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PERFORMANCE STUDY ON SOME SELECTED VEGETABLE OILS USED AS CUTTING FLUIDS IN THE DRILLING OPERATION OF MILD STEEL MATERIAL

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ABSTRACT

The negative impacts of conventional cutting fluids on the manufacturing cost, human health and environment have necessitated its replacement with vegetable oil coolants. This study was centered on determining the optimal vegetable oil cutting fluid from among the considered oils: Castor oil, Neem oil and Gmelina oil that would produce the best surface finish or low surface roughness value for mild steel material. The three oils were extracted from their various seeds using pressing and solvent extraction methods. A minimum quantity lubrication (MQL) system was set-up and was used to regulate the flow of the cutting fluid on the tool-workpiece interface. A vertical drilling machine with a 20mm drill bit attached to it, was used to drill a through hole on the mild steel material with the MQL system being used to supply cutting fluids to the drilling interface of tool-workpiece. The experimental design that was done with Minitab software 21.0 using spindle speed and feed rate as independent variables and surface roughness as response variable was meticulously adhered to while performing the experiment. The values of the response variable at each design point were measured with a surface roughness testing device and noted. Statistical analysis was done in order to determine the individual and interactive effects of the independent factors on the response variable. Mathematical models were also developed for each of the cutting fluids being studied. The response was optimized using response surface methodology (RSM) tool in quest of getting an optimal coolant. From the results obtained, it was deduced that at high spindle speeds and low feed rates, small values of surface roughness will be obtained. Also, each of the independent factors all had an individual and interactive significant effects on the response variable. The type of vegetable oil applied to the drilling zone had the highest significant effect, followed by a two-factor interactive effect of feed rate-oil type and then spindle speed-oil type. The mathematical models that were developed, had a good coefficient of correlation (Castor oil, R= 0.986; Neem oil, R= 0.994; and Gmelina oil, R=1.0), therefore the models are suitable for response prediction at any considered factor levels. In addition, from the optimization outcome, Gmelina oil had the highest composite desirability value of 1.0 and a predicted surface roughness value of 1.3μm at a factor combination of: spindle speed- 290 rpm and feed rate- 0.08967mm/rev. Hence, Gmelina oil should be employed to the drilling zone of mild steel material if good surface integrity is desired.

KEYWORDS: Vegetable oils, Drilling, Mild steel, Optimization.

1 INTRODUCTION

Every machining operation is associated with heat dissipation action caused by frictional effect between the tool-workpiece interface. The generated heat during machining process affects the tool's life and also the surface finish of the workpiece. Machining process involves the application of power driven tools or machines to gradually remove materials from a workpiece for the purpose of achieving a specific dimension or geometric configuration of the workpiece. Such power-driven tools are: drilling machines, milling machines, shapers, grinders, lathe machines etc. The vast areas of application of these power-driven machines ranging from the industrial sector to small-scale utilization in machining operations necessitates an in-depth study of machining, the effect of the generated heat and the cutting fluid on both the tool and workpiece.

Cutting fluids are lubricants applied to the tool-workpiece interface to reduce frictional effect, absorb the generated heat and provide a good surface finish or quality to the workpiece. Cutting fluids are employed to also wash away the chips from the cutting zone. Lopez et al,[1] stated that three major effects produced by cutting fluids during machining operations were heat evacuation, lubrication on the chip-tool interface and removal of chips. Sokovic and Mijanovic,[2] explained that higher surface finish, quality and better dimensional accuracy are gotten through cutting fluid application. Cutting fluids are broadly classed as mineral oils and vegetable oils. The mineral oils pose serious effect to the environment and man; and based on the global requirement for cutting fluids satisfactorily hinged on factors of renewability, biodegradability, safety and health of man, vegetable oils are used as their substitute. Gawrilow,[3] stated that vegetable oils not only offer qualities of environmental safety, renewability, biodegradability etc., but also provide satisfactory performance in a wide array of applications.

The surface integrity of a machined surface is of immense importance since that is one of the major factors the applicability of a material in service operation is dependent on. Sultan et al (2013) defined surface integrity of a material as a set of superficial and in-depth properties of an engineering surface that affect its performance characteristics during service conditions. These properties include: surface finish, texture and profile, fatigue corrosion and wear resistance, adhesion and diffusion properties, etc.

