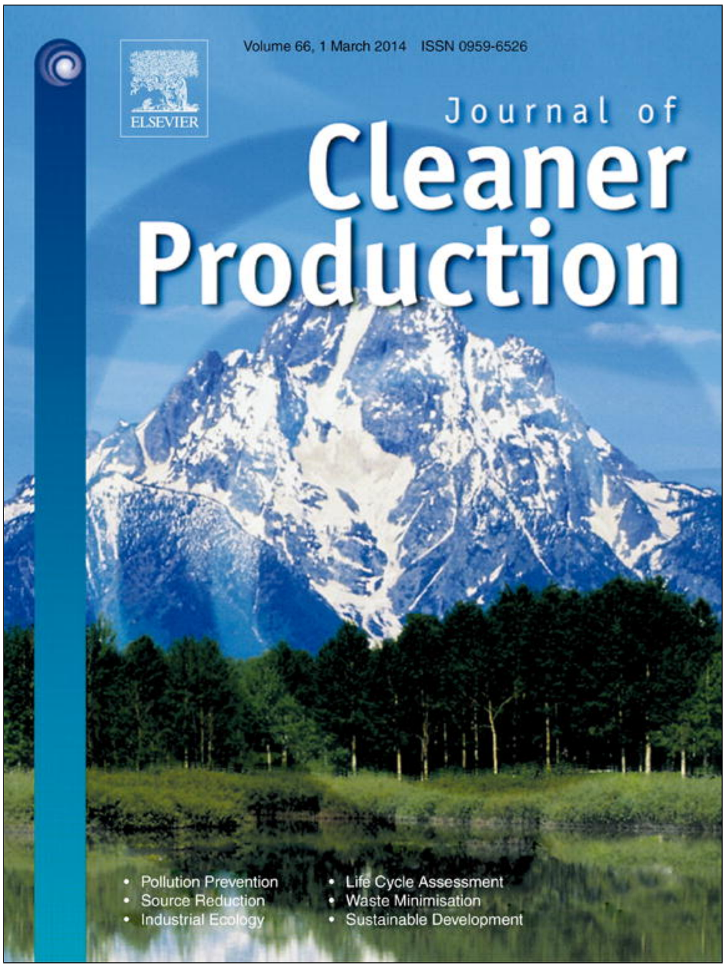
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Evaluation of vegetable and mineral oil-in-water emulsion cutting fluids in turning AISI 4340 steel with coated carbide tools

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A B S T R A C T

The selection of cutting fluid additives for the formulation of oil-in-water emulsion using palm kernel and cottonseed oils are not dangerous or problematic to the environment or harmful to workers. Design of experiment using full factorial method was employed in the process of cutting fluid formulation, while the effect of formulated cutting fluids on surface roughness and cutting force in turning AISI 4340 steel with coated carbide using Taguchi method were investigated and compared with conventional (mineral) oil-in-water emulsion cutting fluid. Four factors and three levels experimental design (L_{27}) was adopted in the Taguchi method. Minitab-14 statistical analysis software which is widely used in engineering application was used in the analysis of S/N (dB) ratio and ANOVA. Cutting speed, feed rate, depth of cut and types of cutting fluids were considered as input parameters. ANOVA results show that cutting speed (64.64%) and feed rate (32.19%) have significant influence on the surface roughness and depth of cut (33.1%) and type of cutting fluids (51.1%) have significant influence on the cutting force.

1. Introduction

The search for sustainable and environmentally friendly substitutes to mineral oils as base oil in metalworking fluids (MWFs) during machining process has become a leading research area in the cutting fluid industry. This is due to the growing concern on the impact of MWFs on the environment. The demand for sustainable biodegradable MWFs for cleaner production and reduction in the use of mineral oils-based cutting fluid that cause environmental degradations can be traced to regulations of many countries like Austria, Canada, Hungary, Japan, Poland, Scandinavia, Switzerland, USA and EU (Bartz, 2006). Vegetable oil-based cutting fluids are environmentally friendly, renewable, less toxic and economical in the reduction of the waste treatment costs due to their inherently higher biodegradability (Cetin et al., 2011). Machining industries concern for development of preventive legislation and the increased interest in almost green products reduce the soil pollution by biodegradability which make the manufacturing processes a clean process (Alves and Oliveira, 2006). Vegetable oil-based cutting fluids seem to be the best alternatives to mineral oil-based cutting fluids due to certain inherent chemical properties and their biodegradability ability. It has been established that vegetable oil-based MWFs have extremely performed better than mineral oil-based cutting fluids during machining processes (Lawal et al., 2013). The better performance of vegetable oil-based cutting fluids can be traced to its high flash point, high viscosity index, high lubricity and low evaporative loss compared to mineral oils (Adhvaryu and Erhan, 2002). Poor oxidative and hydrolytic stability, high temperature sensitivity of tribological behaviour and poor cold flow properties are the limitations of vegetable oils for lubricants (Erhan and Asadauskas, 2000). However, these shortcomings in the vegetable oils can be addressed with addition of chemical additives such as EP, emulsifier, corrosion prevention, pH regulation, binding, anti-foaming, odour prevention, flash point improver, spreading and wetting to improve its functions as lubricant. Though lubricants based on mineral oils have been used in all kinds of applications since the beginning of industrialization including industrial gears, automotive engines, metalworking application, transmission and hydraulic systems, it has been discovered that mineral oil with the same viscosity as that of the vegetable or animal based oils was not as effective a lubricant as the latter. This was attributed to a property of the vegetable or animal oils and fats called “oiliness” or “lubricity” (Ratoi et al., 2000). Lubricity or oiliness of vegetable oils is attributed to their ability to absorb the metallic surfaces and to form a tenacious monolayer, with the polar head of the oil adhering to the metallic surfaces and the hydrocarbon chains orienting in near normal directions to the surface (Weijiu et al., 2003).

