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Studies on Effect of HLB Values of Surfactant on Emulsion Stability and Performance of Castor Oil Based Soluble Cutting Fluids

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Abstract - Castor oil based soluble cutting fluids were prepared using ethoxylated glycol based emulsifier having different hydrophilic-lipophilic balance (HLB) viz., 9, 13 and 16. The thermal properties of prepared cutting fluids were evaluated using Thermogravimetric analyzer (TGA). The storage stability of cutting fluids were assessed by measuring the pH and viscosity as a function of storage duration. Emulsifying ability of prepared soluble cutting fluids were evaluated by diluting with different weight percentage of water. 95: 5 (water: cutting fluid) ratio appears to have better emulsion stability as confirmed by UV visible spectrometer. Emulsions were prepared using cutting fluids having different HLB value diluted with 95:5 (water: cutting fluid) ratio. The rheological behavior of prepared emulsions indicated that, the emulsions were able to maintain the Newtonian behavior at different temperature of study viz., 60, 80 and 100^{0}C . The emulsion prepared using the cutting fluid containing emulsifier with a HLB value of 9 showed better corrosion resistance. The tribological properties of prepared emulsions were measured using oscillating-friction wear measuring device (SRV) and Reichert tester. The effect of emulsion on surface finish and surface roughness of the tool was determined by performing the machining experiments. SRV results showed the lowest coefficient of friction for the emulsion prepared using the cutting fluid containing emulsifier with HLB value of 16.

Key words: Emulsifier, cooling, corrosion, tribology, HLB, emulsion stability.

1. INTRODUCTION

Cutting fluids (CF's) are known as coolants, cutting oils and machining fluids. There are four major class of CF'S straight oils, soluble oils, semi synthetic oils and synthetic oils. CF's provide the cooling effect by reducing the friction in between metal working pieces []. In addition to cooling effect CF's improve the tool life, give the better surface finish and corrosion protection []. Majority of CF's are petroleum oil based due to their suitable lubricating properties. Growing environment concerns and demands the use of renewable, biodegradable based oils to formulate CF's. The performance CF'S is a complex combination of chemical and physical effects []. Cooling effect and stability depends on the emulsifier type used in CF's.

Emulsifying metal working fluid are fluids for cooling and lubricating during metal working operations like boring, drilling, milling sawing, etc. [1]. Cutting fluids are usually liquids that improves the cutting condition and easily reach the metal working interface. CF's formulations may be classified as aqueous and non-aqueous. Aqueous CF's are oil in water emulsion, which made of oils mixed with surfactant that helps in dispersing the oil in continuous water phase [2]. More than 50% of all lubricants used globally are petroleum based and have adverse effect on environment due to improper disposal, toxicity and non-biodegradability. Hence there is an increasing demand for acceptable and biodegradable CF's [3]. Vegetable oil offers properties such as a high viscosity index, high lubricity, high flash point, low volatility, low toxicity and biodegradability makes it to use for CF's [4]. The chemical composition and fatty acid profile of vegetable oils are primary reasons behind their performance as cutting fluids. Long, polar fatty acids chains provides high strength lubrication films that interact strongly with metal surfaces, reducing both friction and wear [5]. Fully formulated vegetable oil lubricants, in comparison to mineral oil counterparts, display a lower coefficient of friction, equivalent scuffing load capacity and better pitting resistance [6]. Surfactants are widely used in metal working fluids to stabilize the oil and water components present in the emulsifiable oil formulations. Emulsifiers contain both hydrophilic and lipophilic groups. The relative solubility's of amphiphilic molecules in water and oil is designated by hydrophilic-lipophilic balance (HLB). Higher HLB molecules are water soluble and lower HLB ones have more affinity to towards oil [7]. In order to emulsify a specific base oil, emulsifiers with suitable HLB values are needed. The required HLB value needs to be adjusted according to the varying fatty acid distribution in vegetable oils or carbon distribution in mineral oils. Jatropha oil based cutting fluid exhibits minimum surface roughness and tool wear compared to mineral oil based cutting fluids in turning of AISI 304 alloy steel [8]. Castor oil based cutting fluid with 1.5% surfactant exhibits lowest broaching force [9].

