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Analysis of the effect of sustainable lubricants in the turning of AISI 304 stainless steel

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Abstract

The rising environmental concerns and threats of contamination and pollution have led to the quest for sustainable cutting fluids. In order to maximize the use and efficiency of cutting fluids, the knowledge about them is necessary. In this study, the suitability of various natural vegetable oils as sustainable lubricants in machining was investigated using the turning of AISI 304 stainless steel on Colechester Master 3250 lathe. Three different natural vegetable oils were used such as palm oil, sunflower oil and coconut oil. The oils were applied as virgin oil using the minimum quantity lubrication method (MQL). The Taguchi method of design of experiments was applied in the study. Cutting parameters such as cutting speed, feed rate and depth of cut were used as input parameters and chip compression ratio and surface finish were used as responses to evaluate the suitability of these oils in machining of AISI 304 stainless steel. The result showed that sunflower oil has a better performance as cutting fluid.

Keywords: Cutting fluids; surface roughness; chip compression ratio; vegetable oils

1. Introduction

The use of cutting fluids in machining operations is a necessity. Cutting fluid reduces friction and wear. It facilitates chips removal from the machined surface as well as provides cooling for the operation. Majority of the lubricants used today are mineral based lubricants. This is partly due to the dominance of the petroleum industry. However, these mineral based lubricants are considered pollutants as they produce critical amount of particulate matter (PM), carbon monoxide (CO), and sulphur dioxide (SO_2) that negatively affect the air quality. Furthermore, most of these mineral based lubricants are not biodegradable [1]. Hence, these may end up polluting waters and causing other environmental problems [1, 2]. Mineral based lubricants have shown harm towards operators [3, 4]. Although the raw materials may be safe, the international agency for cancer research (IRAC) pointed out that petroleum based cutting fluids that contain heterocyclic and polyaromatic rings are carcinogenic and exposure to them cause skin cancer [5]. Ozcelik et

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al. [4] claimed that those hazardous substances with less biodegradability in mineral based cutting fluids can cause lots of serious techno-environmental and health problems. It is also noted that the bacterial growth in cutting fluids tremendously leads to the presence of microbial masses, especially endo-toxin at the shop floor atmosphere. Therefore, chemical additives are added in order to control the bacterial growth in the cutting fluids [6]. An environmentally friendly lubricant should be renewable, non-toxic to plants and animals, with its physical and chemical properties being technologically compatible [7].

Vegetable oils have shown good qualities as lubricants due to some inherent properties [8, 9, 10]. Coconut oil has a specific density of 0.93g/cm. It also has a viscosity index of 155, flash point of 240 and an iodine value of 7-12 [1, 11, 12]. Palm oil has a viscosity index of 189, flash point of 304^{o}C and an iodine value of 50-55. Sunflower oil has a viscosity index of 205, flash point of 272^{o}C and an iodine value of 113-148 [1]. Vegetable oils perform well as lubricants due to some of their desirable properties such as viscosity index and good lubricity [1, 8]. However, some of their limitations include poor thermal properties and their limited resistance to oxidation [1, 8, 12].

2.0 Materials and Method

2.1 Materials

Austenitic stainless steels are characterised by their high work hardening, and low thermal conductivity, which makes their machinability low [11, 13]. The selected workpiece has a dimension of Φ76.2mm x 400 mm. Carbide tools (high cut Inc TNGM160408E-HC8009 ISO) were used in this study. Table 2.1 shows the chemical composition of the used workpiece.

Table 1. Chemical composition of AISI 304 stainless steel

Elements	C	Si	Mn	P	S	Cr	Mo	Ni	Al	V	Fe
% by weight	0.065	0.591	1.197	0.034	0.024	18.53	0.21	8.75	0.001	0.025	Balance

These oils were applied using minimum quantity lubrication method (MQL) in the turning of AISI 304 stainless steel workpiece on a lathe machine.