Vegetable products as well as modified vegetable oil esters can be used as a basestock for preparation of environment friendly,

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rapidly biodegradable lubricants. The production of environment friendly, rapidly biodegradable fluids for lubricants based on petrochemicals such as polyalphaolefins, polyglycols, polyalkylene glycols and synthetic esters are also discussed in literature (van Voorst and Alam, 2000). However, vegetable oils are preferred over these synthetic fluids because they are from renewable resources and cheaper (Adhvaryu and Erhan, 2002). The performance limitations of vegetable-based lubricants stem from inherent properties of the vegetable oil-basestocks rather than composition of additive package. Basestocks usually comprise more than 90% of the lubricants and nearly entirely pre-define properties such as high biodegradability, low volatility, ideal cleanliness or cleaner production, high solvency for lubricant additives, miscibility with other types of system fluids, negligible effects on seals and elastomers, and other less significant properties (e.g. density or heat conductivity) (Erhan and Asadauskas, 2000). Basestocks are also a major factor in determining oxidative stability, deposit forming tendencies, low temperature solidification, hydrolytic stability, and viscometric properties. On the other hand, parameters like lubricity, wear protection, load carrying capacity, corrosion (rust) prevention, acidity, ash content, colour, foaming, de-emulsification (so called demulsibility), water rejection, and a number of others are mostly dependent on the additives or impurities/contaminants (Erhan and Asadauskas, 2000). Wagner et al. (2001) believed that more than 90% of all present day lubricants can be formulated to be rapidly biodegradable from a technical point of view. However, Mang et al. (1997) felt that a great deal of developmental work still needed to be done especially on its present high costs.

Mineral and synthetic oil-based cutting fluids are widely used in machining processes. The effects of mineral oil-based cutting fluids and dry cutting in turning AISI 4340 steel have been well established. Seah et al. (1995) investigated conventional water soluble lubricant on tool wear during turning of AISI 4340 steel with uncoated tungsten tools. Cydas (2010) studied the effect of dry cutting on surface roughness, tool flank wear and temperature during turning of AISI 4340 steel with ceramic tools. Suresh et al. (2012) examined the effect of dry cutting on surface roughness, tool wear, cutting force, machine power during machining of AISI 4340 steel with cemented carbide tools. Dhar et al., 2006) evaluated tool wear and surface roughness under dry, wet (conventional) and MQ during turning of AISI 4340 steel with coated carbide tools. There are other literature on machining of AISI 4340 steel under dry cutting, however, only Avila and Abrao (2001) work investigated the effect of emulsion without mineral oil, emulsion synthetic, emulsion with mineral oil on tool wear, tool life, surface roughness and chip formation during turning of AISI 4340 steel with alumina tools. This study therefore presents emulsion cutting fluids formulated from palm kernel and cottonseed oils using design of experimental (DOE) method. Effects of the formulated emulsion cutting fluids on surface roughness and cutting force during turning of AISI 4340 steel with coated carbide were investigated and compared with conventional (mineral) oil-based cutting fluid.

2. Materials and methodology

2.1. Formulation of the new cutting fluids

The search for a balance in meeting both the technological and environmental requirements of a new cutting fluid for machining process forms the basis of this research. Hence, for the preparation of the new cutting fluids, efforts were made to ensure that the selections of cutting fluid components are not dangerous or problematic to the environment or hazardous to workers. The following materials were used in the formulation of oil-in-water emulsion cutting fluids:

(a) Oils (palm kernel oil, cottonseed oil and mineral oil)
(b) Water (pH value 7.72)
(c) Additives: emulsifier, anti-corrosive agent, antioxidant and biocide.

For both vegetable oil based and mineral oil based cutting fluids, water to oil ratio of 9: 1 was used. The new cutting fluid did not include banned products in their composition like chlorine substances and nitrosamines. Simpler formula was adopted with fewer additives to facilitate easy treatment and disposal of cutting fluid after use as suggested by Hubner (1994). The formulation of oil-in-water emulsion cutting fluids using palm kernel oil (PKO) and cottonseed oil (CSO) involved the application of design of experiment (DOE) method under the conditions established by a 2^4 full factorial design. Tables 1 and 2 show variables (additives) and levels employed in the factorial design and experimental matrix of the 2^4 full factorial designs respectively.

Each run as shown in Table 2 was formulated by first mixing oil in water with additives. This mixture was done with the aid of mechanical stirrer at 760 rpm for 10 min at room temperature of 25 °C as shown in Fig. 1.

The data obtained for the pH values for all the experimental runs were analysed statistically using version 6 of DOE® software. The software used for the analysis uses a second degree polynomial, approximated by equation (1), to predict the response, Y, which includes all factors as well as the most effectual way the factors interact.

$$Y = \beta_0 + \sum \beta_i x_i + \sum \beta_{ii} x_i^2 + \sum \beta_{ij} x_i x_j \tag{1}$$

whereβ_0 is constant, β_i and β_{ij} are coefficient of ij; x_i represents independent variables and x_{ij} denotes the interactions thereof (Montgomery, 2009).

The optimal values were then used to formulate and characterize the new cutting fluid. The mineral (conventional) oil which was sourced as concentrated oil was used to prepare emulsion cutting fluid without any addition of additives.