Although, significant amount of research activities have been undergone in the field of vegetable oil based cutting fluids, effective surfactant HLB values on castor oil based cutting fluids needs to be suitably addressed. Castor oil is readily biodegradable and less costly than synthetic base stocks. Castor Oil is unique among other oils due to the reason (i) it is the only source of an 18-carbon hydroxylated fatty acid with one double bond,(ii) Ricinoleic acid (12-Hydroxyoleic Acid) comprises approximately 90% of the fatty acid composition and product uniformity and consistency are relatively high for a naturally occurring material.

The primary objective of this research is to find out appropriate HLB values of ethoxylated glycol based emulsifier on stability of castor oil based emulsifying metal working fluids. The second object of this work is to determine best stable emulsion concentration from prepared CF's and study the effect of HLB values on tribological, thermal stability, corrosion and rheological properties.

2. MATERIALS AND METHODS

A sample of commercial grade castor oil phase was supplied by Jayant agro organics, India. The physicochemical properties of the used castor oil is tabulated in Table 1. Fresh tap water was used for the preparation of cutting oil emulsions.

Table 1. *Physico-chemical properties of castor oil*

Parameter	**Method**	**Castor oil**
Pour point, ^{0}C	ASTM D 97	-25
Flash point, ^{0}C	ASTMD 92	>280
Kinematic viscosity at 40 ^{0}C	ASTM D 445	244.23
Kinematic viscosity at 100 ^{0}C	ASTM D 445	19.10
Viscosity index	ASTM D 2270	87
Acid value (mg of KOH/g)	ASTM D 664	160
Saponification value (mg of KOH/g)	ASTM D 94	180

2.1 Emulsifier system

Technical grade non-ionic ethoxylated alcohol based surfactant having different HLB values viz., 9, 13 and 16 were used as emulsifiers (Croda chemicals, India). The physicochemical properties of the emulsifier are addressed in Table 2.

Table 2. *Physico-chemical properties of emulsifier having HLB values 9, 13 and 16.*

Test	**Method**	**HLB - 9**	**HLB - 13**	**HLB - 16**
Physical form	Visual determination	Liquid	Liquid	Viscous Liquid
Colour	Visual determination	Colour less	Colour less	Colour less
pH (5% in water)	ASTM D 1293	7	7.5	7.5
Flash point	ASTM D 92	>100	>200	> 200
Hydroxyl number (mg of KOH/g)	DIN 53240	165	100	40

Ploy sulphur based extreme pressure (EP) additive was obtained from Ganesh Benzoplast, India. Phenol based antioxidant (AO) was obtained from Krishna Antioxidant Pvt. Ltd., India. Triethanol amine (Sigma Aldrich, India) and propylene glycol (Indian glycols Ltd, India) were used as anticorrosion additive (AC) and coupling agent (CA) respectively. Tetra hydro-3, 5-dimethyl-2H-1,3,5-thiadiazine-2-thione was used as biocide (Siddharth chemicals, India).

2.2 Methods

2.2.1. Preparation of Soluble cutting oil

Castor oil was mixed with EP, CI, AO and CA. Three different formulations were made using emulsifiers having different HLB values viz., 9, 13 and 16 denoted as SC1, SC2 and SC3 respectively. Each formulation was mixed for 20 min at 1000 rpm for better mixing. The typical formulation was given in Table 3. The physico-chemical properties of soluble cutting oils are tabulated in Table 4.

Table 3. *The soluble oil formulation.*

Component	***Castor oil***	***Emulsifier***	***EP***	***CI***	***AO***	***CA***	***BC***
Formulation (%)	65.9	15	10	5	1	3	0.1

Table 4. *Physico-chemical properties of soluble cutting oil having HLB values 9, 13 and 16*

Test	**Method**	**SC1**	**SC2**	**SC3**
Appearance	Visual determination	Liquid	Liquid	Viscous liquid
Colour	Visual determination	Pale yellow	Brown	Brown
Pour point (^{0}C)	ASTM D97	-18	-12	-5
Flash point (^{0}C)	ASTM D92	>250	>250	>250
Dynamic viscosity at 40 ^{0}C (m.Pa.s)	ASTM D7395-03	142	154	195
Dynamic viscosity at 100 ^{0}C (m.Pa.s)	ASTM D7395-03	11	13	15
Copper corrosion at 100 ^{0}C at 3h	ASTM D130	1	2	2
Density at 25^{0}C (g/cc)	ASTM D1662-08	0.910	0.912	0.920

2.2.2. Preparation of emulsion using soluble cutting oil

The stability of the emulsion depends on the size of the droplets produced during emulsion formation. In order to produce a stable emulsion a powerful homogenizer was used. Emulsions were prepared by mixing different weight percentage of water and cutting oils viz., SC1, SC2 and SC3.The various emulsion samples that were prepared using different weight percentage of water is tabulated in Table 5.