2.2 Method

Turning is a machining process that involves the use of a single-point tool for the removal of material from surfaces of rotating workpieces. This process is usually done on a lathe, which rotates the workpiece at the desired revolution per minute and feed the tool at rate and depth of cut that are specified beforehand. The experiment was designed using Taguchi method L9 with 3 levels and four factors (type of oil, cutting speed, feed rate and depth of cut). This was created using MINITAB 17 Software. These three level experimental factors and Taguchi $L_9(3)^4$ design matrix are shown in Table 2 and 3 respectively. The viscosity at temperature of 40^{o}C for the cutting fluid represents the type of oil. The viscosities for the oils taken were; 41.9 mm^2/sec for palm oil, 38.2 mm^2/sec for sunflower oil and 27.9 mm^2/sec for coconut oil [1].

Table 2. Experimental factors and their levels

Factors	Level 1	Level 2	Level 3
Type of Oil	Palm	Sunflower	Coconut
Cutting Speed RPM	350	550	750
Feed Rate mm/rev	0.18	0.24	0.3
Depth of Cut mm	1.0	1.5	2.0

MQL method was adopted in the application of the oils at a pressure of 8 bar and flow rate of 100 millilitre per hour. Surface roughness values were measured using Mitutoyo device by placing the device on three different location on the workpiece and taking the average. The chips collected were measured using Mitutoyo calliper.

Table 3. Experimental matrix for $L_9(3)^4$

Run	Viscosity of cutting fluid (mm^2/sec)	Spindle speed (rpm)	Feed rate (mm/rev)	Depth of Cut (mm)
1	41.9	350	0.18	1
2	41.9	550	0.24	1.5
3	41.9	750	0.3	2
4	38.2	350	0.24	2
5	38.2	550	0.3	1
6	38.2	750	0.18	1.5
7	27.9	350	0.3	1.5
8	27.9	550	0.18	2
9	27.9	750	0.24	1

3.0 Results and Discussion

3.1 Surface Roughness

The surface roughness was measured using Mitutoyo surface roughness testing equipment. The experimental results for surface roughness along with their S/N ratios values are shown in Table 4. The results were analysed based on SN ratio (smaller the better quality characteristics).

Table 4 Experimental results for surface roughness and signal-to noise (SN) ratios

Run	Viscosity of cutting fluid (mm^2/sec)	Spindle speed (rpm)	Feed rate (mm/rev)	Depth of cut (mm)	Surface Roughness (Ra) µm	S/N (η) Ratio for Ra (dB)
1	41.9	350	0.18	1.0	1.6563	-4.38278
2	41.9	550	0.24	1.5	3.9126	-11.8493
3	41.9	750	0.30	2.0	4.9463	-13.8856
4	38.2	350	0.24	2.0	3.3220	-10.428
5	38.2	550	0.30	1.0	1.8410	-5.30108
6	38.2	750	0.18	1.5	1.8823	-5.49378
7	27.9	350	0.30	1.5	5.1317	-14.2052
8	27.9	550	0.18	2.0	1.9127	-5.63294
9	27.9	750	0.24	1.0	3.5663	-11.0444

Based on the results shown in Table 4, it is clear that sunflower oil outperformed the palm and coconut oils despite it having almost similar viscosity as palm oil. This indicates that many factors beyond the viscosity of the fluid are responsible for the performance of a lubricant. A relationship could be drawn between the oils performance and their saturated fatty acids content. Coconut oil and palm oil have high saturated fatty acids content which may have affected their lubricity. On the other hand, sunflower oils contain less saturated fats.

b. Chip compression ratio

The experimental results for chip compression ratio along with its *S/N* ratio values are shown in Table 5. The results were analysed based on *S/N* ratio applying smaller the better quality characteristics. Chip compression ratio was calculated using the formula in Equation 1

$$Z = \frac{a_2}{a_1} \quad (1)$$

Where Z is chip compression ratio, a_1 is thickness of the uncut layer equals to the feed rate in turning operations and a_2 is thickness of the chip after cut [16].

