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ORIGINAL CONTRIBUTION

Experimental Evaluation and Optimization of Flank Wear During Turning of AISI 4340 Steel with Coated Carbide Inserts Using Different Cutting Fluids

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Abstract The understanding of cutting fluids performance in turning process is very important in order to improve the efficiency of the process. This efficiency can be determined based on certain process parameters such as flank wear, cutting forces developed, temperature developed at the tool chip interface, surface roughness on the work piece, etc. In this study, the objective is to determine the influence of cutting fluids on flank wear during turning of AISI 4340 with coated carbide inserts. The performances of three types of cutting fluids were compared using Taguchi experimental method. The results show that palm kernel oil based cutting fluids performed better than the other two cutting fluids in reducing flank wear. 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 flank wear. Experiments were conducted based on the optimized values to validate the regression equations for flank wear and 5.82 % error was obtained. The optimal cutting parameters for the flank wear using S/N ratio were 160 m/min of cutting speed (level 1), 0.18 mm/rev of feed (level 1), 1.75 mm of depth of cut (level 2) and 2.97 mm^2/s palm kernel oil based cutting fluid (level 3). ANOVA shows cutting speed of 85.36 %; and feed rate 4.81 %) as significant factors.

Keywords ANOVA · Turning process · Cutting fluids · Flank wear

Introduction

Cutting fluids have been used severally in the machining process to improve the tribological characteristics of the workpiece-tool-chip system. The use of water as coolant during machining was first reported by Taylor in 1907, when 40 % increase in cutting speed while machining steel material with high speed tools was achieved [1]. Increased tool life, improved surface finish and reduced cutting force have been reported during machining processes when cutting fluids are used [2]. 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 [3]. 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. Cydas [4] 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. [5] 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. Seah et al. [6] investigated conventional water soluble lubricant on tool wear during turning of AISI 4340 steel with uncoated tungsten tools. Dhar et al. [7] evaluated tool wear and surface roughness under dry, wet (conventional) and MQ during turning of AISI 4340 steel with coated carbide tools.

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Avila and Abrao [8] 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 experiments (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.

Xavior and Adithan [9] studied the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 austenitic stainless steel with carbide tool using three different types of cutting fluids (coconut oil, emulsion and a neat cutting oil-immiscible with water). The experimentation work was based on Taguchi's DOE with L_{27} (3^4) orthogonal array using cutting speed, depth of cut, feed rate and types of cutting fluids as critical input parameters. A model calculation using multiple linear regression models were developed to determine the tool wear and surface roughness; while, ANOVA was used to determine the significant parameters that influenced the tool wear and surface roughness. The results obtained shows that coconut oil had greatest influence on the surface roughness and tool wear followed by straight cutting oil and soluble oil had the least effect at a constant depth of cut. The authors observed that (i) feed rate had greater influence on surface roughness with 61.54 % contribution and cutting speed has greater influence on tool wear with 46.49 % contribution for all the cutting fluids; (ii) the relative performance of the effectiveness of the cutting fluids in reducing the tool wear and improving the surface finish was better when coconut oil was used compared to conventional mineral oil. Similarly, Krishna et al. [10], investigated the performance of nanoboric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel with cemented carbide tool (SNMG 120408). The variation of cutting tool temperatures, average tool flank wear and the surface roughness of the machined surface with cutting speed were studied using nonsolid lubricant suspensions in lubricating oil. The experiments were conducted under the following conditions; cutting speed (60, 80 and 100 m/min); feed rate (0.14, 0.16 and 0.2 mm/rev); depth of cut (1.0 mm). Solid lubricants of boric acid with particle size of 50 nm, lubricating oil SAE-40 and coconut oil with flow rate of 10 ml/min were used for lubrication. Tool flank wear was measured at different lubricating conditions and at various cutting speeds. Flank wear increased gradually with increase in speed and feed rate. The combined effect of solid lubricant and vegetable oil led to the reduction in flank wear with 0.5 % nanoboric acid particles suspensions in coconut oil compared to the remaining conditions.