2.3 Evaluation

2.3.1 Storage stability

During the transportation, soluble cutting oils filled inside the containers can get exposed the extreme climatic variations. In this situations, soluble cutting oils should not show neither evaporation with increase in temperature nor settling tendency with decrease in temperature.

The storage stability of SC1, SC2 and SC3 were studied at 0 and 50 ^{0}C for 60 days. Each prepared cutting oil samples were taken in glass bottle. All the bottles were capped and placed in at 50 and 0 ^{0}C in test chamber. During storage period, at respective time interval viz., 0, 7, 15, 30 and 60 days the samples were observed for any sign of turbidity, separation, gelling, change in pH and viscosity. The pH value of the cutting oils was tested by Metter Toledo pH meter. The dynamic viscosity was evaluated using rotational shear rheometer (Anton Paar, Model-MCR-52).

2.3.2 Thermogravimetric analysis

TGA studies was carried out using TA Instruments TG Q50 device. 6 to 10 mg sample was heated at the rate of 10 ^{0}C/min under nitrogen atmosphere with a flow rate of 100 ml/min and in the temperature range 30 to 500 ^{0}C, using platinum pans.

Cutting fluids were designed to emulsify easily with water and form a long-lasting, stable emulsion. It provides excellent cooling and lubricity for light-to medium-duty cutting and grinding of ferrous and non-ferrous metals, resulting in extended tool life and good surface finishes on the machined parts. Soluble cutting oil emulsion was investigated from points of view of emulsion stability, foaming, rheology, lubricity and corrosion inhibition to select the optimize formula for final machining application.

2.3.4. Emulsion stability test

The emulsion stability of cutting oil is important to use it as a lubricant and rust inhibitor [10]. Emulsion destabilization usually results in loss of lubricity [11]. The destabilization of emulsion is due to the presence of calcium and magnesium ions present in the water [12]. The stability of prepared emulsions were observed at different time interval viz, 0, 8, 16, and 24 hours at room temperature (oil and/or cream separations) according to the standard test method IP263. The percentage stability of percent prepared emulsion were calculated using the following equation [13].

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$$\text{Emulsion stability} = \left(1 - \frac{Volume\ of\ oil\ separated}{Total\ volume\ of\ oil\ in\ emulsion}\right) x\ 100$$

Table 5. *Details of cutting oil emulsions*

Cutting fluids	Composition concentration of emulsion (%)		
	Soluble cutting oil used	Cutting oil (%)	Tap water (%)
SC1E1	SC1	5	95
SC1E2	SC1	10	90
SC1E3	SC1	15	85
SC1E4	SC1	20	80
SC2E1	SC2	5	95
SC2E2	SC2	10	90
SC2E3	SC2	15	85
SC2E4	SC2	20	80
SC3E1	SC3	5	95
SC3E2	SC3	10	90
SC3E3	SC3	15	85
SC3E4	SC3	20	80

UV visible spectrophotometer helps to determine the stability of emulsions [14]. UV visible spectrophotometer (Shimadzu UV-1600; Shimadzu, Kyoto, Japan) was used measure the absorbance at 550 nm wave length was measured at different time interval viz, 0, 8, 16, and 24 hours.

2.3.5 Foaming

Foaming in cutting oil can lead to higher operational costs due to fluid loss and reduce cooling and lubrication at the chip-tool interface [15].Foam can drastically effect fluid performance by contributing to poor wetting and coverage properties. ASTM D 3601 method is useful to determining the foaming tendency of water-based cutting coolant under low shear conditions. The foam height (in ml) was measured for different emulsions for the study.