Table 5. Experimental results for chip compression ratio and signal-to noise (SN) ratios

Run	Viscosity of cutting fluid (mm^2/sec)	Spindle speed (rpm)	Feed rate (mm/rev)	Depth of cut (mm)	a_1 (mm)	a_2 (mm)	Chip reduction Coefficient (Z)	S/N (η) Ratio for Ra (dB)
1	41.9	350	0.18	1.0	0.18	0.31	1.722	-4.72066
2	41.9	550	0.24	1.5	0.24	0.36	1.500	-3.52183
3	41.9	750	0.30	2.0	0.30	0.39	1.300	-2.27887
4	38.2	350	0.24	2.0	0.24	0.26	1.080	-0.66848
5	38.2	550	0.30	1.0	0.30	0.35	1.167	-1.34142
6	38.2	750	0.18	1.5	0.18	0.23	1.278	-2.13062
7	27.9	350	0.30	1.5	0.30	0.34	1.133	-1.0869
8	27.9	550	0.18	2.0	0.18	0.24	1.333	-2.49856
9	27.9	750	0.24	1.0	0.24	0.30	1.250	-1.9382

It can be observed that the chip compression ratio is mainly affected by tool interaction with the workpiece and the nature of chip formed. The three oils generated good chip formations with sunflower oil outperforming the other two.

3.2 Analysis of experimental results

3.2.1 Main effect plot

The main effect plots for surface roughness (Ra) and chip compression ratio (Z) are shown in Figures 1 and 2 respectively. These plots were obtained with the aid of Minitab 17 statistical software using the experimental results shown in Tables 4 and 5.

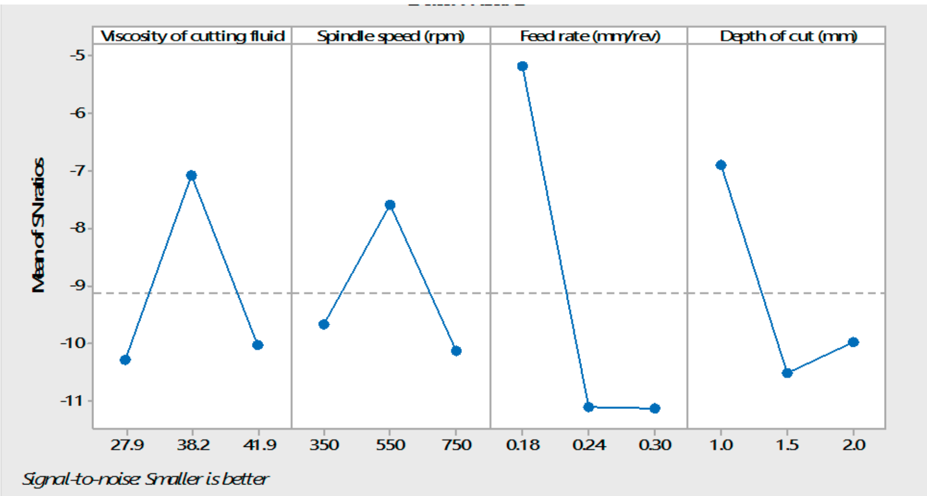


Fig. 1: Main effects plot for surface roughness

As shown in Figure 1, it can be observed that optimal surface roughness (Ra) can be achieved using cutting fluid with viscosity (38.2 mm^2/sec), spindle speed of 550 rpm, feed rate of 0.18 mm/rev and depth of cut of 1 mm.