2.2. Turning test

The turning process was performed on a Colchester VS Master 3250 (165 mm × 1270 mm) gap bed centre lathe rated with 7.5 kW and spindle speed of 3250 rpm as shown in Fig. 2(a and b). A round bar of AISI 4340 steel alloy with 90 mm diameter and 360 mm length was chosen so as to maintain a ratio of cylindrical turning length to the initial diameter of workpiece at 4 in order to ensure the required stiffness of chuck/workpiece/cutting force. AISI 4340 alloy steel of HB 270 -310 hardness has gained wide acceptance in numerous industries for applications such as shafts, gears, and aircraft landing gear and it contains carbon (0.35%), chromium (1.40%), iron (95.95%), manganese (0.70%), molybdenum (0.20%) and nickel (1.40%) by weight.

TiN coated tungsten carbide CNMA 12 04 08 KR tool insert was mounted on a left hand tool holder with model number PSBNR

Table 1
Variables and levels employed in the factorial design.

Factor	Symbol	Level	
		Minimum − (%)	Maximum + (%)
Emulsifier	A	8.0	12
Anticorrosive agent	B	2.0	4.0
Antioxidant	C	0.5	1.0
Biocide	D	0.5	1.0

Table 2
Experimental matrix of the 2^4 full factorial designs.

Array no	Variable examined (levels)			
	A	B	C	D
1	–	–	–	–
2	+	–	–	–
3	–	+	–	–
4	–	–	+	–
5	–	–	–	+
6	+	+	–	–
7	+	–	+	–
8	+	–	–	+
9	–	+	+	–
10	–	+	–	+
11	–	–	+	+
12	+	+	+	–
13	+	–	+	+
14	–	+	+	+
15	+	+	–	+
16	+	+	+	+

2525M12. The experimental set up was based on design of experiment (DOE) via Taguchi method and three cutting parameters namely; cutting speed, feed rate and depth of cut were considered for experimentation. In addition, the type of cutting fluid used was also considered as one of the critical input parameters. Hence, there were four input parameters and for each parameters, three levels were assumed as shown in Table 3.

For a four-factor-three-level experiment, Taguchi had specified L_{27} (3^4) orthogonal array for experimentation as shown in Table 4. In each experimental run a fresh cutting tool insert was used for a fixed cutting time of 15 min for each of the cutting fluid. The cutting fluid was applied using conventional (flood) method.

Surface roughness and cutting force were chosen as output parameters for evaluation using the two vegetable oil-based cutting fluids and mineral oil-based cutting fluid. A portable surface roughness tester MAHR Perthometer M2Pi was used to measure the surface roughness (Ra) of the workpiece material as shown in Fig. 3.

Three measurements were taken along the shaft axis for each sample and the average value was used for the analysis. A tri-axial force dynamometer type: Kistler 9257A model was used to capture the force signals during the cutting process in X, Y and Z directions, which was connected to charge amplifiers and a personal computer through an analogue to digital converter card. The dynamometer consists of three-component force sensors fitted under high preload between a base plate and a top plate. Each sensor contains three pairs of quartz plates, one sensitive to pressure in the Z direction and the other two responding to shear in the X and Y directions respectively. The frequency range of the tri-axial force dynamometer is 10Hz–400 kHz. To obtain and record the force data, LabVIEW 2010 software with data acquisition (DAQ) system was used. Cutting forces and their amplitudes were calibrated with an accuracy of measurement with ±126.95 N, 126.95 N and 278.5 N for the feed force (*Fx*), radial force *(Fy)* and machining cutting force (*Fz*) components of the force respectively.

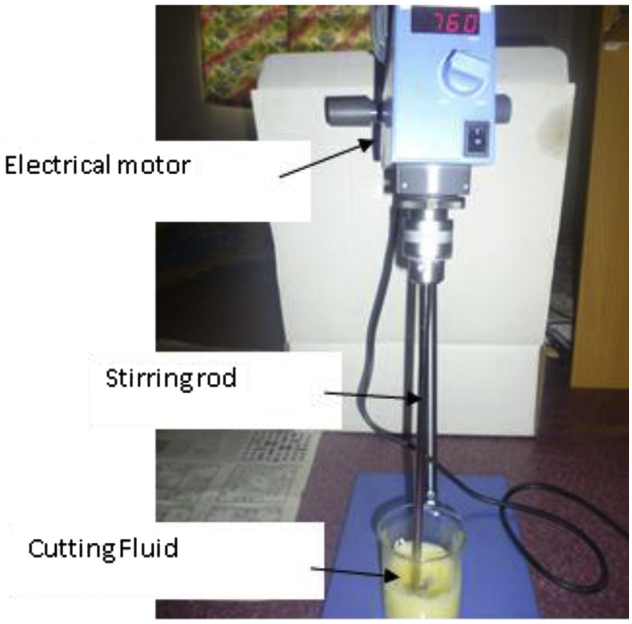

Fig. 1. Mixing with mechanical overhead stirrer.

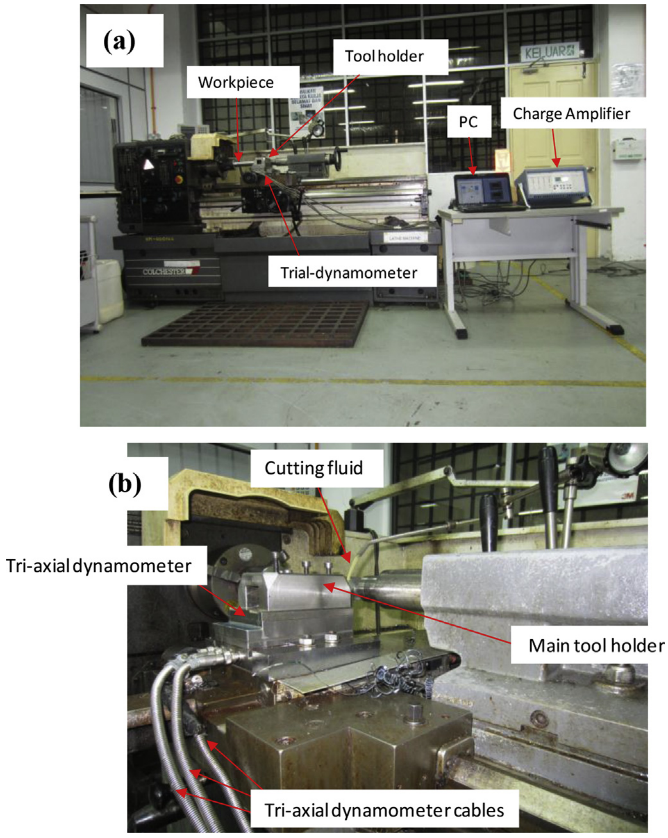

Fig. 2. Experimental set up for turning process.

