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Optimization and Modelling of Performance Parameters in Turning Aisi 1029 Steel Using Hybridized Shea Butter and Baobab Seed Oil Based Cutting Fluids

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Abstract: *This research Optimization and Modelling of performance parameters in turning AISI 1029 steel using hybridized Shea butter and baobab seed oil cutting fluids used the blends of Shea butter (SB) and Baobab seed oil (BSO) in the ratio of 70%SB: 30%BSO (SBBSOCFI), 60%SB:40%BSO (SBBSOCFII) and 50%SB:50%BSO (SBBSOCFIII as base oils to formulate cutting fluids to be used in turning operation. Cutting speed (CS), depth of cut (DC), feed rate (FR) and cutting fluids (FT) were the machining parameters while temperature and metal removal rate (MRR) were the response variables (performance parameters). The experiment was designed using Taguchi OA Design of experiment (DoE)) taking four (4) factors at three (3) levels. Optimization of the performance parameters was done from Design Expert version 11, ANOVA was used to determine the statistical difference between mean of the variables and Signal-to-Noise ratio (SNR) was used to analyze the results. Besides, mathematical models for the process parameters were developed to predict values of the response variables. From the results obtained SBBSOCFIII produced the least tool-work interface temperature of 39.81^{O}C at cutting conditions 50mpm, 1.00mm and 0.750mm/rev. Similarly, SBBSOCF1 achieved the highest MRR of 69993.7mm^3/min at 90mpm, 1.0mm and 0.75mm/rev. It can now be said that these hybrid cutting fluids which are bio oils based cutting fluids that have good prospect for cutting fluids developments and some other industrial applications.*

Keywords: cutting fluids, design of experiment, optimization, performance parameters, process parameters, turning operation.

INTRODUCTION

Cutting fluid is substance either liquid or gas that is applied at the tool – workpiece interface during machining operation for the purposes of friction reduction, heat curtailment,surface enhancement, facilitating chips removal from the machined surface and facilitating energy conservation due to reduction in power consumption (Pay *et al.,* 2017). Cutting fluids are specifically designed for metal cutting processes such as machining and stamping. Cutting fluids have various merits over dry machining; its application improves product surface finish and reduces cutting tool wear (Elewa *et al*., 2015).

The most commonly used cutting fluids in use are mineral oil based cutting fluids (conventional cutting fluids). Mineral oil based cutting fluids (petroleum oil based cutting fluids) are environmentally unfriendly due to their anti – biodegradability; they pose serious threat to the environment on disposal and have adverse effect on the health of the operators (Ogedengbe *et al*., 2019). Owing to the problems associated with the use of conventional cutting fluids, the use of bio oils based cutting fluids as an alternatives have come to a lime light these days. Bio or vegetable oils based cutting fluids are plant products which are highly biodegradable, possess high viscosity, high flash point, high triglycerides contents, average composition of free fatty acids and acid value, low moisture etc. however, vegetable oils are said to possess low thermal and oxidative stability (Kuram and Ozcelik, 2013). Shea butter and baobab seed oil are bio oils and hence possess the desirable attributes mentioned which are required of cutting fluids. In addition, rare use of the oils as cutting fluids and for cutting fluids development is one of the reasons that informed the choice of these oils for the research - Optimization and Modelling of performance parameters in turning AISI 1029 steel using hybridized Shea butter and baobab seed oil based cutting fluids. The properties required of any cutting fluid are: the ability to keep the workpiece and the tool at stable temperature, maximize the life of the cutting tip by lubricating the working edge and reducing tip welding, ensure safety of people handling the cutting fluids, maximizing metal rate, inability to corrode the machine part and the tool. SBBSOCF1 and SBBSOCFII and SBBSOCFIII are Vegetable Oils based cutting fluids (VOBCFs) and VOBCFs could compete favorably with petroleum based cutting fluids owing to the fact that they form a good layer of lubricating film between tool and work thereby giving an improved surface finish and a reduced friction (Syahir *et al*., 2017). Besides, they possess relatively high flash point which gives the chances for an increased metal removal rate (MRR) because of reduced chances of smoke formation and fire hazard during metal cutting. Vegetable oil is a biodegradable fluid that enhances the cutting performance, extend tool life and improve the surface quality (Lawal *et al* 2013). Vegetable oils consist of triglycerides which are glycerol molecules with three long chain fatty acids attached at the hydroxyl groups via ester linkages. The fatty acids in vegetable oil triglycerides are all of similar length, between 14 and 22 carbons long (Sankaranarayanan 2021). The triglycerides structure of vegetable oils provides desirable properties of lubricant. Long, polar fatty acid chains provide high strength lubricant films which interact strongly with metallic surfaces and reduces both friction and wear. Vegetable oils have a higher viscosity index. However thermal and oxidation stability of vegetable oils are limited. Vegetable oils perform better than the other oils and the reason are described as follows (Saleem *et al*., 2013).