Khan et al. [11] studied the effects of minimum quality lubrication (MQL) using vegetable oil-based cutting fluid on turning performance of AISI 9310 low alloy steel using uncoated carbide tool and compared with completely dry and wet machining in terms of chip–tool interface temperature, chip formation mode, tool wear and surface roughness. The process parameters used were cutting velocity (223, 246, 348 and 483 m/min), feed rate (0.10, 0.13, 0.16 and 0.18 mm/rev) and depth of cut (1.0 mm). They found that when machining with MQL, the form of these ductile chips did not change appreciably, but their back surface appeared much brighter and smoother. The colour of the chips became much lighter i.e. blue or golden from burnt blue depending on the cutting velocity and feed rate, due to reduction in cutting temperature by MQL. The gradual growth of average principal flank wear, the predominant parameter to ascertain the expiry of tool life were observed under all the environments and it indicated steady machining without any premature tool failure by chipping, fracturing, etc., establishing proper choice of domain of process parameters. In this study, the effect of palm kernel oil based emulsion cutting fluid, cottonseed oil based emulsion cutting fluid and mineral oil based emulsion cutting fluids on flank wear during turning of AISI 4340 steel with coated carbide inserts have been investigated and optimized using Taguchi method. The coating behaviour of coated carbide after machining was not investigated.

Materials and Methods

Development of the New Cutting Fluids

The materials and method about to be described both for formulation of cutting fluids and turning process have already been published earlier [12] except the tool wear method. Lawal et al. [12] used the same emulsion cutting fluids and turning process to investigate the effect of cutting fluids on cutting force and surface roughness while turning AISI 4340 steel with coated carbide insert. 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.

Table 1 Variables and levels employed in the factorial design

Factor	Symbol	Level (% volume (cm^3))	
		Minimum (−)	Maximum (+)
Emulsifying agent	A	8.0	12
Anticorrosive agent	B	2.0	4.0
Antioxidant	C	0.5	1.0
Biocide	D	0.5	1.0

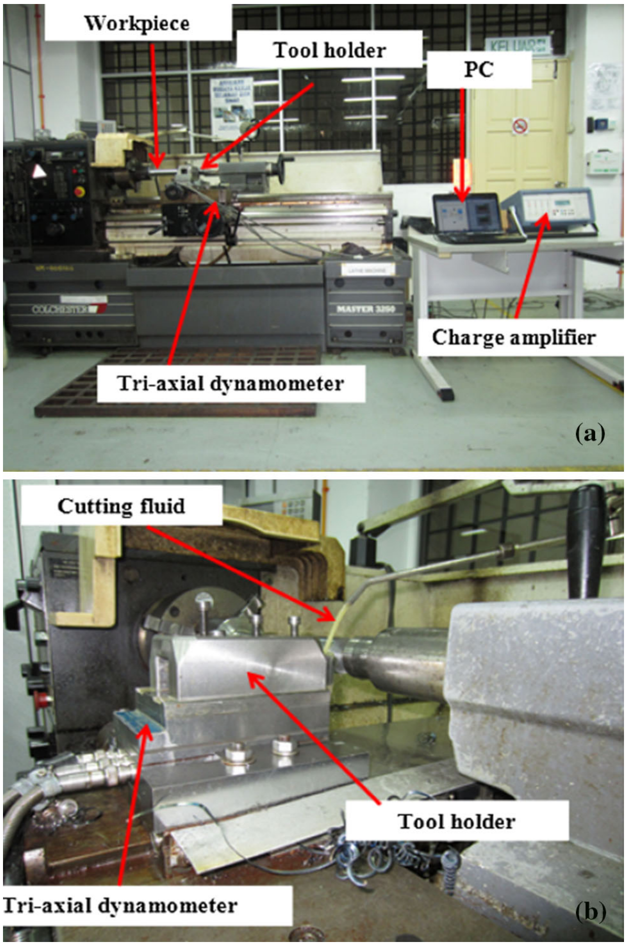

Fig. 1 Experimental set up for turning process **a** set up showing all components, **b** setup showing cutting fluid delivery

Table 2 Process parameters and their levels

Factor	Unit	Level 1	Level 2	Level 3
Cutting speed	m/min	160	200	250
Feed	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	1.04	0.87

Table 3 Experimentation layout using an L_{27} orthogonal array

Trial No.	Cutting speed (m/min)	Feed (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

PKO Palm kernel oil, *CSO* Cottonseed oil, *MO* Mineral oil

For both vegetable oil based and mineral oil based cutting fluids, water and other additives 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 [13]. 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. Table 1 shows variables (additives) and levels employed in the factorial design.

