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Performance Assessment of Vegetable Oil based Cutting Fluids with Extreme Pressure Additive in Machining

B. Satheesh Kumar [*,1,a], *G. Padmanabhan*[2,b] *and P. Vamsi Krishna*[3,c]

[1] Department of Mechanical Engineering, N.B.K.R. Institute of Science & Technology, Vidyanagar 524413, Andhra Pradesh, India
[2]Department of Mechanical Engineering, S.V. University, Tirupati 517502, Andhra Pradesh, India
[3]Department of Mechanical Engineering, NIT Warangal, Warangal 506004, Telangana, India
[a,*]*satheeshkumar76svu@gmail.com,* [b]gpnsvuce@yahoo.co.uk*,* [c]*vamsikrishna@nitw.ac.in*

Abstract – *The present work focuses on the experimental evaluation of the performance of vegetable oil based cutting fluids (coconut, canola and sesame oils) with extreme pressure (EP) additive in machining. Cutting fluids are prepared with three different base oils at three different percentages of EP additives. Performance of these cutting fluids is assessed by measuring cutting forces, cutting tool temperature, tool flank wear and surface roughness in turning AISI 1040 steel with coated carbide tool. Experiments are conducted initially at constant cutting conditions with 5% EP additive in vegetable oils in order to compare their performance with conventional cutting fluid prepared from soluble oil. Further evaluation is done by varying percentage of EP additive and cutting conditions as well. The results indicated that 10% EP additive included in coconut oil based cutting fluid performed better compared to other vegetable oils and other percentages of EP additive.*

Keywords: Turning, Vegetable oil based cutting fluids, EP additive, Machining performance

1.0 INTRODUCTION

During machining, friction between workpiece and cutting tool, cutting tool and chip interfaces results in high temperature, which leads to shorter tool life, higher surface roughness and lower dimensional accuracy of the workpiece. Cutting fluids (CFs) facilitate heat dissipation, friction reduction and chip formation in machining by its cooling and lubricating properties, and thus leads to minimization of workpiece distortion and prolonging the tool life [1]. Hence, to fulfil such functions, chemical composition in cutting fluids must be stable. Vegetable oils have been recognized for having superior lubricating properties. Production rates improved 20 to 30% and 50% increase in tool life experienced with vegetable oil based cutting fluids (VBCFs). Extreme Pressure (EP) additives form a sacrificial film, under heat and pressure that is worn away by sliding. EP-fortified oil films can support a much greater load and offer greater resistance to scuffing than anti wear (AW) or inhibited oils. This greater resistance to scuffing may cause certain friction-dependent devices such as backstops to slip. Today a wide variety of cutting fluids are commercially available. Depending on the machining operations carried

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out and the final surface desired, the properties of cutting fluid required may be more on cooling, lubricating, or both. The effectiveness of cutting fluid depends on a number of factors such as types of machining operation, cutting parameters and methods of cutting fluid application etc.

2.0 LITERATURE REVIEW

In machining steel with HSS tool using water as a coolant and increased cutting speed by 40% [2]. Flow rate, thermal conductivity of CFs also important along with cooling and lubrication properties in machining performance [3-6]. The effect of cutting fluid application was studied on hole accuracy and mist generation [7]. The cooling and chip-transporting ability of CFs was found to have the maximum effect on dimensional accuracy. The performance of palm oil and groundnut oil was studied in terms of workpiece temperature and chip formation. It was found that the temperature of the workpiece is lowest with groundnut oil and highest chip thickness is with palm oil [8]. Belluco et al. [9–12] investigated the effect of vegetable based cutting oil on cutting forces and power, results showed that the vegetable based cutting oils were better than the commercial mineral oil. Coconut oil was proved nonhazardous and environmental friendly [13,14]. Virgin coconut oil (VCO) is reported good quality physio-chemical properties and antioxidant nature [15]. The performance of coconut oil was studied and observed that the coconut oil reduces the tool wear and improves the surface finish with respect to mineral oil [16]. Adding of graphite nano particles to the cutting fluid improved thermal conductivity, cooling effect, kinematic viscosity with respect to the wt.% [17]. Researchers [18–20] reported the effect of VBCFs and other commercial CFs on thrust force and surface roughness with respect to cutting parameters.