Vegetables have good lubricity properties (Saikiran and Kumar, 2019). The highly lubricating properties of vegetable are made possible by the fundamental composition of the vegetable molecules, as well as the chemical structure of the oil itself. Its properties are the direct result of the vegetable oil's smart molecules. These molecules are long, heavy and dipolar in nature; that is, the end of the molecules have opposing electrical charges. Vegetable oils carry slight polar charge but mineral oil have no charge (Chang *et al*., 2021). This polar charge draws the vegetable oil molecule to a metallic surface like magnet; therefore, vegetable adhere to metal surface more tightly than mineral oils. Dense, homogeneous alignment of vegetable oil molecules creates a thick, strong and durable film layer of lubricant (Abutu *et al.,* 2022). This lubricating film gives the vegetable oil a greater capacity to absorb pressure. In contrast, the molecules of mineral oils are intrinsically non-polar. They form a random alignment along a metal surface, which provides a weaker layer of lubrication. Consequently, vegetable oils make a better lubricant (Muhammad *et al.,* 2018).

LITERATURE REVIEW

Machining is any process (operation) in which a cutting tool is used to remove small chips of material from the workpiece To perform the operation, relative motion is required between the tool and the work. This relative motion is achieved in most machining operation by means of a primary motion, called cutting speed and a secondary motion called feed (Enk *et al*., 2004). Machining requires attention to many details for a workpiece to meet the specifications set out in the engineering drawings or blueprints (Enk, *et al* 2004). Besides the obvious problems related to correct dimensions, there is the problem of achieving the correct finish or surface smoothness on the workpiece. The inferior finish found on the machined surface of a workpiece may be caused by incorrect clamping, a dull tool, or inappropriate presentation of a tool. (Kivak *et al.,* 2020). A substantial amount of the energy used is converted into heat energy due to friction generated between the tool and workpiece interface and the plastic deformation of the workpiece during machining. The rapidly accumulated heat causes the temperature of the tool and work interface to rise at fast rate directly affecting the surface finish of the product (Papreja *et al.,* (2014). Resulting temperature induces metallurgical transformation such as softening of the workpiece and also lead to structural breakdown of the workpiece and the tool material. This may negatively affect the quality of the work of the machined products in terms of dimensional accuracy and surface finish. The heat generated during machining is therefore critical in terms of product quality. It is therefore imperative that effective control of the heat generated in the process is crucial in ensuring good workpiece surface quality (Papreja *et al.*, 2014). Material removal rate is the volume of the unwanted materials (chips) removed from the machined surface in a specified period of time (Olanrawaju, 2019). In machining, the process which removes metal at a faster rate may not be the most economical process since power consumed and cost factor must be taken into consideration. Hence, to compare two or more processes, the amount of metal removed per unit of power consumed must be determined. This is called specific metal removal rate and it is expressed in mm^3/W/min if the power is measured in watts. According to Elewa *et al* (2015), the use of vegetable oils gives the opportunity for an increased MRR due to high flash point characterized of bio-oils. The use of coolant during cutting process does not only help in the improvement of surface integrity and increase in tool life, but it also facilitates the conservation of energy due to reduction in power consumed during the process (Abdulkareem *et al.,* 2017)

MATERIALS AND METHODS

Materials and Equipment

The materials used for the research were Shea butter Nut, Baobab seed, Metal workpicce (AISI 1029), HSS cutting Tool, cutting fluid additives and equipment used are as presented in the table 1.

Table 1: Equipment

S/No	Equipment/Model	Function
1	Centre Lathe (E3N -01)	Turning
2	Pensky Martens Close Cup Tester	Flash Point Measurement
3	Tlc40-14 D97 D2500 Bath	Pour Point Assessment
4	Pycnometer	Moisture Content Assessment
5	Infra-Red Gun Thermometer	Temperature measurement
6	Density Bottle	Density Measurement

Methods

Experimental Design

The experiment was designed using Taguchi approach from Design Expert version 11 and L9 orthogonal array was generated as presented in Tables 2. The machining parameters and levels are presented in Tables 3 and 4. The quality characteristics used to analyze the result are smaller-the-better (STB) for Temperature and the larger-the-better (LTB) for MRR since smaller Temperature and larger MRR indicates better performance of the process.