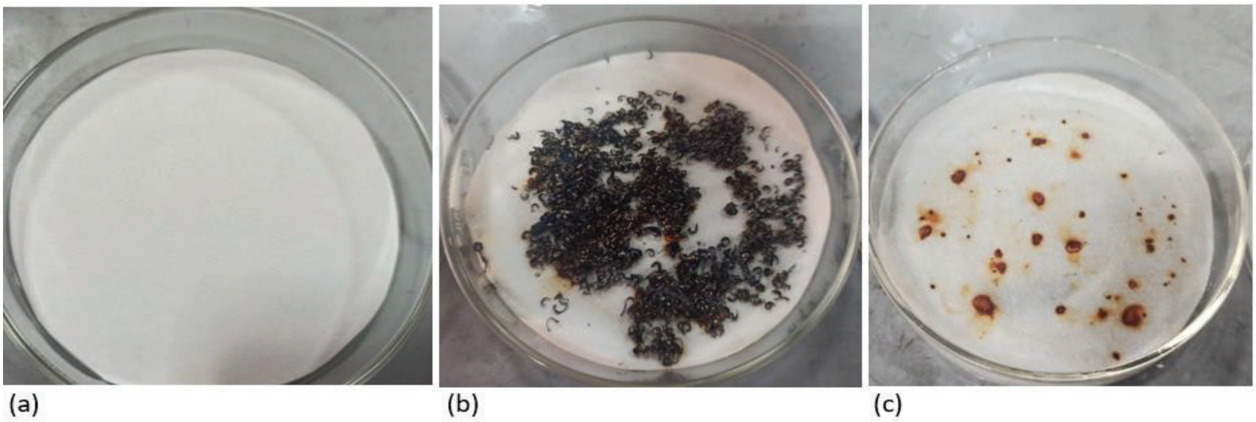
2.3.6 Shear stress and viscosity of cutting fluid

Shear stress and viscosities of cutting fluids are measured as a function of shear rate using a rheometer (Make: ANTON Paars, Model: MCR-52) with a coaxial cylinder tool master. To obtain shear flow conditions, experiments are conducted under steady flow state. Measurements were carried out by linear increase in shear rate from 300 to 3000 s/1 at three different temperatures of 60, 80 and 100 ^{0}C. Average values of three tests are reported.

2.3.7 Iron chip corrosion

Cutting fluids corrosion tests are performed in accordance with ASTM D4627 standard. Fig. 1(a) illustrates 47 mm diameter filter paper made of glass fiber (1.5 mm particle retention) placed inside the petridish. Cutting oils SC1, SC2 and SC3 were mixed with synthetic hard water (calcium chloride dehydrate in distilled water). As per the standard, grey cast-iron chips were selected for corrosion test. Fig. 1(b) illustrates 4 g of chips sprinkled on the top of glass fiber filter paper. After wards, different petri dishes were filled with 25 ml of varying oil concentration of SC1, SC2 and SC3. Fig. 1(c) shows filter paper after the test. All petridishes were covered with top lid. After incubation time of 24 hr, cutting fluids were drained from petridish. The amount of rust stain over the filter paper gives measure of cutting fluid anti- corrosion properties that helps in identifying break point.

Fig. 1 Corrosion test method setup (a) Filter paper with petri dish, (b) Grey cast iron chips on filter paper and (c) Filter paper after the test



2.3.8 SRV test

Cutting fluids provide the cooling effect by reducing the friction in between metal working pieces. By preventing friction at this interface, reduce the heat generation improves the quality of work piece. Friction measurements were carried out using a Schwing-Reib- Verschleiß (SRV) tribometer (Optimal Instruments Prüftechnik GmbH, Munich, Germany) under pure sliding conditions. A stationary ball is pressed against a disc with a fixed track radius at a constant speed and a point load; test specimens and the lubricants are heated to 40 ^{0}C. The experimental parameters and conditions are 400 newton’s load, 40 ^{0}C, 1 mm stroke, speed 10Hz and duration 30 min. The time between the oil supply shut-off and the scuffing initiation has been recorded as the time to failure or degradation of the tribofilm. Lubricants were constantly delivered in front of the contact throughout the running-in stage and each lubricating oil experiment was repeated 3 times. SRV test was used to measure the relative lubricity of SC1E1, SC2E1 and SC3E1.

2.3.9 Reichert test

For evaluating the lubricating abilities of soluble cutting oil emulsion samples the tribology Reichert test has been engaged. This test is very appropriate for the measurement of low-viscosity fluids such as water-miscible lubricants.