Each run 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. The data obtained for the pH values for all the experimental runs were analyzed statistically using version 6 of DOE® software. The software used for the analysis uses a second degree polynomial, approximated by

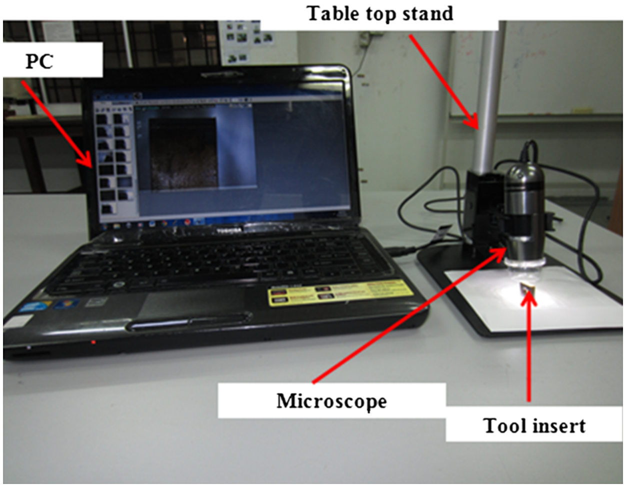

Fig. 2 Microscope setup for tool flank wear measurement

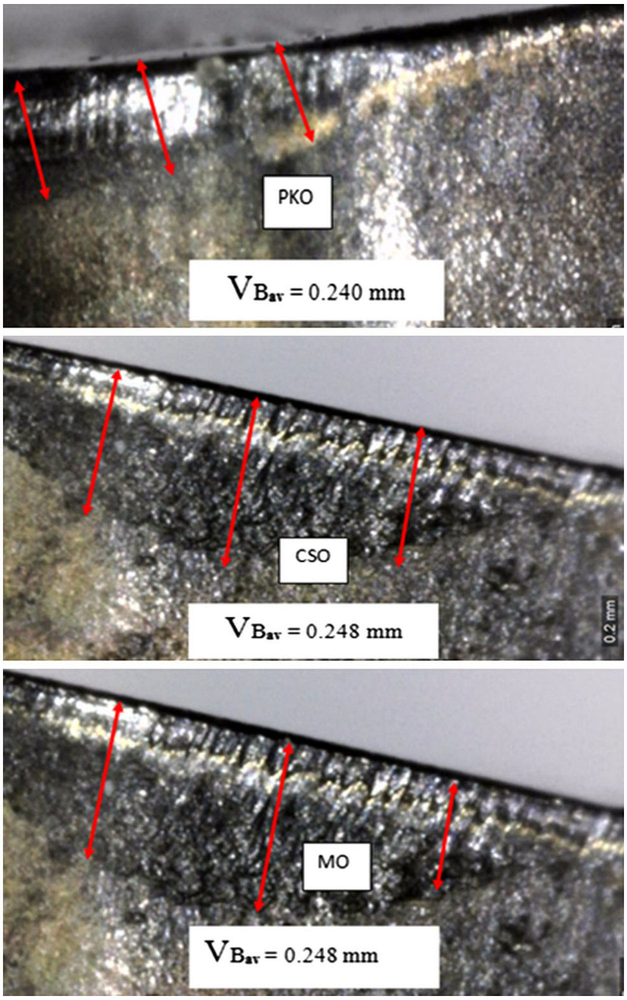

Fig. 3 Flank wear at 200× magnification

Eq. 1, to predict the response, Y, which includes all factors as well as the most effectual way the factors interact.

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

where β_0 is constant, β_i and β_{ij} are coefficient of ij; x_i represents independent variables and x_{ij} denotes the interactions thereof [14].

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.