Table 2: Orthogonal Array for Parameters and Levels

Taguchi P = 4 , L = 3					RESPONSES	
Run	**A**	**B**	**C**	**D**	**Temperature (^oC)**	**MRR (mm^3/min)**
1	1	1	1	1	x_1	x_1
2	1	2	2	2	x_2	x_2
3	1	3	3	3	x_3	x_3
4	2	1	2	3	x_4	x_4
5	2	2	3	1	x_5	x_5
6	2	3	1	2	x_6	x_6
7	3	1	3	2	x_7	x_7
8	3	2	1	3	x_8	x_8
9	3	3	2	1	x_9	x_9

Table 3: Machining Parameters and Level

Level	Cutting Speed (m/min)	Depth of Cut (mm)	Feed Rate (mm/rev)	Fluid Type
1	50	1.00	0.120	SBBSOCF 1
2	70	1.50	0.435	SBBSOCF II
3	90	2.00	0.750	SBBSOCF III

Table 4: Machining Parameter Orthogonal Array

Taguchi P = 4 , L = 3					
Run	**CS (m/min)**	**DC (mm)**	**FR (mm/rev)**	**Fluid Type**	**X**
1	50	1.00	0.120	SBBSOCF 1	X_1
2	50	1.50	0.435	SBBSOCF II	X_2
3	50	2.00	0.750	SBBSOCF III	X_3
4	70	1.00	0.435	SBBSOCF III	X_4
5	70	1.50	0.750	SBBSOCF1	X_5
6	70	2.00	0.120	SBBSOCF II	X_6
7	90	1.00	0.750	SBBSOCF II	X_7
8	90	1.50	0.120	SBBSOCF III	X_8
9	90	2.00	0.435	SBBSOCF 1	X_9

Formulation of Hybrid Cutting Fluids

Hybrid Cutting fluids were formulated from Shea butter and baobab seed oil in three different ratios - (70%SB:30%BSO, 60%SB:40%BSO, 50%SB:50%BSO) using the suggestions given by Eziwhuo (2020) and Lawal *et al* (2007). According to Lawal *et al* (2007), in preparing samples of cutting fluids, required quantity of oil was measured using beaker and mixed with water in the ratio of 1:10. This mixture was afterward blended with ordinary detergent, and other additives in their respective percentages.

Characterizations of the Hybrid Cutting Fluids

The Physicochemical Properties of the hybrid cutting fluids were determined using ASTM standard with appropriate apparatus in the department of Food Science Technology Modibbo Adama University, Yola Adamawa state Nigeria

Machining

AISI 1029 Steel samples of lengths 800mm and cross-sectional diameter of 50mm was straight turned between centers on E3N-01 lathe machine using High-speed steel (HSS) tools of the same tip configurations and process parameters. Each Experiments was run for at least fifteen (15) minutes during which cutting fluid was applied by flood means to dissipate the heat generated at the tool-work interface.

Parameters Assessment

Temperature

The tool-work interface temperature during turning was assessed using infra-red gun thermometer (Non-contact thermometer).

Metal Removal Rate (MRR)

The metal removal rate (MRR) was analytically assessed from the mean diameter (D) using equation1

$$MRR = \pi D f d c \tag{1}$$

Where: D is mean diameter
f is feed rate
d is depth of cut
c is cutting speed

RESULTS AND DISCUSSIONS

Characterization of the Hybrid Cutting Fluids

Characterizations (physicochemical properties) of the Hybrid Cutting Fluids was presented in Table 5

Table 5: Physicochemical Properties of the cutting fluids

Test Properties	SBBSOCF I	SBBSOCF II	SBBSOCF III
Flash Point (°C)	250.0	311.0	287.0
Pour Point (°C)	-6.00	-3.00	-4.00
Moisture Content (% vol/vol)	80.80	87.85	88.18
Free Fatty Acid (mg/KOH/g)	3.380	3.100	2.810
Acid Value (mg/KOH/g)	6.732	6.170	5.610
Specific Gravity	1.039	1.150	1.027
Saponification Value (mg/KOH/g)	271.5	223.1	224.6
Iodine Value (g/100g)	147.00	127.00	157.90
Peroxide Value (mgeq/kg)	0.006	0.014	0.032
Density (kg/m^3)	1.065	1.309	1.027
Viscosity at 40°C and 100°C(mm^2/s)	1.20, 0.93	1.12, 0.84	1.03, 0.79
Viscosity Index	217	220	224