In an experimental study, studied for friction, wear and seizure tendencies and observed that the fatty-based EP additives enhance the performance of synthetic coolants compared with the water-soluble inorganic solids [21]. In an experimental study EP additive based cutting fluids showed better capability of preventing oil mist [22]. The influence of conventional EP and AW additives was investigated [23] on the tribological performance of hard low-friction coatings in the boundary lubrication regime. The presence of ZDDP additive in the Refined, Bleached and Deodorized (RBD) palm stearin cutting fluid experienced less coefficient of friction and wear scar diameter [24]. Load-scanning tests were performed under boundary lubrication conditions using four lubricants showed that introduction of hard low-friction coatings and usage of additivated oils significantly improve the tribological performance. In another study, found that the oil specimens with EP and AW additive had higher welding loads, higher load wear indexes and smaller scars for the same load [25]. The tribo chemical mechanism of lubrication was analyzed and found that the polysulfide additive was found to exhibit the best efficiency (decrease of specific cutting energy and tool wear) [26]. The experimental studies were conducted on the performance of VBCFs (refined sunflower and canola oils) including different percentage of EP additive and two commercial cutting fluids [27]. The results indicated that 8% of EP included canola based cutting fluid performed better than the rest. In another study showed that sunflower and canola based cutting fluids perform better than the others [28]. Authors [29] carried out investigation on Purple Sweet Potato (PSP) starch by adding glycerol as plasticizer and kappa carrageenan as gelling agent and observed improvement in the formation of the edible film. The friction behavior of grinded and polished surfaces mitigated in presence of lubrication with EP additive compared to base oil [30].

Journal of Advanced Research in Materials Science
ISSN (online): 2289-7992 | Vol. 19, No.1. Pages 1-13, 2016

From the literature it is observed that investigations related to VBCFs have shown better performance than mineral, synthetic and semi-synthetic cutting fluids. Addition of EP additive to vegetable oils enhanced performance of base oils. However, research on performance of different vegetable oils with addition of EP additive is seldom found. Owing to this reason, coconut oil, canola oil, sesame oil are used as lubricants in the present work. Hence, the purpose of this study is to compare the performances of VBCFs included EP additive (coconut, canola and sesame based cutting fluids each having 5%, 10% and 15% of EP additive) in terms of cutting forces, cutting tool temperature, tool flank wear and surface roughness during turning of AISI 1040 steel.

3.0 EXPERIMENTATION

A mixture of emulsifier and vegetable oil is prepared first in the ratio of 15% and 85% by weight respectively. Then EP additive is added to the mixture by varying 5%, 10% and 15% by weight. Oil to water ratio of 9:100 is used to prepare required VBCFs. Sulfur based EP additive (HiTEC343) is used to prepare VBCFs because it is less viscous, possesses good solubility in water and high lubricating ability [31]. To assess the effectiveness of the CFs physical properties like kinematic viscosity, flash point and pH value were estimated. Kinematic viscosity of VBCFs with different proportions of EP additive was estimated using Redwood viscometer. The flash point of the different VBCFs was measured using Cleveland open-cup tester. A digital pH meter was used to estimate the pH value of the VBCFs. A PSG-124 lathe was used for conducting machining experiments. Coated carbide tool (CNMG120408NC6110) and heat treated AISI 1040 steel of 30±2 HRC (Rockwell Hardness) were used as cutting tool and work piece respectively. The experimental setup is shown in Fig. 1. Initially the experiments were conducted at constant cutting conditions (cutting speed = 80 m/min; feed rate = 0.14 mm/rev; depth of cut = 0.5 mm) with conventional cutting fluid prepared from soluble oil (SO), VBCFs with 5% EP additive and without EP additive. Further the experiments were conducted at variable cutting conditions for nine different VBCFs formulated from coconut, canola and sesame oils. The experimental conditions are given in Table 1. Online measurement of cutting forces during machining was done using Kistler 9272 dynamometer. Cutting temperatures were sensed by an embedded thermocouple (K-type shielded (Chrome/Alumel) thermocouple) online. Tool wear was measured by using GX51 optical microscope offline. Surface roughness (R_a) was measured offline using surface roughness tester (Surf test, SJ-301) and an average of three measurements was considered as a response value.