Based on the application and preference of vegetable-based oils over the petroleum-based cutting oils, researches have been conducted in quest of determining the performance characteristics of some vegetable oils when used in machining operations. Kuram et al,[4] worked on the formulation of vegetable-based cutting fluids (VBCFs) and it application in machining operations. They carried out chemical and physical analyses on the formulated cutting fluids. Three of the vegetable oils were developed from crude and refined sunflower oils, and two commercial types, were investigated for thrust force and surface roughness during drilling of AISI 304 with HSS-E tool. They considered the spindle speed, feed rate and drilling depth as the machining parameters. L9 orthogonal array was used for the experimental design. The results they obtained were evaluated using regression analysis and analysis of variance-ANOVA. The analysis of the results showed that vegetable oils made from sunflower cutting fluid using two different surfactants gave smaller force and surface roughness values as compared with sunflower cutting fluid prepared using only one surfactant which might be related to difference in viscosity. The later gave lower surface roughness values. It was also deciphered that the feed rate had the highest physical as well as statistical influence on both thrust force and surface roughness from the ANOVA analysis performed.

Also, Charles et al,[5] evaluated the performance of two vegetable oils – castor and neem oil in comparison to the conventional or soluble oil and dry drilling operations using HSS drill bit as a cutting tool and mild steel material as the experimental workpiece. The response variable used in the study was surface finish while the independent variables employed were: feed rate, spindle speed and type of cutting fluid applied. Minimum quantity lubrication method (MQLS) was used for cutting fluid application at the tool-workpiece interface. The response was optimized using response surface methodology (RSM) tool in quest of finding a cutting fluid with the least surface roughness value. From the result obtained, castor oil at a spindle speed of 290 rpm and feed rate of 0.0985mm/rev. had the least surface roughness value of 1.57186μm and the highest composite desirability of 95.6% compared to other considered cutting fluids. In addition, Ezekeil and Aminu,[6] worked on the effects of neem oil as base in cutting fluid for machining operations in Adamawa State Polytechnic. They applied three different cutting fluids- neem seed oil, soluble oil and straight oil on mild steel-HSS cutting tool interface at varying spindle speed, feed rate and constant depth of cut. It was deduced that neem seed oil well reduced the machining temperature, had the best surface finish at a spindle speed of 540rpm and feed rate lower than 0.2mm/rev. than the other cutting fluids.

This present study was based on the performance study of some vegetable oils (castor oil, neem oil and gmelina oil) extracted from their various seeds and applied in drilling operation of mild steel material at varying spindle speeds and feed rates. These operational conditions-spindle speed and feed rate were used as independent factors while the surface finish of the material was the response variable. The quest was to output the best cutting fluid from the mentioned vegetable oils using response surface methodology (RSM) tool.

2. MATERIALS AND METHOD

2.1 Research Materials

The materials used in this study were: mild steel material, vegetable oils (castor oil, neem oil and gmelina oil) and some essential machines/tools.

2.1.1 Mild Steel Material

This material was locally sourced from the market in Warri, Delta State.

2.1.2 Equipment/Tools

The equipment/tools used in the experimental stage of this research work are as follows.

2.1.2a Vertical Drilling Machine

The vertical drilling machine of column type having a spindle speed of 80 to 1400 rpm and feed rate of 0.05 to 0.3mm/rev. was used in the drilling operation of the mild steel material. The drilling machine used in this study is shown in figure 1.

Figure 1: Vertical drilling machine used in the study.

2.1.2b Surface Roughness Tester

The surface roughness tester is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. The equipment was used to measure the degree of roughness/smoothness of the drilled mild steel surface.

2.1.2c High Speed Steel (HSS) Drill Tool

Drill bit of diameter 20mm and length 120mm were employed together with the vertical drilling machine to perform drilling operation on the test material- mild steel.