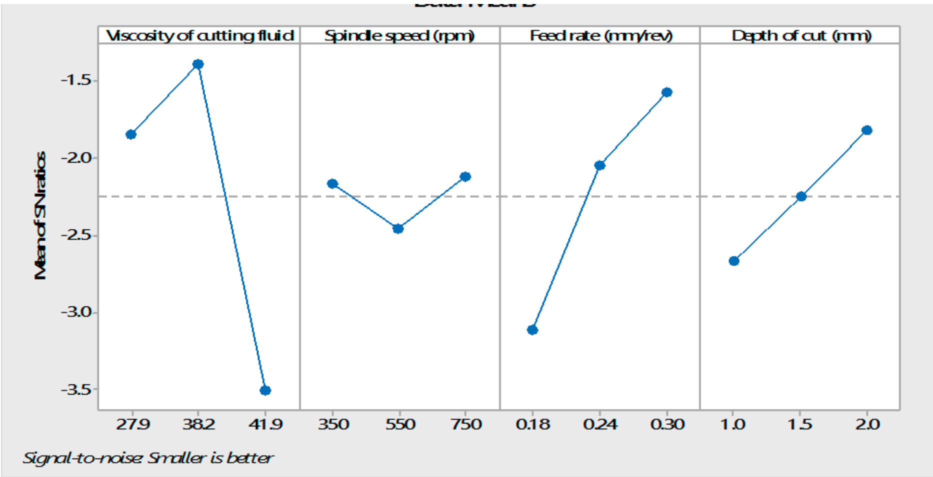


Fig. 2: Main effects plot for chip compression ratio

Furthermore, Figure 2 shows that optimal chip compression ratio can be obtained using cutting fluid viscosity of 38.2 mm^2/sec, spindle speed of 750 rpm, feed rate of 0.24 mm/rev and depth of cut of 2.0 mm. The results indicate that in order to obtain a better surface roughness and chip compression ratio, spindle speed of 27.9 and 350 rpm respectively were inadequate for the cutting process. As a result, any alteration from the optimal factor combination may lead to poor surface roughness and chip compression ratio.

3.2.2 Analysis of variance (ANOVA)

ANOVA was conducted on the experimental results in order to study the significant effects and percentage contribution of process factors on the surface roughness and chip compression ratio. This analysis was conducted at 95% confidence level and 0.05 (5%) significance level. Table 6 and 7 present the ANOVA for surface roughness and chip compression ratio. The symbol *DOF, SS, MS, F,* and *P* represent the values of degree of freedom, sum of squares, mean square, f-value and percentage contribution respectively. The value of SS_{Total} was calculated using Equation 2. For ease of analysis of the experimental results, the process factor which had the least effect on each response is being pooled leaving out three remaining factors which showed more significant effects on the response.

$$SS_{Total} = \sum_{i=1}^{n} {y_i}^2 - \frac{1}{N}(y_i)^2 \quad (2)$$

Table 6. ANOVA for surface roughness

Factor	DOF	SS	MS	F	P (%)
Viscosity of cutting fluid	2	4.971	2.486	4.414	33.10
Spindle speed (rpm)	2	3.72	1.86	3.303	24.77
Feed rate (mm/rev)	2	pooled	pooled	pooled	pooled
Depth of cut (mm)	2	5.2	2.6	4.617	34.63
Pooled Error	2	1.1263	0.563		7.50
Total	8	15.017	1.877		100

The ANOVA results shown in Table 6 indicate that depth of cut (34.63 %) has the most significance effect on the surface roughness of the workpiece.

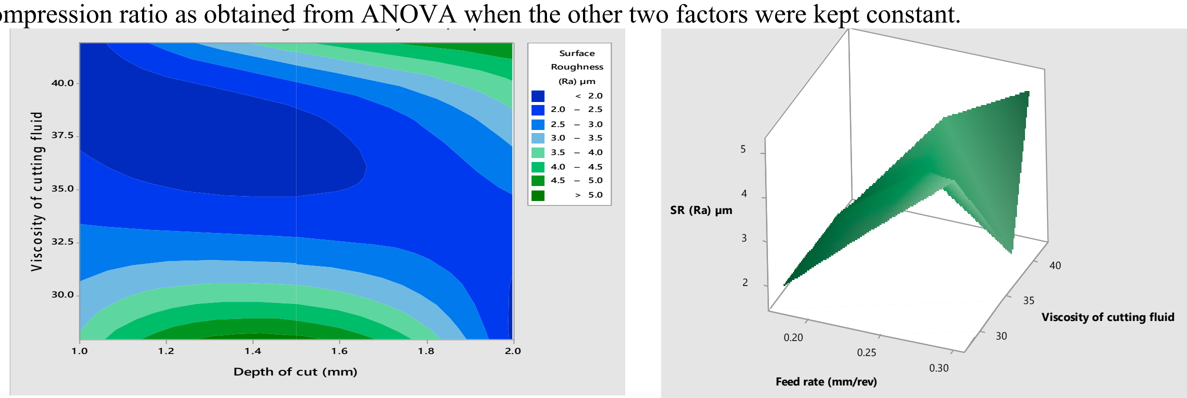
Table 7. ANOVA for chip compression ratio