Figure 1: Experimental set up

Penerbit Akademia Baru
Journal of Advanced Research in Materials Science
ISSN (online): 2289-7992 | Vol. 19, No.1. Pages 1-13, 2016

Table 1: Experimental Details

Workpiece Material:	AISI 1040 (C: 0.36–0.45%, Mn: 0.6–1%, Si: 0.2–0.3%, S: 0.025%, P: 0.015%)
Hardness	30 ±2 HRC
Tool holder	PSRNR12125F09
Cutting tool (insert)	CNMG120408NC6110 Coated carbide (TiCN/Al_2O_3 coating)
Cutting speed	60, 80 and 100 m/min
Feed rate	0.14, 0.17 and 0.20 mm/rev
Depth of cut	0.5 mm (constant)
Cutting fluids	Coconut, canola and sesame based cutting fluids
% EP additive inclusion	5, 10 and 15

4.0 RESULTS AND DISCUSSION

4.1 Basic properties

Table 2 represents density, pH values, kinematic viscosity and flash point for different VBCFs with EP additive and without EP additive. All cutting fluids density increased with increase in EP additive percentage, this may be because of higher density of EP additive. It is observed that viscosity of the VBCFs is decreased with increase in percentage of EP additive. Increase in proportion of EP additive in VBCFs is increased the flash points of the cutting fluid.

Table 2: Properties of vegetable oil based cutting fluids

Type of cutting fluid	Density (gm/ml)	pH value	Viscosity, 40^0C (mm^2/s)	Flash point (^{0}C)
CCF0	0.962	7.09	2.386	219
CCF5	0.967	7.17	2.373	223
CCF10	0.974	7.24	2.261	228
CCF15	0.989	7.28	2.186	234
CNCF0	0.965	7.86	2.297	229
CNCF5	0.967	7.93	2.111	232
CNCF10	0.978	8.07	1.805	238
CNCF15	0.989	8.08	1.997	247
SCF0	0.966	7.63	2.986	205
SCF5	0.954	7.94	2.920	207
SCF10	0.967	7.75	2.739	212
SCF15	0.973	7.87	2.557	221

4.2 Machining performance at constant cutting conditions

Machining performance of conventional cutting fluid, CCF0, CNCF0, SCF0, CCF5, CNCF5 and SCF5 is evaluated at constant cutting conditions in turning operation.

Penerbit Akademia Baru
Journal of Advanced Research in Materials Science
ISSN (online): 2289-7992 I Vol. 19, No.1. Pages 1-13, 2016

4.2.1 Cutting force (F_c)

Behavior of cutting force (F_c) with respect to time for different cutting fluids is presented in Fig 2. It is observed that coconut based oils having less cutting forces compared to other oils due to the medium viscosity. Though CCF0 is having good viscosity, CCF5 has experienced less cutting forces due to the presence of EP additive [16]. The organic molecules in EP additives form lead sulfide and iron chloride, which are having weak shear strength compared to the base metals. Due to less shear strength this surface offers less frictional forces compared to the base metal [28]. Thus addition of EP additives in CFs resulted in less cutting forces.