The tribological system of the Reichert test consists of a cylindrical test specimen and a friction roller (both standard components of rolling bearings), which are crossed at an angle of 90°. The test specimens are pressed against the friction roller at a constant load of F = 300 N, while the friction roller is immersed in the investigated fluid. In the experiment, the friction roller rotates for a duration of 57 s with speed of 1000 rpm, supplying a continuous contact zone with the test fluid. The size of the resulting worn area on the test specimen is benchmark for the lubricating ability of the examined fluid. The lower the worn area, the higher the lubricating ability.

2.3.10 Machining experiments using cutting fluid emulsion

Machining experiments are carried out using a lathe equipped with a tool holder and tungsten carbide tool insert. Machining experiments are carried out at MQL environment using sustainable SC1E1, SC2E1 and SC3E1.Cutting tool insert was TiN coated on flank face. This inserts were selected as during machining MQL spray was only injected in-between work piece and cutting tool rake face. AISI 1045 mild steel were chosen as work piece material due to its various applications. Machining conditions are depth of cut 0.5 mm, feed rate 0.16 mm/rev cutting speed 250, 500, and 750 rpm and air pressure 5 bar. Surface roughness (Ra) was measured using surface roughness tester (Surf test, SJ-301). All experiments are repeated thrice and average values are plotted. SC1E1, SC2E1 and SC3E1 were applied using MQL technique for enhanced lubrication with minimum amount of cutting fluid during hard turning of AISI 1045 mild steel.

3. RESULT AND DISCUSSION

3.1 Storage stability – Soluble cutting oils

The stability of soluble cutting oils SC1, SC2 and SC3 were judged by continuously monitoring the appearance, pH and viscosity of the samples for 60 days. The change of appearance was given in Table 8. Change in pH and viscosity during 60 days storage was depicted in Figs. 2(a-b) and Figs. 3(a-b) respectively.

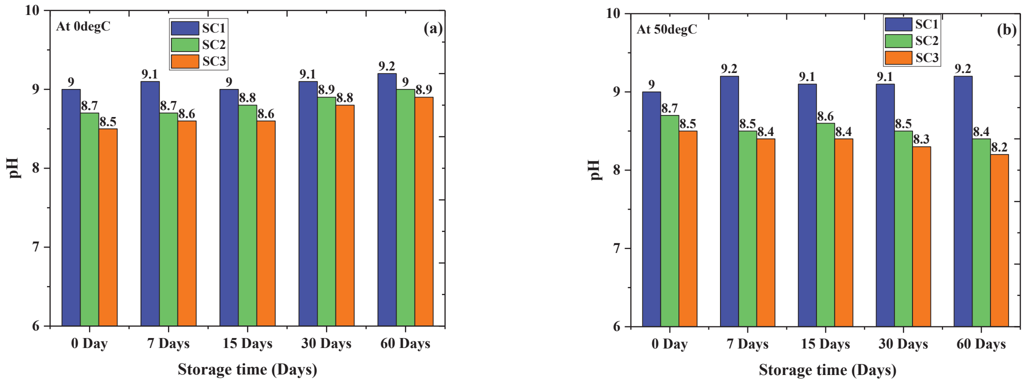


Fig. 2 Change in pH during storage at (a) 0 ^{0}C and (b) 50 ^{0}C

From the Table 8, it was found the there was no obvious change for appearance at 0 and 50 ^{0}C. The long term storage stability is due to optimum the percentage of non-ionic emulsifier system and coupling agent present in the formulations. The pH value of cutting fluid defines the condition of the fluid. A decrease in the pH value of cutting fluid of less than 7, shows that such cutting fluid cannot be used to iron base. When pH value of cutting fluid are too low or high, it has the tendency to be very hazardous to human operator and challenge of waste disposal.

The higher pH value for SC1 compared to SC2 and SC3 was due to assumption of higher hydroxyl number of emulsifier system present in the SC1 formulation. Subsequently, the PH values of all the three soluble cutting oils was kept stable for 60 days at 0 and 50 ^{0}C Figs. 2 (a-b).