3. Results and discussion

3.1. Formulation and characteristics of cutting fluids

The optimized values obtained for PKO based cutting fluid were emulsifier (8.31 vol. %); anticorrosive agent (2.93 vol. %);

Table 3
Process parameters and their levels.

Factor	Unit	Level 1	Level 2	Level 3
Cutting speed	m/min	160	200	250
Feed rate	mm/rev	0.18	0.24	0.32
Depth of cut	mm	1.0	1.75	3.0
Type of cutting fluids	mm^2/s	2.97(PKO)	1.04(CSO)	0.87(MO)

PKO (palm kernel oil), CSO (cottonseed oil) and MO (mineral oil) based cutting fluids.

Table 4
Experimentation layout using an L27 orthogonal array.

Trial no.	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Cutting fluids η (mm^2/s)
1	1	1	1	PKO
2	1	1	1	CSO
3	1	1	1	MO
4	1	2	2	PKO
5	1	2	2	CSO
6	1	2	2	MO
7	1	3	3	PKO
8	1	3	3	CSO
9	1	3	3	MO
10	2	1	2	PKO
11	2	1	2	CSO
12	2	1	2	MO
13	2	2	3	PKO
14	2	2	3	CSO
15	2	2	3	MO
16	2	3	1	PKO
17	2	3	1	CSO
18	2	3	1	MO
19	3	1	3	PKO
20	3	1	3	CSO
21	3	1	3	MO
22	3	2	1	PKO
23	3	2	1	CSO
24	3	2	1	MO
25	3	3	2	PKO
26	3	3	2	CSO
27	3	3	2	MO

antioxidant (0.95 vol. %) and biocide (0.99 vol. %). For CSO formulated cutting fluid, the optimal values were emulsifier (11.81 vol. %); anticorrosion (3.67 vol. %); antioxidant (0.76 vol. %), biocide (0.64 vol. %). The new cutting fluid concept consists of high concentration of water to oil with a ratio of 9:1 with few additives that do not contain banned substances. This will help in the treatment and disposal of the cutting fluids after usage. It is therefore, possible to have a better heat conductivity and good environmental properties in one fluid. The same water to oil ratio used for vegetable oil was used for the mineral oil without any additive because the mineral oil was in concentrated form. The physical and chemical characteristic of the new cutting fluid and mineral oil based cutting fluid are presented in Table 5.

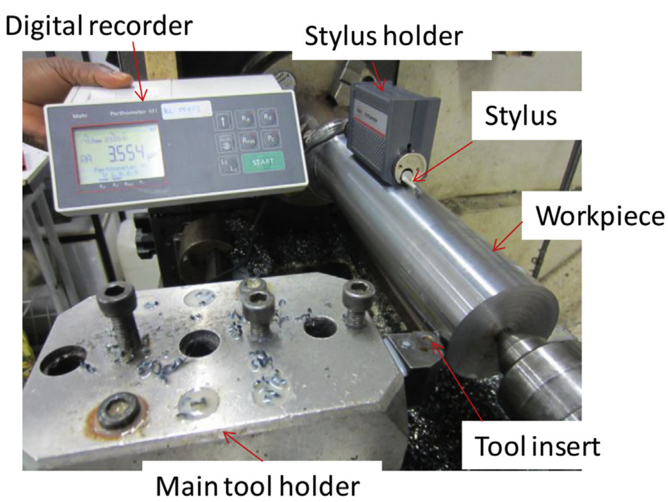

Fig. 3. Set up for surface roughness measurement.

Table 5
Characteristics of oil-in-water emulsion cutting fluid.

S/N	Property	Value		
		PKO	CSO	MO
1	pH value	10.46	10.98	8.9
2	Viscosity	2.97 mm^2/s	1.04 mm^2/s	0.87 mm^2/s
3	Corrosion level	Corrosion resistant	Corrosion resistant	7% Breakpoint (DIN51360/11)
4	Stability	Stable	Stable	Stable
5	Colour	Whitish	Yellowish	Milky whitish

3.2. Surface roughness

Three measurements were taken along the shaft axis of the workpiece material for each sample and the average value as shown in Table 6 was used for analysis. The S/N ratio values for both surface roughness and cutting force are shown in Table 7 and in optimizing the process in this study, the lower the S/N (dB) ratio the better characteristic as shown in equation (2) was chosen. Minitab-14 statistical analysis software widely used in engineering application was used in the analysis of S/N (dB) ratio and ANOVA.

$$S/N = -10\log\frac{1}{n}\left(\sum y_i^2\right) \qquad (2)$$

where S/N is signal to noise ratio, n is the number of repetition in a trial and y is the measure quality characteristic for the ith repetition

The main effect plot of S/N ratio for surface roughness shown in Fig. 4, the optimal cutting parameters for the surface roughness as: 200 m/min of cutting speed (level 2), 0.18 mm/rev of feed rate (level 1), 1.75 mm of depth of cut (level 2) and PKO based cutting fluid with viscosity of 2.97 mm^2/s (level 3). Vegetable oil with 2.97 mm^2/s viscosity is seen to have more influence on surface roughness than the other cutting fluids. PKO has a greater effect in comparison to

Table 6
Experimental data and results for AISI 4340 steel machining with coated carbide tools.