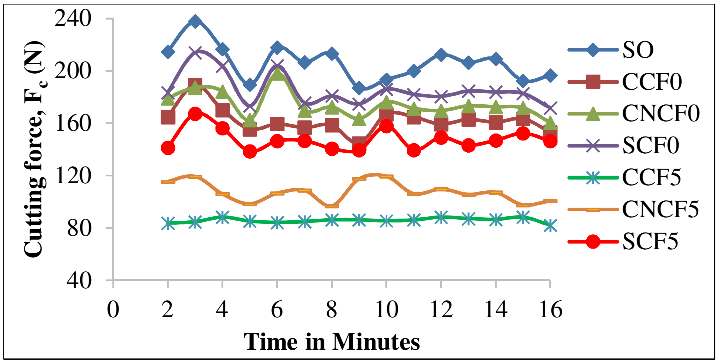

Figure 2: Variation of cutting force with machining time

4.2.2 Cutting tool temperature (T)

Conventional cutting fluid (SO) shows high cutting tool temperature due to low thermal conductivity and less viscosity. The cutting fluids with EP additives like CCF5 are effective in diminishing cutting tool temperature compared to conventional cutting fluid and VBCFs without EP additive (Fig. 3). Addition of 5% EP additive in coconut based cutting fluid would result in less cutting tool temperature than canola and sesame based cutting fluids. The possible reason for this is abridgement of coefficient of friction between chip and tool with proper lubrication using coconut based cutting fluid. The film formed by vegetable oils is intrinsically strong and lubricious, which improves workpiece quality and reduces friction and so cutting tool temperature. EP additive in coconut based cutting oil generates thicker soapy film compared to other cutting fluids and it prevents asperities of metal from welding between two metal pieces [9]. Eventually the cutting tool temperature is mitigated with CCF5 compared to other CFs and conventional cutting fluid.

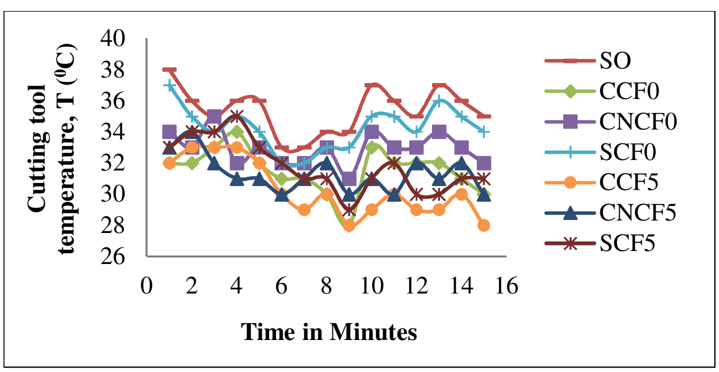

Figure 3: Variation of cutting tool temperature with machining time

Journal of Advanced Research in Materials Science
ISSN (online): 2289-7992 I Vol. 19, No.1. Pages 1-13, 2016

4.2.3 Tool flank wear (V_b)

The tool flank wear is observed after 5, 10 and 15 minutes of machining time in presence of different CFs and results are presented in Fig. 4. The graph depicts that higher wear rate for conventional oil, due to higher rate of oxidation. Among all other cutting fluids CCF5 is having good wear resistance. Addition of EP additive to the CFs helped in reduction of tool wear. This EP additive offers resistance to oxidation and causes less wear rate, hence CCF5 showed better performance.