Turning Process

The turning process was performed on a Colchester VS Master 3250 (165 × 1,270 mm) gap bed centre lathe rated with 7.5 kW and spindle speed of 3,250 rpm as shown in Fig. 1a, 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 2525M12. The experimental setup was based on 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 2. The selections of these parameters were based on machine rating and configuration of the tool insert.

For a four-factor-three-level experiment, Taguchi had specified L_{27} (3^4) orthogonal array for experimentation as shown in Table 3. 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 with flow rate of 6 l/min at 0.5 bar.

Flank wear was observed and measured after each turning for 15 min using an optical microscope (DINO-LITE AM7013MZT matel case, 5MP come polarizer). The microscope is equipped with software for measuring flank wear and investigating the microscopic picture of the tool insert of up to 250× magnification. An average of three reading measured at 50× magnification was reported. The setup for tool flank wear using DINOLITE optical microscope is shown in Fig. 2.

Results and Discussion

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%); 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 4.

Table 4 Characteristics of oil-in-water emulsion cutting fluids

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

Flank Wear

For every tool insert, three measurements were taken using DINOLITE AM7013MZT matel case, (5MP come polarizer) instrument to determine the amount of wear after 15 min of turning and an average value as shown in Table 5 was used for analysis. The S/N ratio values for flank wear are equally shown in Table 5. In optimizing the process in this study, the lower the S/N (dB) ratio the better characteristic as shown in Eq. 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.

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

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.

While Fig. 3 represents the flank wear pictures taken at cutting speed of 250 m/min, feed of 0.18 mm/rev and depth of cut of 3.0 mm under the three cutting fluids environment at 200× magnification.

Fig. 4 Main effect plots of SN ratios for flank wear

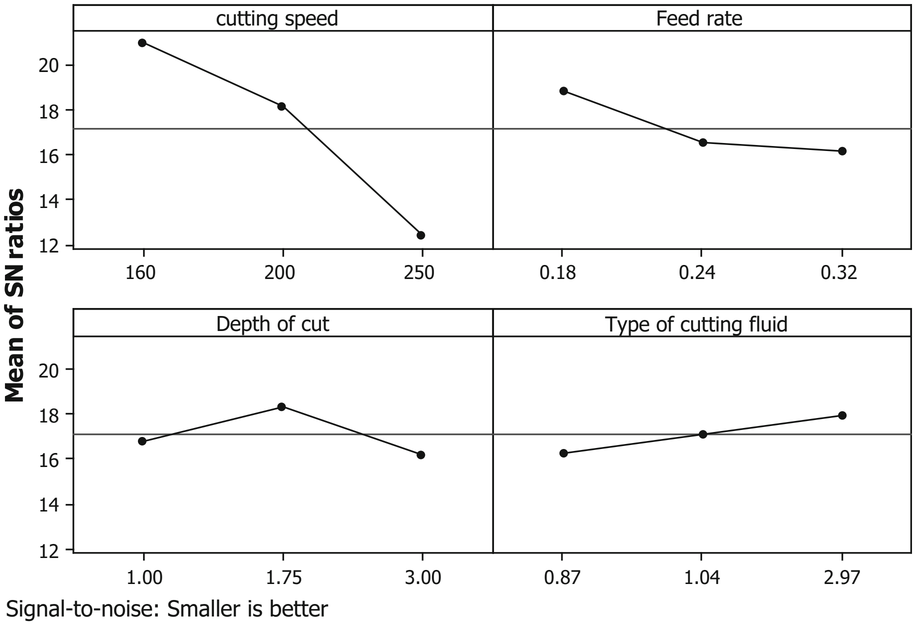

Table 5 Data from the experimental conducted and S/N (dB) ratios values for flank wear