Trial no.	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Cutting fluids η (mm^2/s)	Surface roughness (Ra, μm)	Cutting force (N)
1	160	0.18	1.0	2.97	0.48	508.93
2	160	0.18	1.0	1.04	0.56	543.76
3	160	0.18	1.0	0.87	0.88	636.66
4	160	0.24	1.75	2.97	1.12	563.76
5	160	0.24	1.75	1.04	1.3	862.41
6	160	0.24	1.75	0.87	1.42	990.14
7	160	0.32	3.0	2.97	1.82	767.62
8	160	0.32	3.0	1.04	2.04	1086.28
9	160	0.32	3.0	0.87	1.82	1214.00
10	200	0.18	1.75	2.97	0.4	396.47
11	200	0.18	1.75	1.04	0.62	715.12
12	200	0.18	1.75	0.87	0.66	842.85
13	200	0.24	3.0	2.97	0.81	589.92
14	200	0.24	3.0	1.04	0.92	908.57
15	200	0.24	3.0	0.87	1.04	1036.30
16	200	0.32	1.0	2.97	1.6	340.31
17	200	0.32	1.0	1.04	1.76	658.96
18	200	0.32	1.0	0.87	2.08	786.68
19	250	0.18	3.0	2.97	2.16	563.40
20	250	0.18	3.0	1.04	2.28	882.05
21	250	0.18	3.0	0.87	2.34	1009.78
22	250	0.24	1.0	2.97	2.2	283.37
23	250	0.24	1.0	1.04	2.48	602.03
24	250	0.24	1.0	0.87	2.64	729.75
25	250	0.32	1.75	2.97	3.24	667.26
26	250	0.32	1.75	1.04	3.4	985.92
27	250	0.32	1.75	0.87	3.62	1113.64

Table 7
Corresponding S/N (dB) ratios for surface roughness and cutting force.

Trial	Surface roughness	Cutting force	S/N ratio for surface roughness	S/N ratio for cutting force
1	0.48	508.93	6.3751	−54.1332
2	0.56	543.76	5.0362	−54.7081
3	0.88	636.66	1.1103	−56.0781
4	1.12	563.76	−0.9843	−55.0218
5	1.3	862.41	−2.2788	−58.7143
6	1.42	990.14	−3.0457	−59.9138
7	1.82	767.62	−5.2014	−57.7029
8	2.04	1086.28	−6.1926	−60.7188
9	1.82	1214.00	−5.2014	−61.6843
10	0.4	396.47	7.9588	−51.9642
11	0.62	715.12	4.1521	−57.0876
12	0.66	842.85	3.6091	−58.5149
13	0.81	589.92	1.8302	−55.4158
14	0.92	908.57	0.7242	−59.1672
15	1.04	1036.30	−0.3406	−60.3097
16	1.6	340.31	−4.0823	−50.6374
17	1.76	658.96	−4.9102	−56.3771
18	2.08	786.68	−6.3612	−57.9159
19	2.16	563.40	−6.6890	−55.0163
20	2.28	882.05	−7.1586	−58.9098
21	2.34	1009.78	−7.3843	−60.0845
22	2.2	283.37	−6.8484	−49.0471
23	2.48	602.03	−7.8890	−55.5923
24	2.64	729.75	−8.43207	−57.2634
25	3.24	667.26	−10.2109	−56.4859
26	3.4	985.92	−10.6295	−59.8768
27	3.62	1113.64	−11.1741	−60.9348

other cutting fluids. The effectiveness of each cutting fluid in improving the value of surface roughness follows this sequence: palm kernel oil-based cutting fluid, cottonseed oil-based cutting fluid and mineral oil-based cutting fluid.

The different behaviour of vegetable oil based cutting fluids can be explained by the structure of the plants which contain different number of fatty acids. The saturated nature of palm kernel oil imparts a strong resistance to oxidative stability at higher values of the investigated parameters, which help in maintaining its properties compared with cottonseed oil which is unsaturated oil. This is in agreement with literature (Xavior and Adithan, 2009).

The ANOVA analysis for surface roughness as in Table 8 shows the contribution of each input parameter as: cutting speed

Table 8
ANOVA analysis for surface roughness.

Factor	DF	SS	MS	*F*	*P* %
Cutting speed (m/min)	2	14.026	0.779222	53.53435	0.644636
Feed rate (mm/rev)	2	7.004	0.389111	26.73282	0.321905
DOC (mm)	2	0.067	0.003722	0.255725	0.003079
Type of cutting fluid (mm^2/s)	2	0.399	0.022167	1.522901	0.018338
Error	18	0.262	0.014556		0.012042
Total	26	21.758			

(64.64%); feed rate (32.19%); depth of cut (0.31%) and cutting fluids (1.83%). It shows that cutting speed (64.64%) and feed rate (32.19%) have significant influence on the surface roughness during the turning process. The influence of various depths of cut and cutting fluids on the surface roughness is less significant. The confidence level specified for this analysis is 95%.

Figs. 5 and 6 show the contour plot and normal probability plot for surface roughness. Surface roughness increase as cutting speed increases with increase in feed rate as depicted in Fig. 5. The normal probability plot shows that cutting speed and feed rate are independent significant factors that affect surface roughness. While the combinations of (i) feed rate and depth (ii) cutting speed and depth of cut have significant effect on the surface roughness.