The flash points of the hybrid cutting fluids are found to be higher (250°C and 287°C) and would be safe from fire hard hazard even when used in an area with an elevated temperature. The use of vegetable oils based cutting fluids gives the opportunity for an increased MRR due to high flash point (Chaudhari *et al*., 2021). The greater volume of metal is removed by SBBSOCFI (76726mm^3/min at cutting speed of 90m/min depth of cut of 2.00mm and fed rate of 0.435mm/rev). The density of SBBSOCFI was found to be 1.065kg/m^3, SBBSOCFII (1.309kg/m^3), SBBSOCFIII (1.027kg/m^3). These higher values is an indication that the cutting fluids have the tendency of an increased oiliness relative to the control fluid having density of 0.765kg/m^3. The moisture contents of SBBSOCFI was found to be 80.80%vol/vol, SBBSOCFII (87.85%vol/vol) and SBBSOCFIII (88.18%vol/vol). These values are higher than that of the control fluid (65.00%vol/vol) indicating that the formulated cutting fluids are more susceptible to rancidity owing to higher moisture content. Viscosity of the cutting fluid is the resistance to flow of the fluid and is affected inversely by temperature. Viscosity has considerable influence on the properties of the cutting fluids. Higher viscosity improves the lubrication abilities of the cutting fluids and decreases the cooling performance. Similarly, lower viscosity provides better cooling performance and easier removal of solid particles. The viscosities of SBBSOCFI at 40^{o}C and 100^{o}C were found to be 1.20/0.93mm^2/s, SBBSOCFII (1.12/0.84 mm^2/s) and SBBSOCFIII (1.03, 0.79). These values indicate that the cutting fluids have good lubricity and may be good in terms of cooling performance. The Viscosity Index of SBBSOCFI was found to be 217, SBBSOCFII (220), SBBSOCFIII (224),). The Viscosity Index of 253 of SBBSOCFIII indicates that the cutting fluid would be more stable under varying working conditions than the reference fluid having a viscosity index of 51.00.

Performance Parameters Assessment

The experimental results obtained for tool-work interface temperature and metal removal rate was presented in table 6

Table 6: Temperature and Metal Removal Rate

Run	CS (m/min)	DC (mm)	FR (mm/rev)	Cutting Fluid	Response	
					Temperature (^{o}C)	MRR(mm^3/min)
1	50	1.00	0.120	SBBSOCF 1	39.77	5820
2	50	1.50	0.435	SBBSOCF II	42.17	30978
3	50	2.00	0.750	SBBSOCF III	41.70	70500
4	70	1.00	0.435	SBBSOCF III	46.00	28927
5	70	1.50	0.750	SBBSOCF1	39.77	73210
6	70	2.00	0.120	SBBSOCF II	45.23	15120
7	90	1.00	0.750	SBBSOCF II	49.73	66438
8	90	1.50	0.120	SBBSOCF III	43.57	15956
9	90	2.00	0.435	SBBSOCF 1	48.00	73210

Analysis of Responses from Turning with SBBSOCF 1, II and III

Design (Actual)

The design (actual) for turning using the third set of cutting fluid was presented in Table 7.

Table 7: Design (actual) for the third set of cutting fluids

Std	Run	CS	DC	FR	Fluid Type	Temperature	MRR
6	1	70	2.0	0.120	SBBSOCFII	46.00	15120
1	2	50	1.0	0.120	SBBSOCF1	39.77	5820.0
3	3	50	2.0	0.750	SBBSOCFIII	42.17	70500
2	4	50	1.5	0.435	SBBSOCFII	41.70	30978
7	5	90	1.0	0.750	SBBSOCFII	46.77	66438
5	6	70	1.5	0.750	SBBSOCF1	45.23	73210
9	7	90	2.0	0.435	SBBSOCF1	49.73	73210
4	8	70	1.0	0.435	SBBSOCFIII	43.57	28927
8	9	90	1.5	0.120	SBBSOCFII	48.00	15956

Build Information

The build information for the design model was presented in table 8

Table 8: Build information

File Version	**8.0.6.1**		
Study Type	Factorial	Subtype	Randomized
Design Type	Taguchi OA	Runs	9
Design Model	Main Effects	Blocks	No Blocks
Center Points	0	Build Time (ms)	2.57