2.1.2d Minimum Quantity Lubrication System (MQLs)

For the purpose of regulating the lubricant or cutting fluid application to the drilling zone of the workpiece and drill bit tool interface, a minimum quantity lubrication system was set-up. The MQLs comprised of: the mixing chamber, nozzle, compressor and lubricating oil reservoir. For each cutting fluid being studied, it was mixed with air inside the mixing chamber. Two pipes convey the lubricant and the air to the mixing chamber from there, it was sent to the nozzle tip. A knob controls the flow of the lubricants-air mixture. Figure 2 shows the MQL system set-up and how it was employed in cutting fluid application at the workpiece-tool interface.

Figure 2: The minimum quantity lubrication system set-up and its application.

2.1.2e Vegetable Oil Cutting Fluids

The cutting fluids used in this study were castor oil, neem oil and gmelina oil. Castor seeds and gmelina seeds were obtained from Onitsha and Uli environs respectively all in Anambra State. Neem seeds were sourced from National Research Institute for Chemical Technology (NARICT) in Zaria. From the physiochemical analysis of Charles et al (2021) of castor and neem oils as shown in table 1, castor oil had better physiochemical properties than neem oil.

Table 1: Physiochemical characteristics of castor oil and neem oil (Sourced from Charles et al, 2021).

Parameters	Castor oil	Neem oil
Saponification value (mg/kg)	169.70	206.17
Acid value (mgKOOH/g)	9.554	4.215
FFA (mgKOH/g)	4.777	2.107
Peroxide value (mleq/kg)	12.2	23.0
Specific gravity	0.9784	0.9449
Density (g/ml)	0.9955	0.9614
Iodine value (g/100g)	121.82	100.25
Refractive index	1.4641	1.4571
Viscosity (Pa.s) @32^{o}	1.9449	0.7562

2.2 Research Method

The method employed in this study stemmed from the extraction of the vegetable oils (castor oil, neem oil and Gmelina oil) from their seeds, experimental design (DOE), description of the experimental procedures, experimental measurement of surface roughness/finish of the mild steel sample used, numerical optimization and comparative study of the performances of each cutting fluid applied. These methodical procedures followed in achieving accurate results from the study are elucidated in the following sections.

2.2.1 Extraction of the Cutting Fluids (Castor, Neem and Gmelina oils)

The extraction methods used in extracting the oils from their seeds was a combination of pressing and solvent extraction methods. According to Charles et al (2021), the seeds of castor oil contain about 30%-50% oil. The castor seeds were first allowed to dry very well such that the hull opened for the seeds to be obtained. The seeds were thoroughly cleaned to remove sands, dirt and other unwanted materials. The seeds were crushed using a hydraulic pressing machine and castor oil was extracted. The left-over castor cake was further pressed to extract some castor oil from that too. The same process was followed meticulously to extract neem oil and Gmelina oil from their seeds. The three extracted oils are shown in figure 3.

Figure 3: Extracted vegetable oils.

2.2.2 Design of Experiment (DOE)

Minitab software 21.0 was used to design an experimental procedure to be followed in determining the performance of the cutting fluids applied the drilling operation of mild steel material. The software tool is specialized for the purposes of statistical analysis, optimization and constructing response surfaces. The statistical analysis gives the applicable mathematical model in the optimization process, informs about the individual and interactive effect of the factors on the response variable(s), gives an insight into the correlation degree between the actual and predicted response values etc. The optimal (custom) design tool which is a flexible design structure that accommodates custom models, categoric factors, and irregular (constrained) regions was employed in designing the experiment. The input/independent factors used were: spindle speed, feed rate and cutting oil type. While the response variable was surface roughness/finish of the drilled mild steel material.

The mathematical inequalities that governed the experimental design using the independent factors were;

$0.05 \leq \text{feed rate (mm/rev)} \leq 0.25$

$75 \leq \text{spindle speed (rpm)} \leq 290$

2.2.3 Description of the Experimental Procedures

The mild steel sample was rigidly fixed on the drilling machine and the machine was powered to begin the drilling operation using a drill bit of 45mm diameter at a constant depth of cut. The extracted cutting fluid- castor oil was applied at the drilling zone of cutting tool-workpiece interface using the minimum quantity lubrication (MQL) system which regulated the amount of cutting fluid supplied to the drilling zone. The cutting fluid was supplied to the drilling zone till the material was drilled through. The surface roughness of the drilled material was measured and noted. This process was repeated at various spindle speeds, feed rates and vegetable oil types-castor oil, neem oil and Gmelina oil.