A careful study of Fig. 6 shows that there is a general trend of improvement on surface roughness by PKO and CSO based cutting fluids over MO based cutting fluid. This is in agreement with literature (Cetin et al., 2011).

3.3. Cutting force

The cutting force was determined from the following relationship in equation (3) and shown in Table 6.

$$F_c = \sqrt{F_x^2 + F_y^2 + F_z^2} \qquad (3)$$

where F_c = machining force; F_x = feed force; F_y = radial force and F_z = main cutting force.

Similarly, using Minitab-14 and the-lower-the-better characteristic for the cutting force response. The main effect plot of S/N ratio for cutting force shown in Fig. 7, the optimal cutting

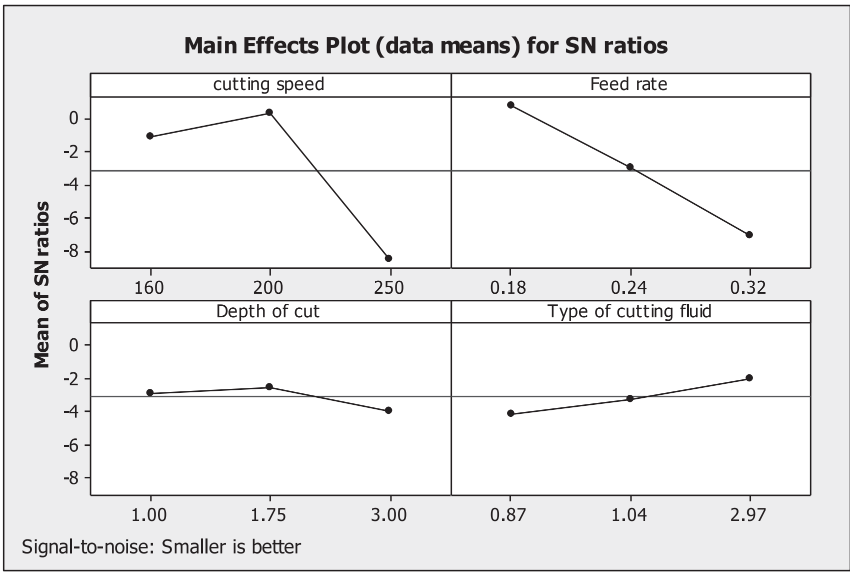

Fig. 4. Main effects plot for SN ratios for surface roughness.

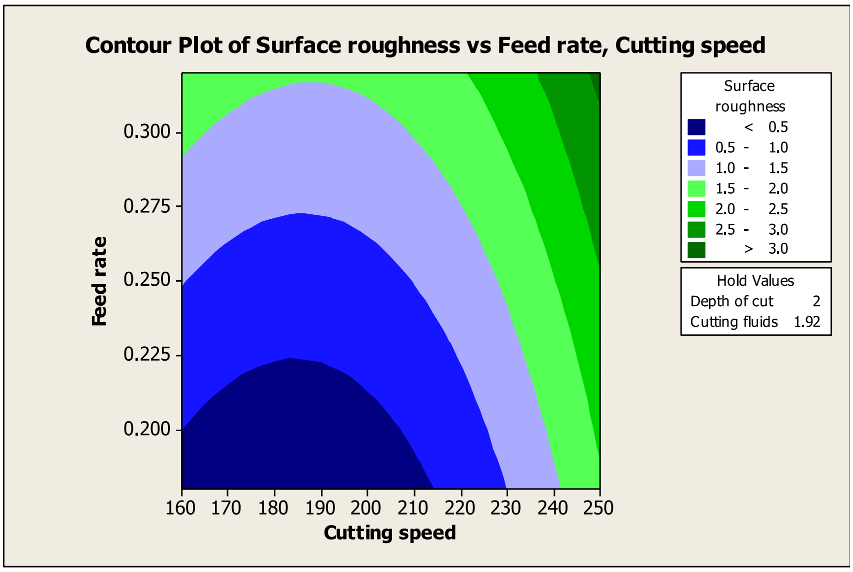

Fig. 5. Contour plots for surface roughness (Feed rate vs Cutting speed).

parameters for the cutting force as: 200 m/min of cutting speed (level 2), 0.18 mm/rev of feed rate (level 1), 1.00 mm of depth of cut (level 2) and 2.97 mm^2/s viscosity of palm kernel oil based cutting fluid (level 3). To reduce the cutting force in this experiment, cutting fluids can be used in the following sequence; palm kernel oil-based cutting fluid (2.97 mm^2/s), cottonseed oil-based cutting fluid (1.04 mm^2/s) and mineral oil-based cutting fluid (0.87 mm^2/s). The behaviour of different cutting fluids on the cutting force can be attributed to their fatty acid properties of the oils used to develop them. The application of cutting fluid is believed to reduce the friction coefficient between the tool–workpiece interfaces and hence there is a significant cutting force reduction. It is believed that a thin boundary film was formed between the tool–workpiece interfaces. Palm kernel oil has a high proportion of saturated fatty acids and viscosity, therefore enabling the oil to provide high strength lubricant films that interact strongly with the contact surfaces despite the small amount of oil in the formulation. Triglycerides of vegetable oils are known to provide excellent lubricity due to the trigycerol molecule that attaches to the metal surface. This enables the monolayer film formation with the non-polar fatty acids chains, which provides sliding at the contact surface (Yunus et al., 2004). Both vegetable oils in this study show lower cutting force compared with the mineral oil based cutting fluid which is in agreement with Belluco and De Chiffre (2004).

The ANOVA analysis for cutting force as in Table 9 shows the contribution of each input parameter as: cutting speed (2.9%); feed rate (8.7%); depth of cut (33.1%) and cutting fluids (51.1%). It shows that depth of cut (33.1%) and type of cutting fluids (51.1%) have significant influence on the cutting force during the turning process. The influence of various cutting speed and feed rate on cutting force is less significant. The confidence level specified for this analysis is 95%.