Factors

The interacting factors for the model was presented in table 9

Table 9: Factors of Design Model

Factor	Name	Units	Type	Min	Max		
A	Cutting Speed	Mpm	Numeric	50.00	90.00	**Levels:**	3
B	Depth of Cut	Mm	Numeric	1.000	2.000	**Levels:**	3
C	Feed Rate	mm/rev	Numeric	0.120	0.750	**Levels:**	3
D	Fluid Type		Categoric	SBBSOCF1	SBBSOCFIII	**Levels:**	3

Interface Temperature

ANOVA

The analysis of variance (ANOVA) for interface temperature of the set of the cutting fluids was presented in table 10

Table 10: ANOVA Table of Interface Temperature

Source	Sum of Squares	df	Mean Square	F-value	P-value	
Model	0.0418	4	0.0104	217.71	< 0.0001	Significant
A-Cutting Speed	0.0366	2	0.0183	381.42	< 0.0001	
B-Depth of Cut	0.0052	2	0.0026	54.01	0.0013	
Residual	0.0002	4	0.0000			
Cor Total	0.0420	8				

The Model F-value of 217.71 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case A, B are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

Fit Statistics

The fit statistics for the model is shown in table 11

Table 11: Fit statistics of Interface Temperature

Std. Dev.	0.0069	R^2	0.9954
Mean	3.8000	Adjusted R^2	0.9909
C.V. %	0.1823	Predicted R^2	0.9769
		Adeq Precision	41.4438

The Predicted R^2 of 0.9769 is in reasonable agreement with the Adjusted R^2 of 0.9909; i.e. the difference is less than 0.2. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 41.444 indicates an adequate signal. This model can be used to navigate the design space.

Model Equation in Terms of Coded Factors

The Final Equation in Terms of Coded Factors is shown in table 12.

Table 12: Final Equation in Terms of Coded Factors of Interface Temperature

ln(Interface Temperature)	=
+44.770	
-0.0808	A[1]
+0.0057	A[2]
-0.0317	B[1]
+0.0052	B[2]

$$T_i = 44.770 - 0.0808A_1 + 0.0057A_2 - 0.0317B_1 + 0.0052B_2 \quad (1)$$

R^2 = 97.69%, R^2 (adj) = 99.09%

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as – The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

Metal Removal Rate (MRR)

ANOVA

The analysis of variance (ANOVA) for interface temperature of the third set of cutting fluid is presented in table 13

Table 13: ANOVA of MRR

Source	Sum of Squares	df	Mean Square	F-value	P-value	
Model	5.30	2	2.65	13.44	0.0061	Significant
C-Feed Rate	5.30	2	2.65	13.44	0.0061	
Residual	1.18	6	0.1974			
Cor Total	6.49	8				

The Model F-value of 13.44 implies the model is significant. There is only a 0.61% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate model terms are significant. In this case C is a significant model term. Values greater than 0.1000 indicate the model terms are not significant.

Fit Statistics

The fit statistics for the model is shown in table 14

Table 14: Fit Statistics Table of MRR

Std. Dev.	0.4443	R^2	0.8175
Mean	42239	Adjusted R^2	0.7567
C.V. %	4.2900	Predicted R^2	0.5894
		Adeq Precision	7.1453

The Predicted R^2 of 0.5894 is in reasonable agreement with the Adjusted R^2 of 0.7567; i.e. the difference is less than 0.2. Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 7.145 indicates an adequate signal. This model can be used to navigate the design space.

Model Equation in Terms of Coded Factors

The table describing and showing the equation of the model terms is shown in table 16

Table 16: Model Equation Table of MRR

ln(Metal Removal Rate)	=
+42239	
-1.04	C[1]
+0.2434	C[2]

$$\text{MRR} = 42239 - 1.04C_1 + 0.2434C_2 \quad (2)$$

$R^2 = 58.94\%$, R^2 (adj) = 75.67 %

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

Optimization of Responses

Interface Temperature

For the set of cutting fluids - SBBSOCF 1, SBBSOCF II, SBBSOCF III, the optimal value of interface temperature is 39.8122°C achieved by SBBSOCFIII at a CS of 50mpm, DC of 1.0mm and FR of 0.750mm/rev as shown in figure 1