2.2.4 Measurement of Surface Roughness/Finish of the Drilled Material

The experimental design was followed conscientiously and at each factor combinatorial level, the response variable- surface roughness was measured using the TR 200 roughness testing machine.

2.2.5 Optimization Technique

The measured values of the response variable- surface roughness was noted at the corresponding factor level and the response was optimized using response surface methodology tool. The quest was to get the optimal cutting fluid with a minimal/lowest surface roughness value.

3 RESULTS AND DISCUSSION

3.1 Effect of Feed Rate and Cutting Fluid Type on Surface Roughness of Mild Steel Material

Figure 4 shows the effect of varying feed rates and three vegetable oil cutting fluids that were applied in the drilling operation of mild steel material on surface roughness of the test sample.

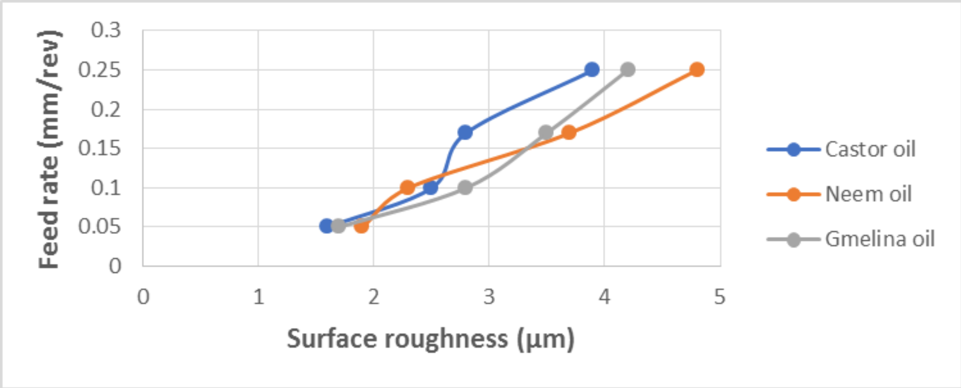

Figure 4: The effect of feed rate and cutting fluids on surface roughness of mild steel material.

From figure 4, it was observed that at a lower feed rate of 0.05mm/rev., castor oil had the lowest value of surface roughness, followed by Gmelina oil and then Neem oil. But as the feed rate applied in the drilling process was increased, the surface roughness values of the three vegetable oils started increasing too. Therefore, to achieve good surface finish of a machined workpiece, a low feed rate is required. Also, castor oil appeared to be the best since it gave the lowest value of surface roughness. Feed rate is the distance moved by the drill bit for each revolution of the spindle. The seen increasing values of surface roughness at an increasing feed rate for all the cutting fluids applied was caused by dimensional inhomogeneity associated with high feed rate machining operations.

In addition, the effect of spindle speed and cutting fluids on surface roughness of mild steel material is shown in figure 5.

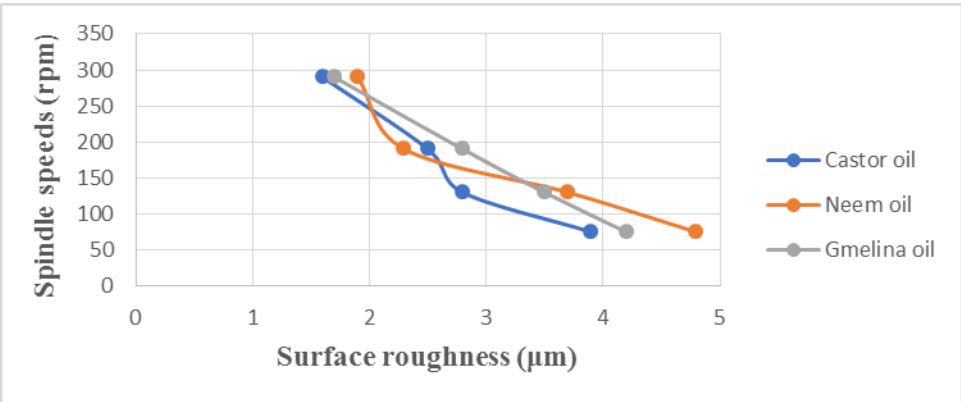

Figure 5: Effect of spindle speed and cutting fluid on surface roughness of mild steel material.