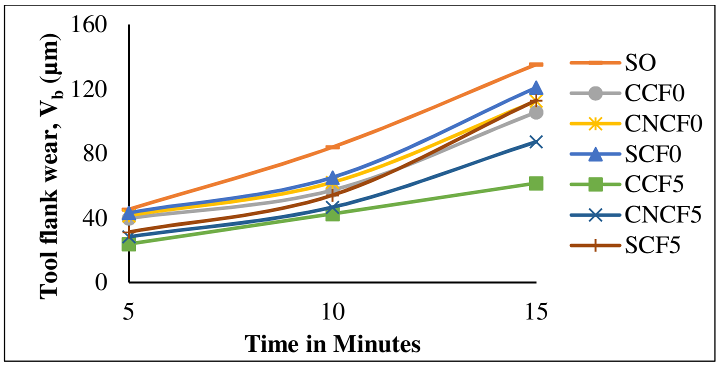

Figure 4: Variations of tool flank wear with time

4.2.4 Surface roughness (R_a)

From Fig. 5, it is observed that surface roughness is high during conventional cutting fluid followed by VBCFs without EP environment. Addition of 5% EP additive in CCF results greater decrease in surface due to the good lubrication property of coconut oil, which reduced the frictional forces and temperature between the tool and workpiece, resulting in the lower surface roughness values [27]. CFs without EP additives contain unsaturated fatty acids which absorbs oxygen easily and gets oxidized. It forms a deposit which will weld on surface and cause scratchen on surface, may reduce the surface finish. CFs with EP additives show more resistant to oxidation, which are causes to less surface roughness.

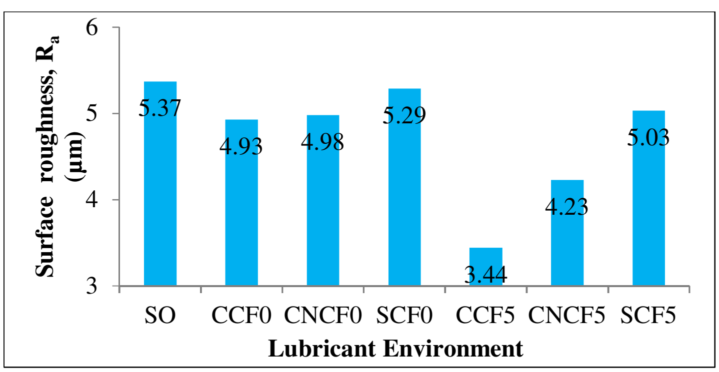

Figure 5: Variation of surface roughness (R_a) at different lubricating conditions

4.3 Machining performance at varying cutting conditions

Since 5% EP additive included VBCFs performed better compared to soluble oil and VBCFs without EP additive at constant cutting conditions, it is further extended to investigate the comparative performance of 5%, 10% and 15% of EP additive included VBCFs (coconut, canola and sesame oils) at varying speed and feed by keeping depth of cut as 0.5 mm. feed of 0.14mm/rev kept constant while varying speed and speed kept constant (80m/min) while varying feed.

4.3.1 Cutting force (F_c)

The cutting forces increased initially and then decreased with speed at constant feed rate. Initially formation of BUE has observed and it reached maximum at 80m/min (Fig. 6). Further increase in speed, increment of cutting temperatures avoid formation of BUE, hence cutting forces were reduced. This says that at higher speeds (100m/min) usage of cutting fluids gives maximum efficiency.