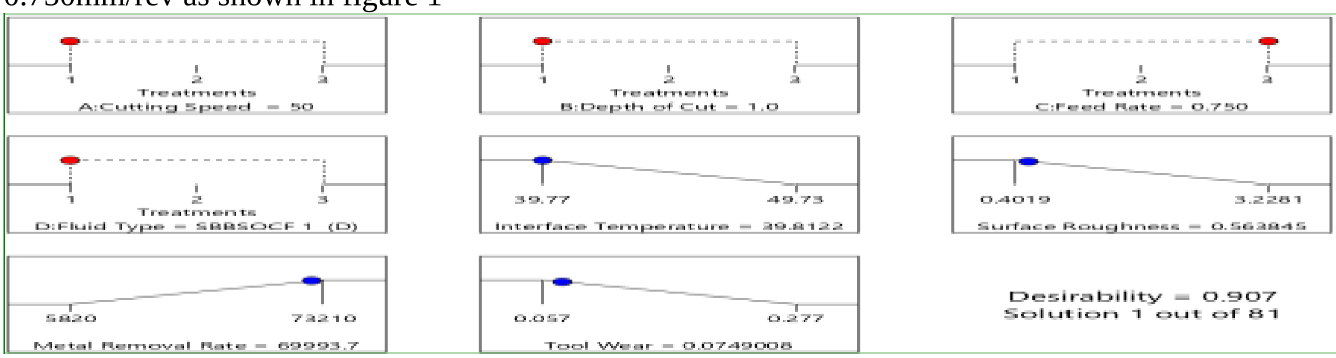

Figure 1: Optimized Interface temperature

Metal Removal Rate

For the set of cutting fluids -SBBSOCF 1, SBBSOCF II, SBBSOCF III, the optimal value of MRR is 69993.7mm^3/min achieved by SBBSOCF 1 at a CS of 50mpm, DC of 1.0mm and FR of 0.750mm/rev as shown in figure 2

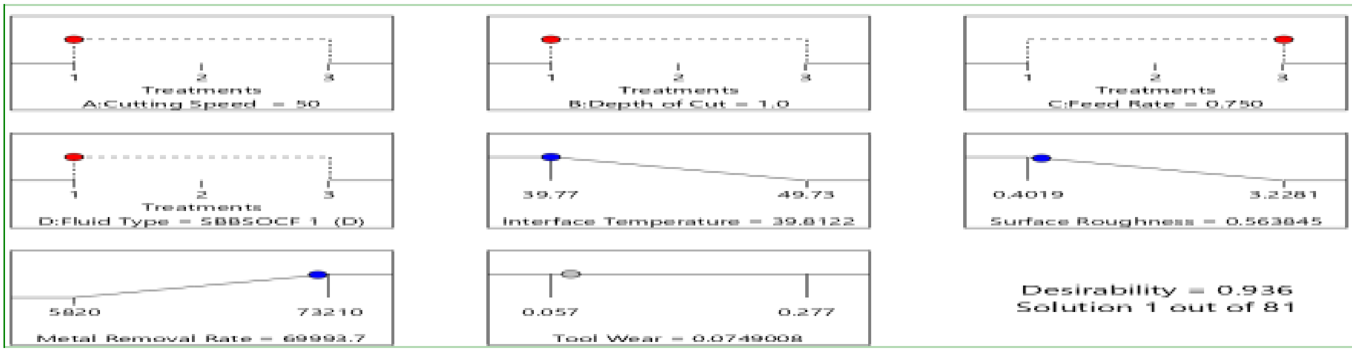

Figure 2: Optimized MRR

CONCLUSION

This research Project which is formulation and performance evaluation of Shea butter and Baobab seed oil based cutting fluids in turning operation presents the following conclusions:
1. Taguchi's robust design was successfully used for optimizing the turning parameters on low carbon steel (AISI 1029).
2. For the sets of the cutting fluids - SBBSOCFI, SBBSOCFII and SBBSOCFIII the optimal value of temperature was 39.81^{o}C achieved by SBBSOCF III at 70mpm, 1.5mm, 0.750mm/rev and MRR of 69993.7mm^{3}/min achieved by SBBSOCF I at 70mpm, 2.0mm, 0.750mm/rev
3. From the ongoing and following the evaluation of the performance parameters (characteristics) of vegetable oils based cutting fluids in turning operation, they were found to function better as cutting fluid relative to the mineral oil based cutting fluids.

Recommendations

The following recommendations have been proffered based on the findings of the research project:
1. Other bio oils should be used for same experiments with view for exploring their potential.
2. Same experiment should be run on the same workpiece, adopting same tool and process parameters with view to further refining (fine-tuning) the outcome of the research.
3. The same experiment should be run using different turning tools of different materials, tool point angles, different machine tools on same workpiece materials or some other classes of plain carbon steels.
4. Local contents research drive initiative should be encouraged not only in the area of machining but in the all the sectors of manufacturing.

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