From figure 5, castor oil had the lowest value of surface finish, followed by Gmelina oil and then Neem oil at the highest spindle speed of 290 rpm. The surface roughness values started increasing as the spindle speed was decreased. Therefore, high spindle speed is essential for good surface finish of machined parts to be obtained.

3.2 Statistical Analysis

The significant effect of the categorical variable (oil type) and continuous variable (feed rate and spindle speed) on the response variable (surface roughness) was studied using the Pareto chart shown in figure 6.

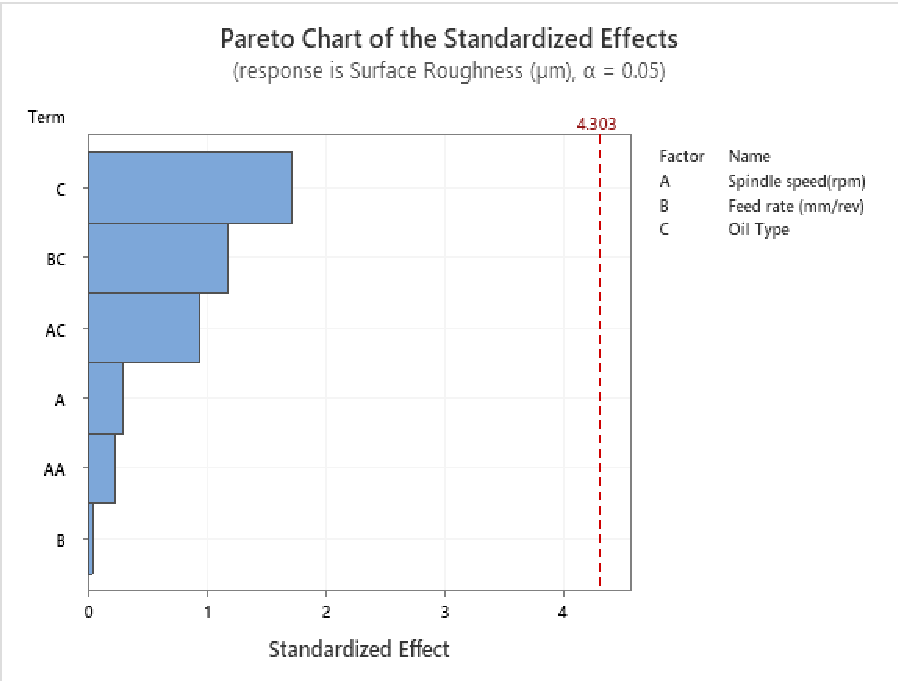

Figure 6: Effect significance of the independent variables on surface roughness.

From figure 6, spindle speed had more significant effect on surface roughness of mild steel material than feed rate. Also, the cutting fluid applied in the drilling or machining operation had the greatest significant effect on the response variable. In other words, each of the independent variables had an individual significant effect on surface roughness parameter of the material. An interactive factor effects were also observed. Feed rate-oil type factor interaction had a greater significant effect than spindle speed-oil type interaction on the surface roughness factor. This, therefore, implied that both the categorical and continuous variables all had an individual and factor-interactive effect on surface roughness.

The mathematical models (in un-coded units) that were developed using quadratic regression analysis tool for each oil type employed in the drilling process, had good Pearson correlation coefficients for the predicted values and experimentally measured values of surface roughness as shown in table 2. These mathematical models are shown in equations 1, 2 and 3.

For Castor oil: Surface Roughness (µm) = $7.0 - 0.030A - 4.7B + 0.000042A^2$ (1)

For Gmelina oil: Surface Roughness (µm) = $9.2 - 0.036\ A - 10.0\ B + 0.000042\ A^2$ (2)

For Neem oil: Surface Roughness (µm) = $4.2 - 0.022\ A + 8.4\ B + 0.000042\ A^2$ (3)

Their respective Pearson correlative coefficients are shown in table 2.