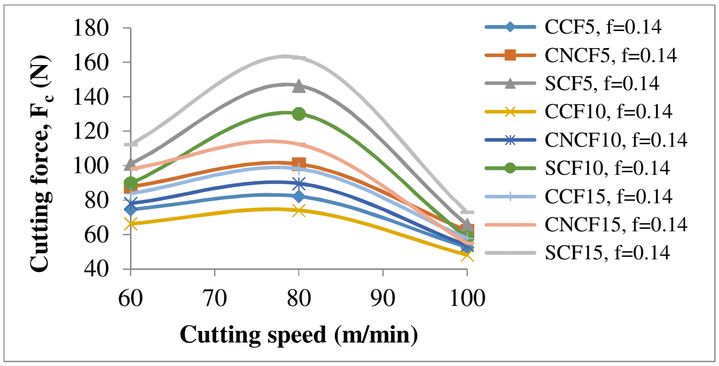

Figure 6: Variation of cutting force with cutting speed

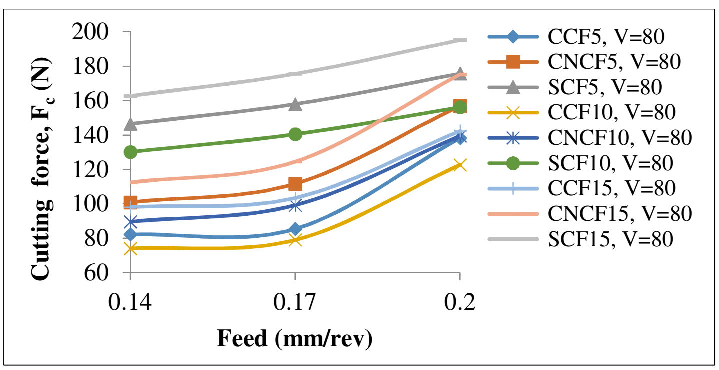

Figure 7: Variation of cutting force with feed

The cutting force increased with increase in feed rate (Fig. 7). Cutting force changed linearly with feed rate at higher cutting speeds, but at lower speeds the change is more. From the perspective of varying percentages of EP additive, 10% EP included VBCFs showed better performance compared to 5% and 15% EP included VBCFs. Among 10% EP additive included VBCFs, CCF10 is found to be effective in reducing cutting forces by 17% and 43% compared to CNCF10 and SCF10 respectively.

Out of taken VBCFs coconut based cutting fluid experiences less cutting force due to medium viscosity. EP Additive reacts chemically with metal surfaces and forms easily sheared layered surface which causes reduction of cutting force [28].

Journal of Advanced Research in Materials Science
ISSN (online): 2289-7992 I Vol. 19, No.1. Pages 1-13, 2016

4.3.2 Cutting tool temperature (T)

With increasing speed, generation of temperature also increases and at lower speeds BUE is formed, hence up to 80m/min the cutting tool temperature (T) is less (Fig. 8). But in case of constant speed and varying feed rate T is almost linear for all cutting fluids. It is observed that CCF10 showed better performance compared to all other environments. It is perceived that, 10% EP included VBCFs are effective in reducing T compared to 5% and 15% EP additive included VBCFs. Further, 10% EP included CCF has shown 7% and 10% improvement in reduction of cutting tool temperatures when compared to 10% EP included CNCF and SCF respectively. Film formation between tool-work interfaces is more and consistent at mid-range proportion of EP additive. In addition to this, the thermal conductivity and heat transfer coefficient are high for coconut oil when compared to canola and sesame oils which in turn influence reduction in cutting temperatures [32]. A dense homogenous alignment of coconut oil molecules, creates a thick strong and durable film of lubricant [33] due to which coconut oil outperforms the other two oils in the present investigation. Besides this, EP additive generates a soapy film which prevents particles of metal from welding, which reduces the cutting tool temperature [27]. Thus, coconut based cutting fluids are more effective in reducing cutting temperatures when compared to canola and sesame based cutting fluids due to its ability to form better soapy film.