Figs. 8 and 9 show the contour plot and normal probability plot for cutting force. Cutting force increases as depth of cut increases

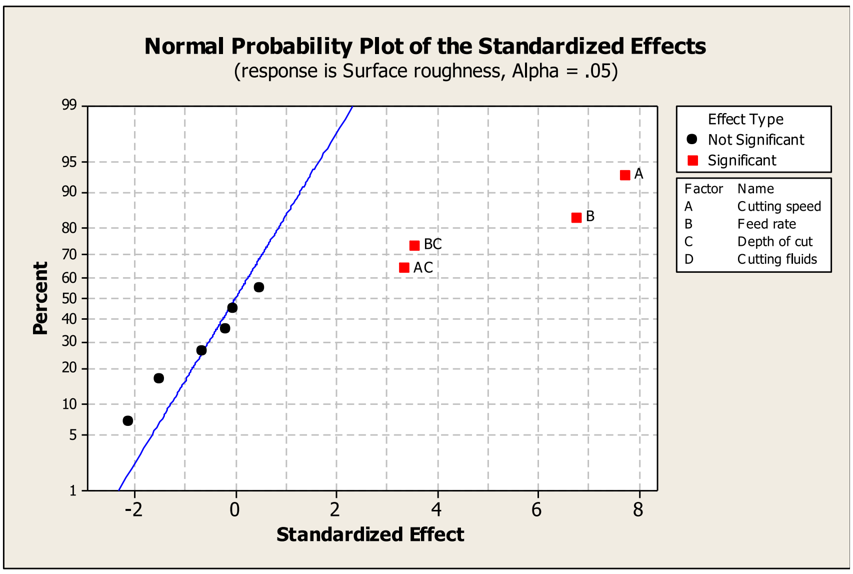

Fig. 6. Normal probability plot for surface roughness.

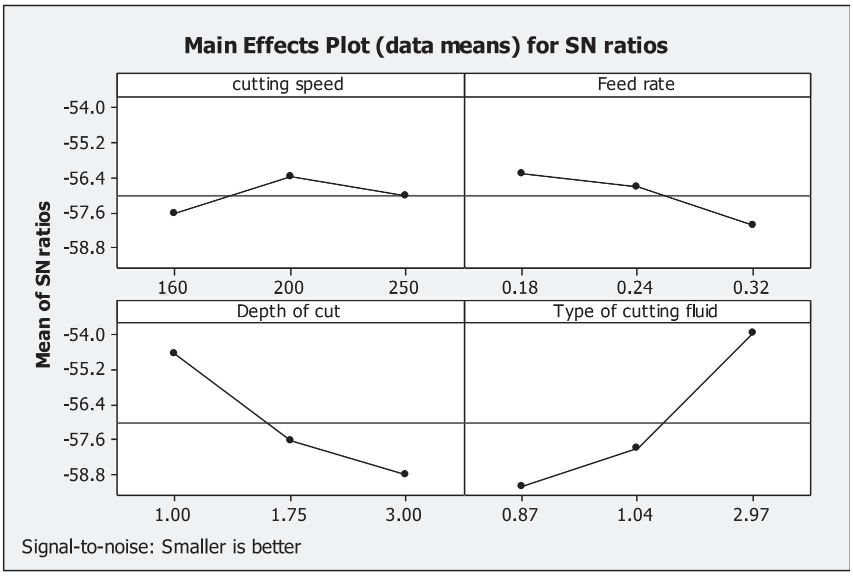

Fig. 7. Main effects plot of SN ratios for main cutting force.

Table 9
ANOVA for cutting force.

Factor	DOF	SS	MS	*F*	*P* %
Cutting speed (m/min)	2	45,781	22,890.5	6.60	0.029
Feed rate (mm/rev)	2	135,019	67,509.5	19.47	0.087
DOC (mm)	2	512727	256,363.5	73.93	0.331
Type of cutting fluid (mm^2/s)	2	790,749	395,374.5	114.02	0.511
Error	18	62,419	3467.7		0.040
Total	26	1546,695			

with decrease in viscosity of cutting fluids as depicted in Fig. 8. The normal probability plot shows that feed rate, depth of cut and types of cutting fluids are independent significant factors that affect cutting force.

A careful study of Table 6 shows that there is a general trend of cutting force reduction by PKO and CSO based cutting fluids over MO based cutting fluid. This is in agreement with Avila and Abrao (2001) who reported that mineral oil based cutting fluids possessed low efficiency at high cutting speeds.

3.4. Confirmation tests

Mathematical models for cutting parameters such as cutting speed, feed rate, depth of cut and cutting fluids were obtained from regression analysis using MINITAB 14 software to predict surface roughness and cutting force. Experiments were conducted based on the optimized values to validate the regression equations for both surface roughness and cutting force. Table 10 shows the percentage error during validation. The following notations were used in the mathematical models V_c: cutting speed, f: feed rate, a_p: depth of cut, CF: cutting fluid, *Ra:* surface roughness and F_c: cutting force.