Viscosity has considerable influence on the properties of a cutting fluid. Higher viscosity improves the lubrication abilities of the fluid, but decreases the cooling performance. Lower viscosity provides better cooling performance and easier removal of solid particles. From Fig.3 (a) and Fig. 3(b) all the cutting oil show the slight increasing viscosity at 0 and 50 ^{0}C. SC1 shows 2.5 % increase in viscosity at 50 ^{0}C compared to SC2 and SC3. It was due to assumption of evaporation of low molecular weight components at 0 and 50 ^{0}C and presence of high hydroxyl number of emulsifier in the SC1 formulation.

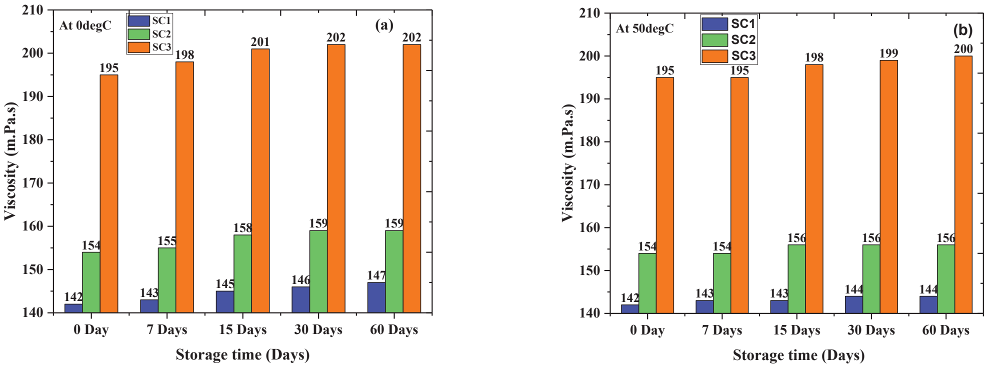


Fig. 3 Change in viscosity during storage at (a) 0 ^{0}C and (b) 50 ^{0}C

3.2 Thermogravimetric analysis

The thermal stability of the samples was determined in terms of the thermal degradation temperature and mass loss. As observed in Fig. 4 (a), the curves of the cutting oils have similar behaviour, i.e., the mass loss started to occur at 100 ^{0}C. This mass loss starting at 100 ^{0}C indicates the safe operating temperature (without giving off toxic vapours). When reaching 300 ^{0}C, cutting oils had lost 20 % of its mass through degradation/evaporation. When reaching 400 ^{0}C, about 80 % of the fluid had been consumed for SC1, SC2 and SC3. The degradation curve between 300 – 450 ^{0}C shows the presence of very little residual material, supporting the hypothesis that the fluid is basically composed of fatty acids, with low contribution of inorganic compounds.

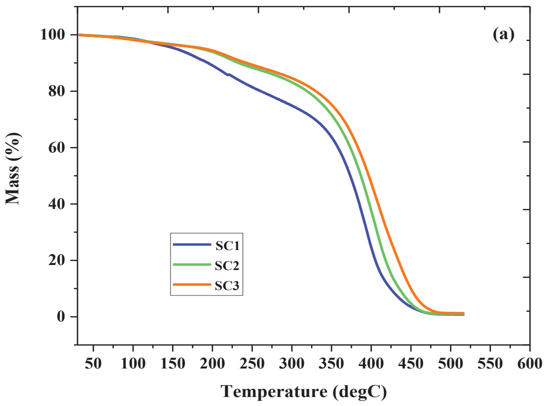


Fig. 4 (a) TGA curves up to 500 ^{0}C for SC1, SC2 and SC3

Fig 4(a) presents a detailed TG curve of the cutting fluids from 50 to 500 ^{0}C. There was no meaningful mass loss until 100^{0}C. This result indicates the absence of water. The mass loss between 50 – 200 ^{0}C reached 5 ± 3 % for SC2 and SC3. But SC1 show mass loss 10 ± 3 % between 50 – 200 ^{0}C due to presence of low molecular weight components and shows lower thermal stability. The final mass loss reached 98 ± 3 % for all the cutting oils at 450 ^{0}C. It was not possible to define whether the components of the cutting oil volatilized or degraded, but both phenomena could have happened. It can also be displayed in Fig. 4(a) that no residues were observed after 450 ^{0}C, indicating there was no significant content of inorganic compounds or char formation during heating. The SC1 fluid had lower thermal stability than the other fluids, so it is not recommended for use at high temperatures.