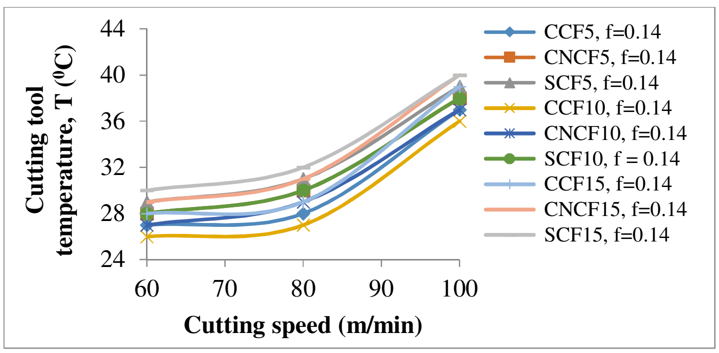

Figure 8: Variation of cutting tool temperature with cutting speed

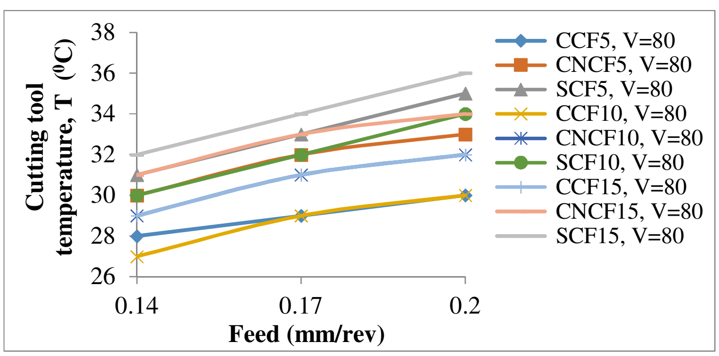

Figure 9: Variation of cutting tool temperature with feed

4.3.3 Tool flank wear (V_b)

Tool flank wear increased gradually (Fig. 10 and Fig. 11) with increase in cutting speed and feed rate for all the lubricating environments. 10% EP additive included VBCFs showed better

Journal of Advanced Research in Materials Science
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performance in reducing tool flank wear. Lower tool flank wear is observed for CCF10 compared to other lubricants. CCF10 is found to be effective in reducing tool flank wear by 30% and 45% corresponding to CNCF10 and SCF10 respectively. An increase in the speed and feed usually leads to heat generation causes more oxidation which results increase in coefficient of friction because of wear debris formation causing increase in tool wear. Addition of EP additive to the VBCFs reduced the tool flank wear. Under high cutting temperatures, EP additive creates a thin lubricating film on the workpiece and tool. The plastic contact between the workpiece and cutting tool decreases when exposing interface to the vegetable oil flow with EP additive, which leads reduction in tool flank wear [26] and this is found to be more effective with 10% EP additive in coconut oil due to the low viscosity of the CCF.

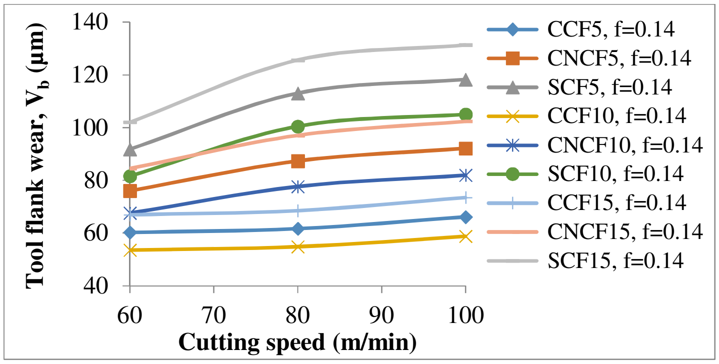

Figure 10: Variation of tool flank wear with cutting speed

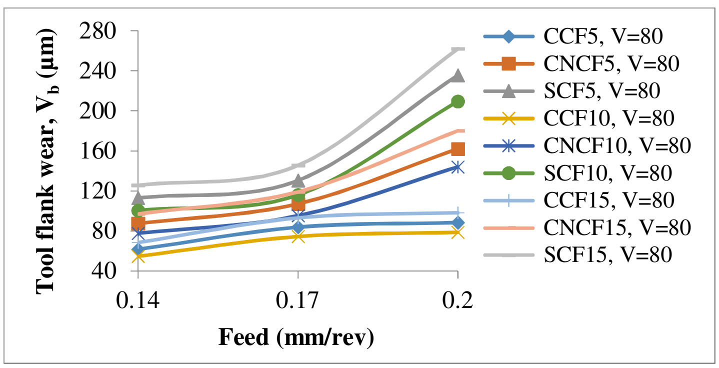

Figure 11: Variation of tool flank wear with feed

4.3.4 Surface roughness (R_a)

Surface roughness (R_a) with respect to cutting speed (Fig. 12) initially increased up to 80m/min and then decreased at 100m/min in presence of VBCFs with EP additive. Surface roughness is obtained by the application of CCF5, CNCF5, SCF5, CCF10, CNCF10, SCF10, CCF15, CNCF15 and SCF15 is found to increase with feed rate (Fig. 13). The surface roughness is observed to be less by the application of 10% EP additive included CCF compared to CNCF10 and SCF10, which indicates better lubrication characteristics of CCF10 as the viscosity of coconut based cutting fluid is low when compared to canola and sesame based cutting fluids, which tends to reduce the friction between tool-chip and tool-workpiece interfaces, which in turn lead to the improvement in surface finish. It is found that too lower and too higher percentages of EP additive in cutting fluids have resulted in enhancement of surface roughness

