for various cutting fluids are shown in Table 4 and Table 5.

Tables 4 and 5 show that experimental values of temperature and surface roughness are higher than the predicted values. This is due to the various uncertainties during experimental operation. It is observed that the average error is 3.97%, and 3.96% for temperature and surface roughness respectively for various cutting fluids. It can be concluded that experimental results and optimum values are in good agreement. The error percentage is within the range of 5% so the response equation for the performance parameter evolved through RSM can be used effectively to predict the performance. The optimum conditions that are determined for minimizing the temperature and surface roughness are precise and true.

Table 4: Temperature- comparison of predicted and experimental results.

Cutting parameter/ condition	Speed (m/min)	dp (mm)	Feed (mm/rev)	Expt.T	Pred.T	%Error
Blaso Cut	58.6	0.35	0.5	61.2	59.1	3.431
Soyabean Oil	50.8	0.35	0.5	53.74	55.8	3.833
Sunflower Oil	52.17	0.35	0.5	63.4	60.3	4.889
Coconut Oil	59.98	0.35	0.5	69.4	67.7	2.449
Groundnut Oil	55.85	0.35	0.5	66.4	63.1	4.969

Table 5: Surface Roughness - comparison of predicted and experimental results.

Cutting parameter/ condition	Speed (m/min)	dp (mm)	Feed (mm/rev)	Expt.Ra (µm)	Pred.Ra (µm)	%Error
Blaso Cut	58.6	0.35	0.5	1.78	1.74	2.247
Soyabean Oil	50.8	0.35	0.5	1.51	1.456	3.576
Sunflower Oil	52.17	0.35	0.5	1.72	1.64	4.651
Coconut Oil	59.98	0.35	0.5	1.84	1.78	3.260
Groundnut Oil	55.85	0.35	0.5	1.87	1.82	2.637

V. CONCLUSION

The cooling as well as lubricating properties of vegetable oil offers a competitive performance in comparison with conventional mineral-based oil. The most outstanding performance was observed in the case of soybean oil, among the other vegetable oils. The higher molecular weight of the soyabean oil results in very less evaporation loss of the sample. Soybean oil has the highest number of unsaturated fatty acid esters of any vegetable oil, resulting in greater lubrication and performance.

Soybean oil has a temperature reduction of about 3%, 7%, 12%, and 16%, when compared to blassocut, sunflower oil, groundnut oil, and coconut oil respectively. In comparison to sunflower oil, groundnut oil, blassocut, and coconut oil, the surface roughness values are reduced by 4%, 8%, 15%, and 16%, respectively, when soybean oil is used as a cutting fluid.

The multi-responses in machining were optimized using the RSM-based desirability technique. Obtained optimum value of the depth of cut is 0.5 mm, the feed rate is 0.35 mm /rev, speed value is in between 50-60 m/min, which gives minimum temperature, and minimum surface roughness. Desirability analysis indicates that the optimization process is feasible. A Confirmation experiment was performed to verify the predicated results. The optimum conditions that are determined for minimizing the temperature and surface roughness are precise and true.

AUTHOR CONTRIBUTIONS

N. C. Ghuge: Study conception and design, Experimentation, data collection, Manuscript Preparation. **D. D. Palande**: Analysis and Interpretation of Results. **P. B. Belkhode**: Manuscript Preparation

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