3.3 Emulsion stability

The emulsion stability of cutting fluids with various concentration of tap after 24 h was studied. From Table 7, SC1E1, SC2E1 and SC3E1 showed relatively better emulsion stability. It was found that, irrespective of HLB value of soluble cutting oils (SC1, SC2 and SC3), the emulsion with 5% soluble cutting fluid and 95% water showed better stability.

The UV-absorbance versus time plots for all the samples mentioned in Table7 is given in Fig.5 (a-d). The absorbance value was higher with higher concentration of cutting fluids present in the emulsion (SC1E4, SC2E4 and SC3E4). However, over a period of 24h duration, the decrease in absorbance was minimal for the samples SC1E1, SC1E2 and SC1E3. This could be due to the presence of emulsifier (HLB value of 9) having higher hydroxyl content in SC1 based soluble cutting fluid. SC1E1, SC2E1 and SC3E1 samples were selected for further evaluations.

3.4 Foaming

Foam in metalworking fluids is generally caused by the presence of alkanolamine soaps and certain anionic and non-ionic surfactants. These compounds, when added to water and subjected to the high shear and agitation encountered in high-speed machining operations, will generate copious quantities of foam. When a metalworking fluid is mixed with water, a certain amount of foam will develop.

This foam will either collapse or remain stable. The foaming behavior of SC1E1, SC2E1 and SC3E1 versus different time is showed in Fig.6. Relatively, SC3E1 showed better antifoaming property compared to SC1E1 and SC2E1. This could be due to the presence of lower hydroxyl content emulsifier in SC3E1

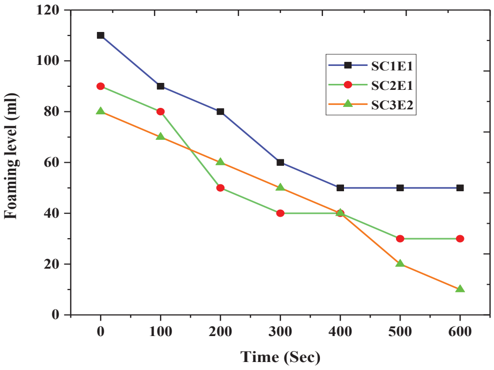
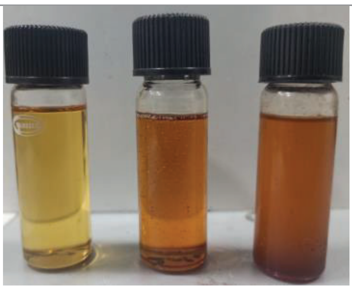
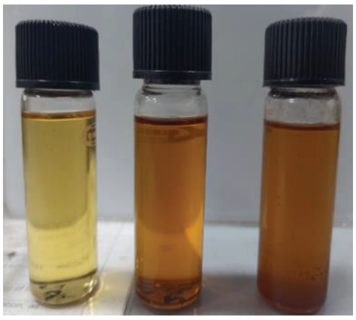
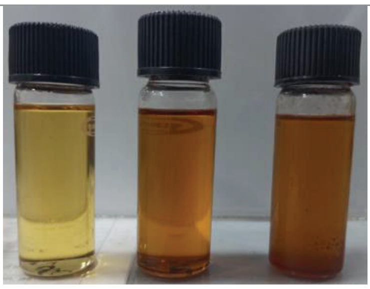
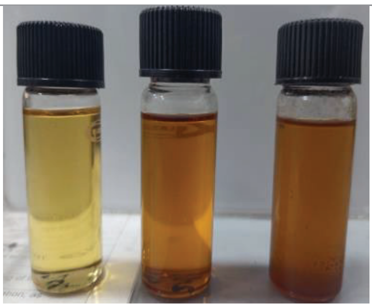
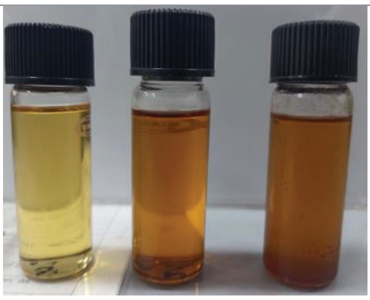