Journal of Advanced Research in Materials Science
ISSN (online): 2289-7992 I Vol. 19, No.1. Pages 1-13, 2016

as the sulfur based EP additive provide a tougher, more stable film of lubrication at the tool chip interface [27] decreasing shear stresses on the surface increases built up edge (BUE) with addition of high proportion [34]. The combined effect of 10% EP additive and coconut oil is better compared to other lubricating conditions. It can be observed that, by using CCF10 surface quality is improved by 20% and 33% compared to CNCF10 and SCF10 respectively.

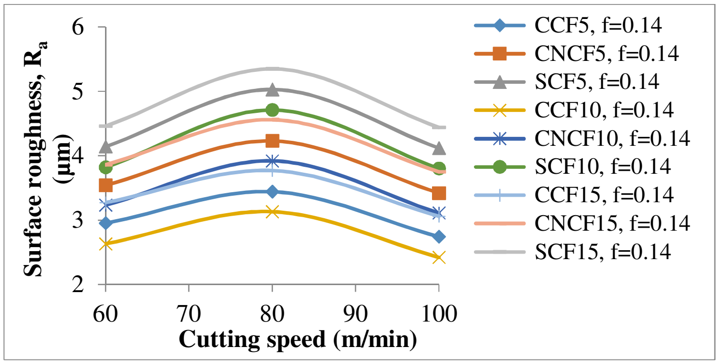

Figure 12: Variation of surface roughness (R_a) with cutting speed

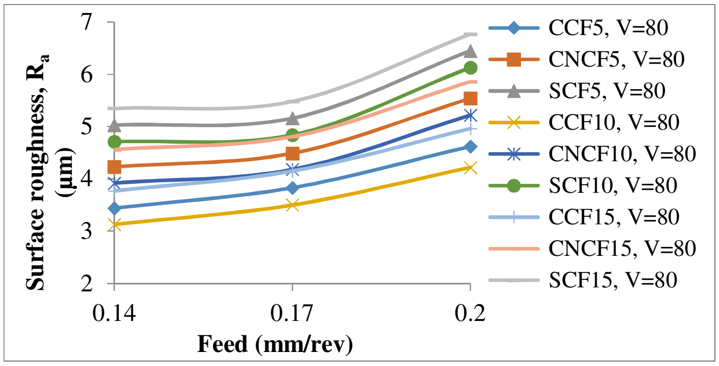

Figure13: Variation of surface roughness (R_a) with feed

5.0 CONCLUSIONS

In the present work, performance of VBCFs including EP additive are compared to conventional cutting fluid and VBCFs without EP additive. The following conclusions are drawn:

- Cutting force got reduced more with CCF compared to other vegetable oils. From the perspective of varying percentages of EP additive, 10% of EP included CCF recorded 17% improvement over CNCF10 and 43% improvement over SCF10.
- Among 5%, 10% and 15% of EP additive inclusions, 10% of EP additive is found to be effective in decreasing cutting tool temperature. By using CCF10, cutting tool temperature decreased by 7% and 10% compared to CNCF10 and SCF10 respectively.
- CCF10, CNCF10 and SCF10 have shown reduction in tool flank wear to a good extent. By using CCF10 reduction in tool flank wear is observed by 30% and 45% corresponding to CNCF10 and SCF10 respectively.

Journal of Advanced Research in Materials Science
ISSN (online): 2289-7992 | Vol. 19, No.1. Pages 1-13, 2016

- Better surface quality is obtained with the application of CCF10 compared to other lubricating conditions. CCF10 increased the surface quality by 20% and 33% better than CNCF10 and SCF10 respectively.

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