Table 2: Pearson correlation coefficients for the three models.

Oil Type	Coefficient of Correlation, R
Castor oil	0.986
Neem oil	0.994
Gmelina oil	1.000

To further visualize, graphically, the prediction errors of the three models a normal probability plot shown in figure 7 was done.

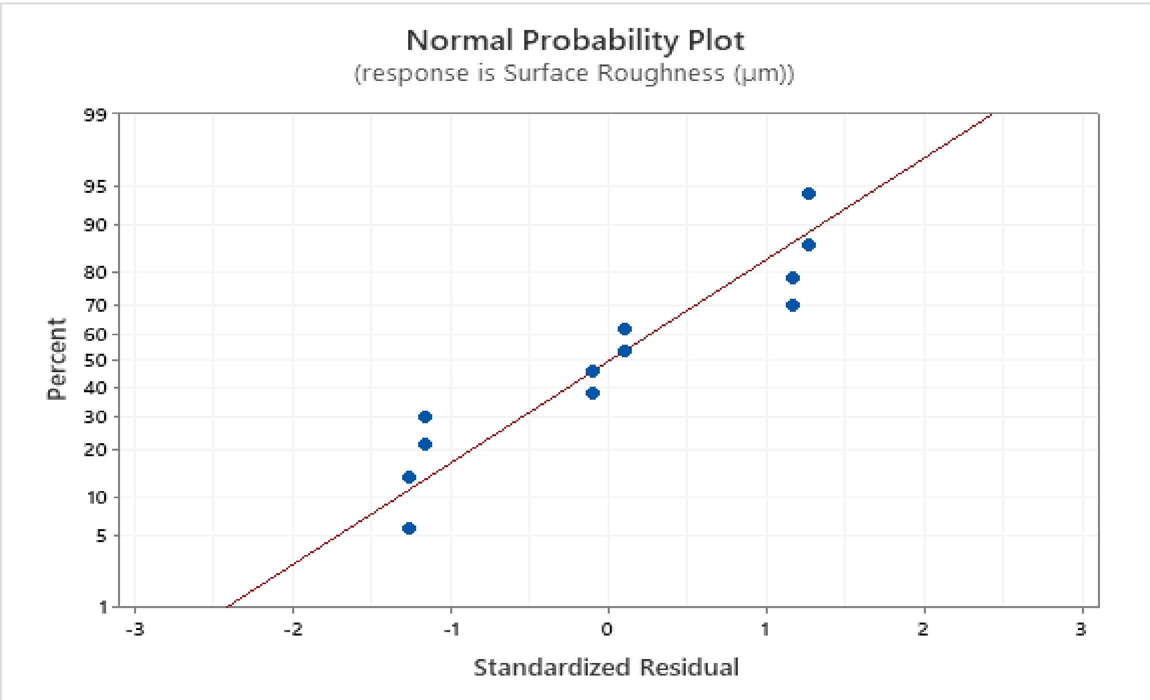

Figure 7: Normal probability plot of percentage deviations against standardized residuals.

From figure 7, it could be seen vividly that residuals were close to the regression fit or line. This, therefore, attests that the prediction errors of the mathematical models were not much compared to the measured or actual values of surface roughness. There is a good correlative association between the predicted and actual values of surface roughness for all the models.

A summary of the standardized residuals or estimation errors of the models is shown in figure 8 using a histogram.