(a) the surface roughness (Ra) model equation is as follows:

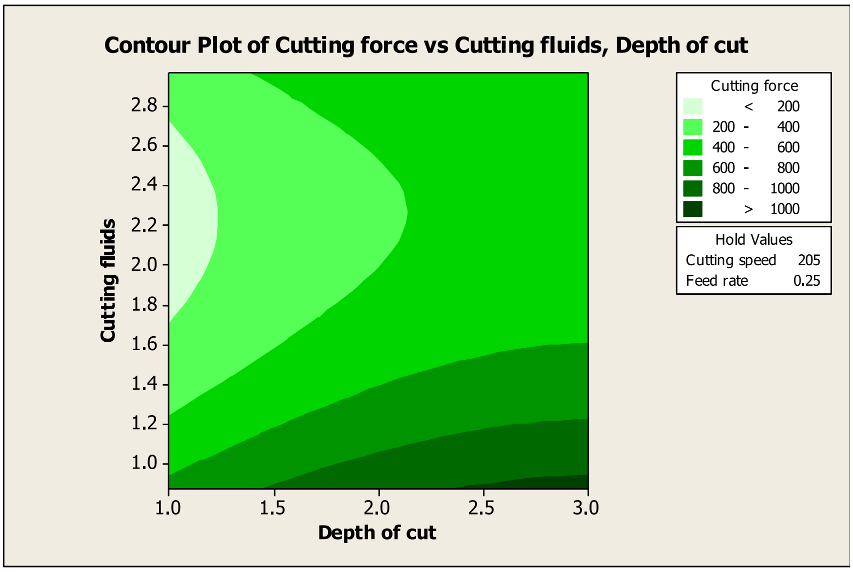

Fig. 8. Contour plots for cutting force (cutting fluid vs depth of cut).

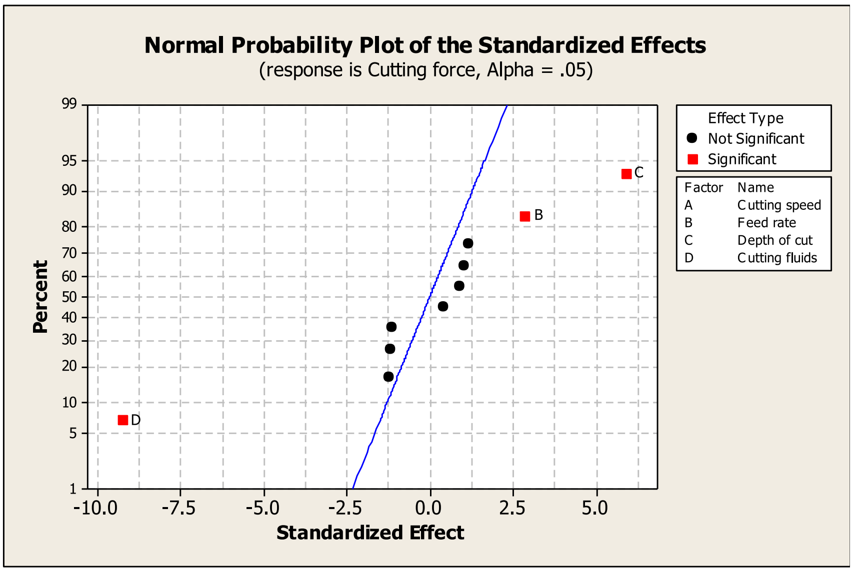

Fig. 9. Normal probability plot for cutting force.

$$R_a = -3.71 + 0.0166V_c + 8.82f + 0.022a_p - 0.119CF$$

When $V_c = 200$ m/min, $f = 0.18$ mm/rev, $a_p = 1.75$ mm and CF = 2.97 mm^2/s

$$R_a = 0.883\ \mu\text{m}$$
$$R^2 = 79.8\% \text{ and } R^2(\text{adj}) = 76.1\%$$

(b) the cutting force (Fc) model equation is as follows:

$$F_C = 497 - 0.323V_C + 1223f + 157a_p - 173CF$$

When $V_c = 200$ m/min, $f = 0.18$ mm/rev, $a_p = 1.0$ mm and CF = 2.97 mm^2/s

$$F_C = 295.73\ \text{N}$$
$$R^2 = 85.1\% \text{ and } R^2(\text{adj}) = 82.4\%$$

All the values of R^2 obtained from surface roughness, cutting force and flank wear are in agreement with regression models. In any multiple linear regression analysis, R^2 is a value of correlation coefficient and should be between 0.8 and 1.0 (Montgomery et al., 1998).

4. Conclusions

The main contribution of this study is that novel vegetable oil-in-water emulsion cutting fluids formulations have been developed, which could be used to improve the surface roughness and cutting force during turning of AISI 4340 steel with coated carbide tools. The pH values for PKO (10.46) and CSO (10.98) cutting fluids are within the acceptable level required to avoid corrosion during machining process and does not pose any health hazard to worker.

Table 10
Confirmation test percentage error.

Parameter	Calculated value	Experimental value	Percentage error (%)
Surface roughness	0.883 µm	0.921 µm	4.13
Cutting force	295.73 N	285.83 N	3.35

The higher percentage of water (90%) to oil (10%) in the formulation of vegetable oil-in-water emulsion cutting fluids makes it possible to have better heat conductivity and environmentally friendly properties.

The optimal cutting parameters for the surface roughness using S/N ratio are: cutting speed (200 m/min); feed rate (0.18 mm/rev); depth of cut (1.75 mm) and cutting fluid (2.97 mm^2/s). And the optimal cutting parameters for the cutting force are: cutting speed (200 m/min), feed rate (0.18 mm/rev); depth of cut (1.00 mm) and cutting fluid (2.97 mm^2/s). ANOVA shows cutting speed (64.64%) and feed rate (32.19%) as significant factors that affect surface roughness. While depth of cut (33.1%) and cutting fluid (51.1%) are significant factors that affect the cutting force.

Multiple regression analysis performed indicated the fitness of the experimental measurements. Regression models obtained for both surface roughness and cutting force were at acceptable points and the confirmation tests applied for the regression equations showed reliable results. The results obtained from this experiment clearly showed that both PKO and CSO based cutting fluids are better alternatives for machining AISI 4340 steel with coated carbide.

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