Trial	Vc (m/min)	Feed (mm/rev)	Doc (mm)	Viscosity η (mm^2/s)	Flank wear (VB, mm)	S/N ratio for flank wear
1	160	0.18	1.0	2.97	0.072	22.85
2	160	0.18	1.0	1.04	0.083	21.62
3	160	0.18	1.0	0.87	0.092	20.72
4	160	0.24	1.75	2.97	0.088	21.11
5	160	0.24	1.75	1.04	0.090	20.92
6	160	0.24	1.75	0.87	0.102	19.83
7	160	0.32	3.0	2.97	0.078	22.16
8	160	0.32	3.0	1.04	0.090	20.92
9	160	0.32	3.0	0.87	0.120	18.42
10	200	0.18	1.75	2.97	0.062	24.15
11	200	0.18	1.75	1.04	0.077	22.32
12	200	0.18	1.75	0.87	0.088	21.11
13	200	0.24	3.0	2.97	0.148	16.59
14	200	0.24	3.0	1.04	0.161	15.87
15	200	0.24	3.0	0.87	0.167	15.53
16	200	0.32	1.0	2.97	0.141	17.04
17	200	0.32	1.0	1.04	0.168	15.49
18	200	0.32	1.0	0.87	0.180	14.89
19	250	0.18	3.0	2.97	0.204	13.81
20	250	0.18	3.0	1.04	0.221	13.11
21	250	0.18	3.0	0.87	0.247	12.14
22	250	0.24	1.0	2.97	0.217	13.26
23	250	0.24	1.0	1.04	0.230	12.76
24	250	0.24	1.0	0.87	0.237	12.52
25	250	0.32	1.75	2.97	0.241	12.35
26	250	0.32	1.75	1.04	0.254	11.89
27	250	0.32	1.75	0.87	0.261	11.68

Figure 4 shows the main effects plot for S/N ratio for flank wear. It can be observed from the figure that the optimal turning parameters for the flank wear are 160 m/min of cutting speed (level 1), 0.18 mm/rev of feed (level 1), 1.75 mm of depth of cut (level 2) and 2.97 mm^2/s palm kernel oil based cutting fluid (level 3). It is pertinent to note that palm kernel oil-based cutting fluid exhibited the lowest tool wear than other cutting fluids.

This is definitely unconnected with the high saturated fatty acid content in palm kernel oil, which helps significantly to improve reduction friction and wear. Cottonseed oil carbon chain is shorter compare with palm kernel oil. Carbon chain length of fatty acid enhances durability of the contact with material interface. Because of reaction between metal oxide layer and fatty acid, smooth sliding and low friction can be obtained during machining process. In addition, the high viscosity of palm kernel oil-based cutting fluid has the tendency to resist the flow thus provide effective lubrication at the tool-chip interface, which reduces the friction and subsequently prevent the cutting tool from rapid wear.

ANOVA Analysis

The ANOVA analysis shows that the cutting speed has more significant effect on the flank wear which account for 85.36 %; follow by 4.81 % of feed, 2.5 % of depth of cut and 1.8 % of cutting fluids as shown in Table 6. It is a known fact that flank wear increase with increased in cutting speed. High speed machining with stainless steel usually result in an extremely high temperature on cutting tools in the cutting zone leading to faster tool wear. Trent [15] reported that the application of cutting fluid is unable to prevent high temperatures at the tool-chip interface due to the fact that it cannot access the flow zone, where a considerable amount of heat is generated. However, the cooling action can reduce the volume of the tool material that might be damaged by excessive heating.

Table 6 ANOVA analysis for flank wear

Factor	DF	SS	MS	F	P
Cutting speed (m/min)	2	0.109657	0.054829	140.5258	0.853628
Feed (mm/rev)	2	0.00619	0.003095	7.932507	0.048186
DOC (mm)	2	0.00322	0.00161	4.126442	0.025066
Type of cutting fluid (mm^2/s)	2	0.00237	0.001185	3.037164	0.018449
Error	18	0.007023	0.00039		0.054671
Total	26	0.12846			