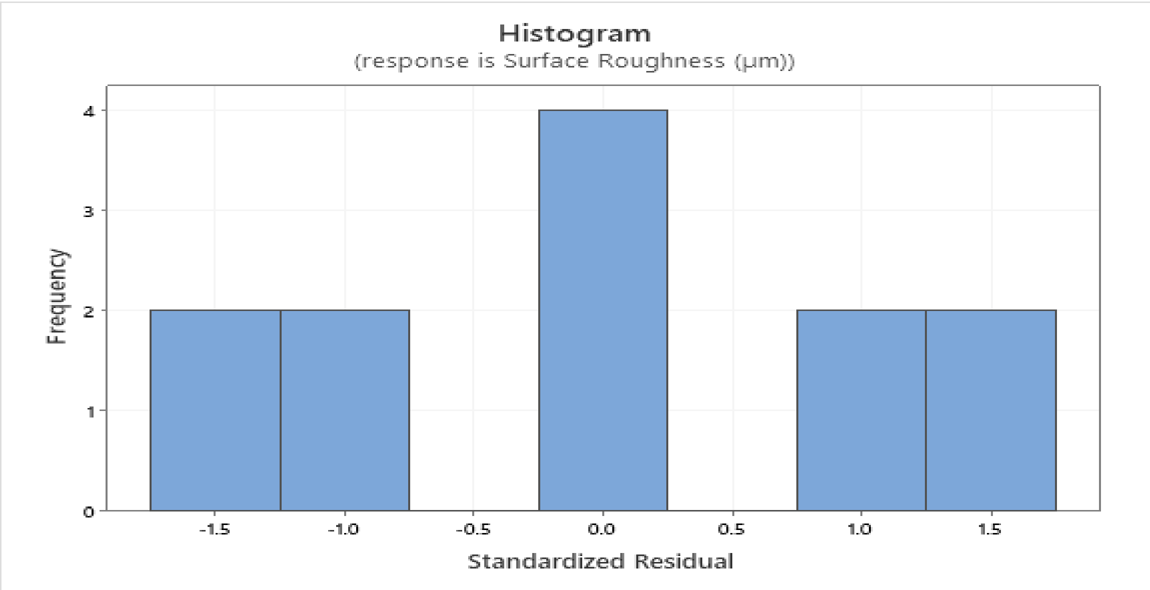

Figure 8: Plot of frequency against standardized residuals.

From figure 8, it could be clearly seen that the frequency of error or deviation for ranges of -1.5-1, 0, and 1-1.5 occurred twice, quadruple and twice respectively. This implied that, the errors were not much and the models had a good estimation performance which is suitable for response prediction at any factor level considered.

3.3 Optimization Result

From the numerical optimization performed, the contour plot and three-dimensional plot of the optimization outcome are shown in figures 9 and 10.

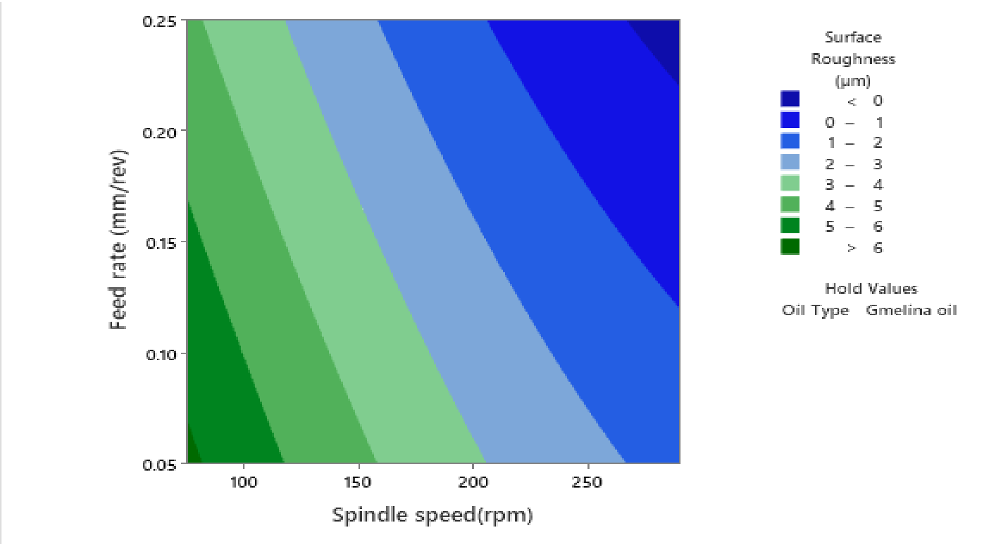

Figure 9: Contour plot of surface roughness, feed rate and spindle speed.