Factor	DOF	SS	MS	F	P (%)
Viscosity of cutting fluid	2	0.1866	0.0933	36.987	59.13
Spindle speed (rpm)	2	pooled	pooled	pooled	pooled
Feed rate (mm/rev)	2	0.0937	0.0469	18.575	29.69
Depth of cut (mm)	2	0.0303	0.0151	5.9960	9.585
Pooled Error	2	0.0051	0.0025		1.599
Total	8	0.3156	0.0395		100

This is followed by viscosity of cutting fluid (33.10 %) and spindle speed (24.77 %). In addition, the ANOVA for chip compression ratio shown in Table 7 specified that viscosity of cutting fluid (59.13 %) has the most significance effect on chip compression ratio followed by feed rate (29.69 %) and finally, depth of cut (1.599 %). The effects of all the process factors are significance since their p-values are greater than 0.05.

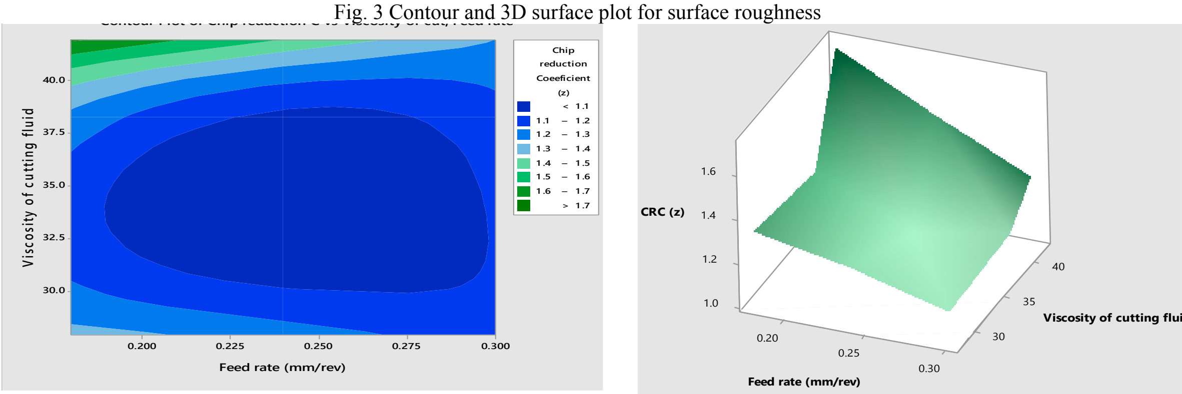
3.2.3 Contour and 3D surface plots

The contour and 3D surface plots for surface roughness and chip compression ratio are shown in Figures 3 and 4. This plot was used to study the interaction between the two most influential factors on the surface roughness and chip compression ratio as obtained from ANOVA when the other two factors were kept constant.



a. Contour plot b. 3D surface plot

Fig. 3 Contour and 3D surface plot for surface roughness



a. Contour plot b. 3D surface plot

Fig. 4 Contour and 3D surface plot for chip compression ratio

The contour levels in Figure 3(a) revealed that surface roughness of < 2.0 µm can be achieved using cutting fluid viscosity of 38 (mm^2/sec) and depth of cut of 1.4 mm while contour levels in Figure 4(a) shows that chip compression ratio of < 1.1 can be obtained using cutting fluid viscosity of 35 (mm^2/sec) and feed rate of 0.25 mm/rev. Furthermore, the 3D surface plots shown in Figure 3 (b) and 4 (b) show that value of surface roughness or chip compression ratio changes when the value of one or two of the experimental factor is altered while the other factors remained unchanged.

3.2.4 Interaction plots

The interaction plots for contour and 3D surface shown in Figure 5 and 6 indicate that the relationship between cutting fluid viscosity, spindle speed, feed rate and the response (surface roughness or chip compression ratio) is dependent on the depth of cut.