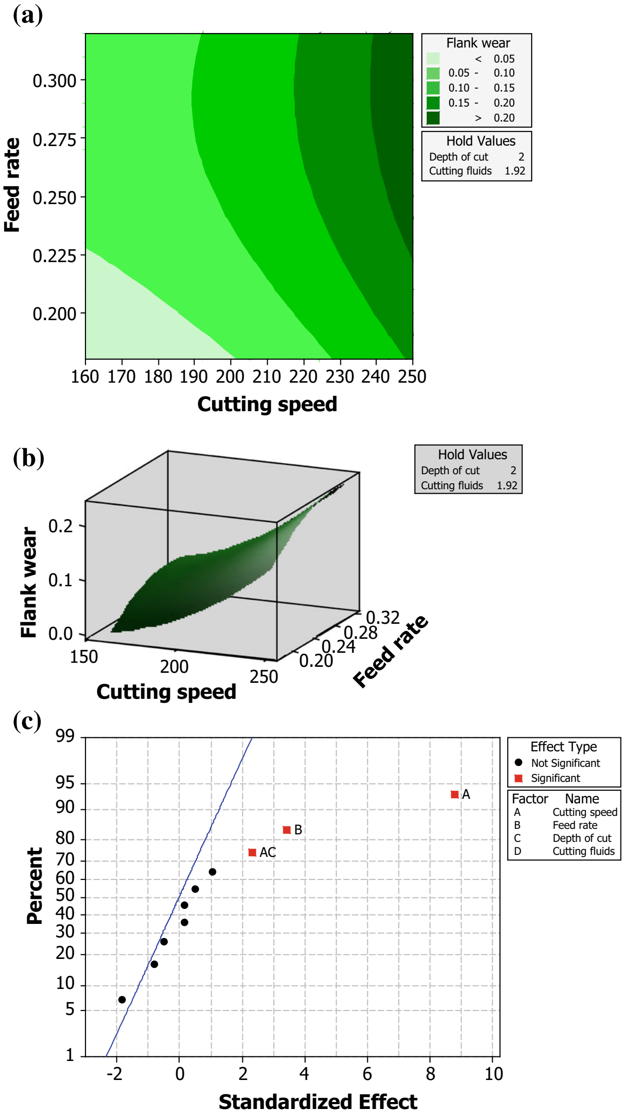

Fig. 5 **a** Contour plots for flank wear, **b** 3D surface graph for flank wear, **c** normal probability plot for flank wear

Figure 5a shows the contour plots of the effect of cutting speed and feed on flank wear. It is observed that as cutting speed increased with feed the flank wear also increased.

Table 7 Confirmation test percentage error

Parameter	Calculated value	Experimental value
Cutting speed (m/min)	160	160
Feed rate (mm/rev)	0.18	0.18
Depth of cut (mm)	1.75	1.75
Cutting fluid (mm^2/s)	2.97	2.97
Flank wear (mm)	0.0515	0.0485
Percentage error (%)		5.82

Figure 5b shows the 3D graph of the effect of feed and cutting speed on the flank wear of the tool. The curve shape obtained is in accordance to the model fitted and in agreement with the contour plot. Flank wear increase as cutting speed increased with increase in feed. The normal probability plot in Fig. 5c shows that both cutting speed and feed are significant factors that affect the flank wear and the combination of cutting speed and depth of cut are equally significant factors that affect flank wear.

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 flank wear. Experiments were conducted based on the optimized values to validate the regression equation in Eq. 3 for flank wear. The same experimental method (turning process) was adopted for the confirmation test. Table 7 shows the calculated and experimental values for the optimized values (input parameters) as well as the percentage error. The following notations were used in the mathematical models V_c: cutting speed, f: feed rate, a_p: depth of cut, CF: cutting fluid, V_B: flank wear. The model equation for the flank wear (VB) is as follows:

$$V_B = -0.249 + 0.00170V_c + 0.250f + 0.00608a_p - 0.00913CF \quad (3)$$

All the values of R^2 obtained from flank wear ($R^2 = 88.8$ % and R^2 (adj) $= 86.8$ %) 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 [16].

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 flank wear 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. The higher percentage of water to oil 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 flank wear using S/N ratio are: 160 m/min of cutting speed (level 1), 0.18 mm/rev of feed (level 1), 1.75 mm of depth of cut (level 2) and 2.97 mm^2/s palm kernel oil based cutting fluid (level 3). ANOVA shows cutting speed of 85.36 %; and feed rate 4.81 %) as significant factors that affect flank wear. While depth of cut 2.5 % and cutting fluid 1.8 % are insignificant factors. Regression model obtained for the flank wear can be relied on as multiple regression analysis performed indicated the fitness of the experimental measurements. The confirmation tests value is 0.0485 mm as against calculated value of 0.0515 mm. 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. The authors recommend the investigation coating behaviour of coated carbide after machining.

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