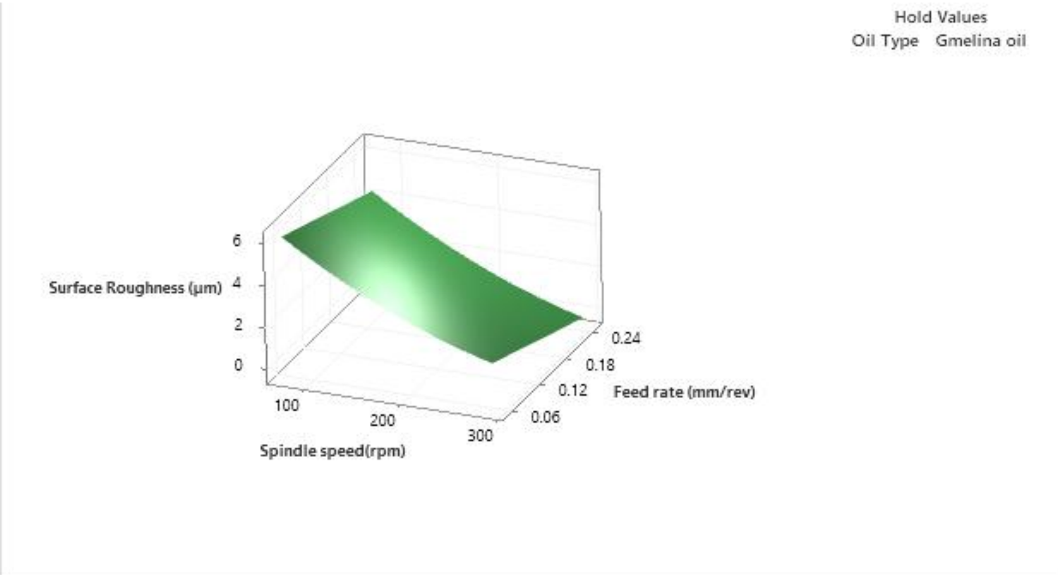

Figure 10: Surface plot of surface roughness, feed rate and spindle speed.

From figures 9 and 10, it is evident that the optimal solution that would yield a minimized value of surface roughness of mild steel material would be obtained at a low feed rate and high spindle speed of the machine. The best cutting fluid gotten from the optimization process using the composite desirability values was Gmelina oil and its factor level combination that yielded the optimal value of surface roughness is shown in table 3.

Table 3: Optimal solution obtained.

Solution	Spindle speed(rpm)	Feed rate (mm/rev)	Oil Type	Surface Roughness (µm) Fit	Composite Desirability
1	290	0.0896779	Gmelina oil	1.3	1

Table 4: Standard error of the optimal solution.

Response	Fit	SE Fit	95% CI	95% PI
Surface Roughness (µm)	1.30	2.02	(-7.40, 10.00)	(-7.47, 10.07)

Table 3 shows that Gmelina oil at a factor level of: spindle speed 290 rpm and feed rate of 0.0897 (approx.) had the highest composite desirability value of 1 and a low surface roughness value of 1.3. The standard error in fit at this optimal solution as shown in table 4 was 2.02 µm.

4. CONCLUSION

The application of cutting fluid (vegetable oils) in machining operations helps greatly in achieving good surface finish of the machined part or components. This study focused on the determination of the optimal cutting fluid that would give the best surface roughness value or surface finish of a mild steel material. The statistical analysis that was done showed that each of the considered independent factors (oil type- castor oil, neem oil and Gmelina oil; spindle speeds, and feed rates) all had an individual significant effect on the response variable-surface roughness and an interactive factor effect of oil type-feed rate and spindle speed-oil type having a more significant effect on surface roughness. The mathematical models that were developed for response prediction at any considered factor level had good correlation coefficients, which thus, endorsed them to be employed in estimating surface roughness values at specific factor levels. The result of the numerical optimization that was performed showed that Gmelina oil at factor levels of: spindle speed- 290 rpm and feed rate-0.0897mm/rev. gave the highest composite desirability value of one (1) and a surface roughness value of 1.3. Therefore, Gmelina oil is more suitable for use in drilling mild steel materials if good surface finish is desired.

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