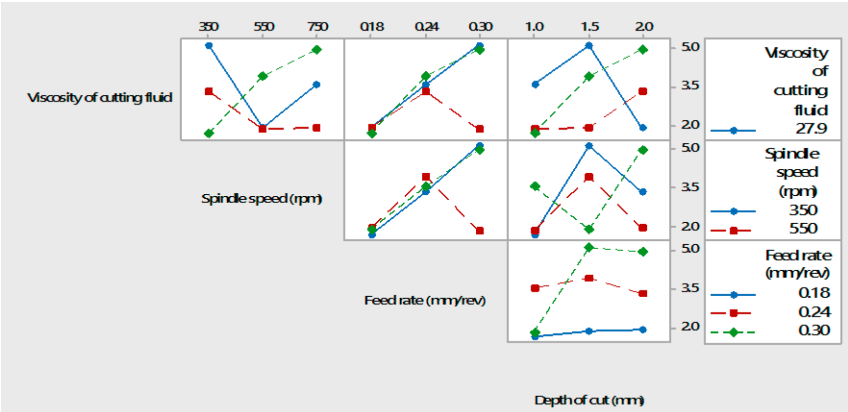


Fig. 5 Interaction plots for surface roughness

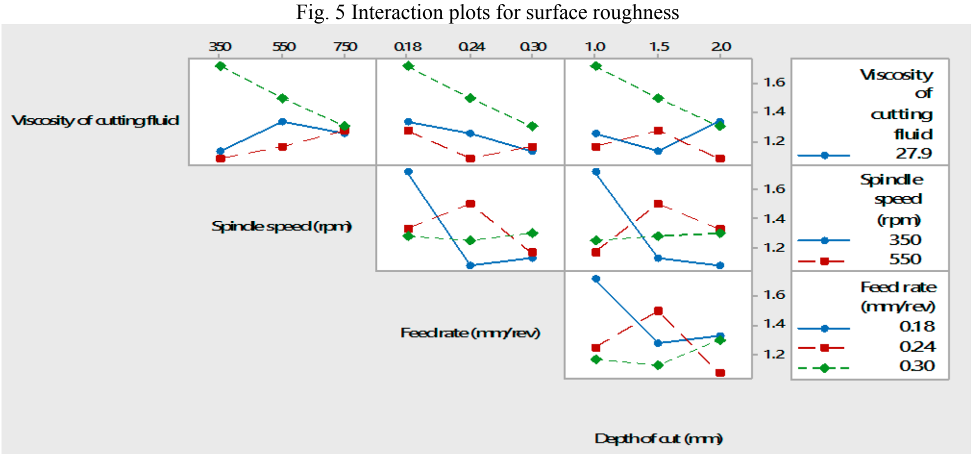


Fig. 6. Interaction plots for surface roughness

3.2.5 Regression model

The regression models along with the respective correlation coefficient (Rsq) for surface roughness (Ra) and chip compression ratio (*Z*) are shown in Equations 3 and 4. These models were developed using Minitab 17 statistical software. The independent variables *VCF, SS, FR* and *DOC* represent the cutting fluid viscosity, spindle speed, feed rate and depth of cut respectively.

a. Surface roughness

$$Ra = -1.91 - 0.0266\ VCF + 0.00024\ SS + 17.97\ FR + 1.04\ DOC \quad (3)$$

R-sq = 78.79% and R-sq (adj) = 37.58%

b. Chip compression ratio

$$Z = 1.564 + 0.0137\ VCF - 0.000089\ SS - 2.04\ FR - 0.142\ DOC \quad (4)$$

R-sq = 77.37% and R-sq (adj) = 34.73%

As shown in Equation 3 and 4, it can be seen that R-sq $_{adj}$ values for surface roughness and chip compression ratio values falls below 80%. This may be attributed to noise from the experimental processes.

Conclusion

This study investigated the suitability of using virgin neat palm, sunflower, and coconut oils as lubricants in the turning of AISI 304 Stainless Steel. The study evaluated the surface roughness when machining with the three different oils. Taguchi L9 method was used to design the experiment and the results were analyzed using signal-to-noise ratio smaller-the-better. Sunflower oil performed better in terms of surface roughness. Based on the analyzed results using MINITAB 17 software, it was observed that sunflower oil was the best despite it having almost similar viscosity as palm oil. The study also investigated the chip compression ratio and observed that sunflower oil generated the best chip compression ratio. It was further observed that smokes were generated during the turning process due to the low flash points of the vegetable oils used. Hence, it is recommended that the oils should be improved in terms of the low flash points and poor thermal properties. It is further recommended that more studies on vegetable oils as cutting fluid is necessary in order to ascertain their suitability. Finally, a comparison between machining using vegetable oils and conventional oil should be conducted to further investigate their performance.

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