Fig. 6 Foaming level with time for SC1E1, SC2E1 and SC3E1 at room temperature

Table 6. *Appearance of soluble cutting oil during storage at 0 and 50 ^{0}C*

Temperature/Storage time (days)		^{0}C			^{0}C	
	SC1	SC2	SC3	SC1	SC2	S

0		
7		
15		
30		
60		

The increase in cutting quantity and decreasing water in the emulsion is expected to increase the viscosity and affecting the emulsion stability

Table 7. *Emulsion stability of soluble cutting fluids*

Cutting fluid	**Composition concentration of emulsion (%)**		**Emulsion stability after 24h at 27^0C**	
	Soluble cutting oil (%)	**Tap water (%)**	**Oil separated/cream separated (ml)**	**Emulsion stability (%)**
SC1E1	5	95	**0/0**	**100**
SC1E2	10	90	**0/0**	**100**
SC1E3	15	85	**0/1**	**99**
SC1E4	20	80	**0/2**	**98**
SC2E1	5	95	**0/1**	**99**
SC2E2	10	90	**0/2**	**98**
SC2E3	15	85	**0/3**	**97**
SC2E4	20	80	**0/4**	**96**
SC3E1	5	95	**0/2**	**98**
SC3E2	10	90	**0/4**	**96**
SC3E3	15	85	**0/5**	**95**
SC3E4	20	80	**0/8**	**92**

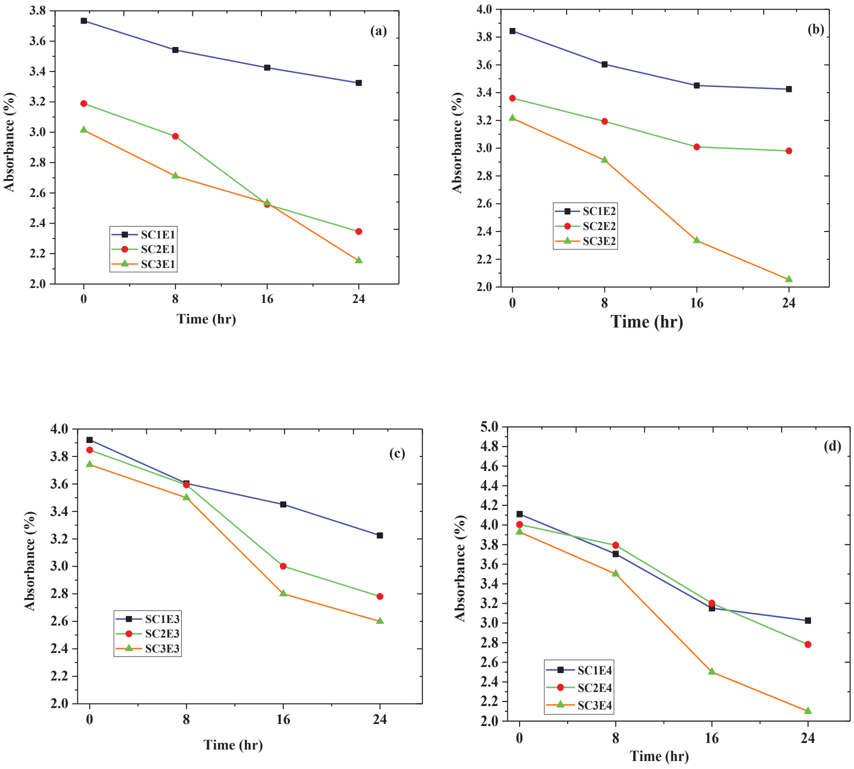


Fig. 5 Absorbance at 550 nm vs time (a) SC1E1, SC2E1 and SCE3E1, (b) SC1E2, SC2E2 and SC3E3 and (c) SC1E4, SC2E4 and SC3E4

3.5 Shear stress and viscosity of cutting fluid

It is obvious that all cutting fluids cannot follow the same lubrication mechanism. Lubrication depends on various properties such as viscosity, density, composition, etc. However, cutting fluid viscosity is the most important among them. Cutting fluids having higher viscosity are believed to have better lubricating properties. Apparently viscosity can decrease, remain unchanged or increase with respect to shear rate for time dependent fluids. These fluids are known as pseudo plastic ($n < 1$), Newtonian ($n = 1$) and dilatant ($n > 1$), respectively.

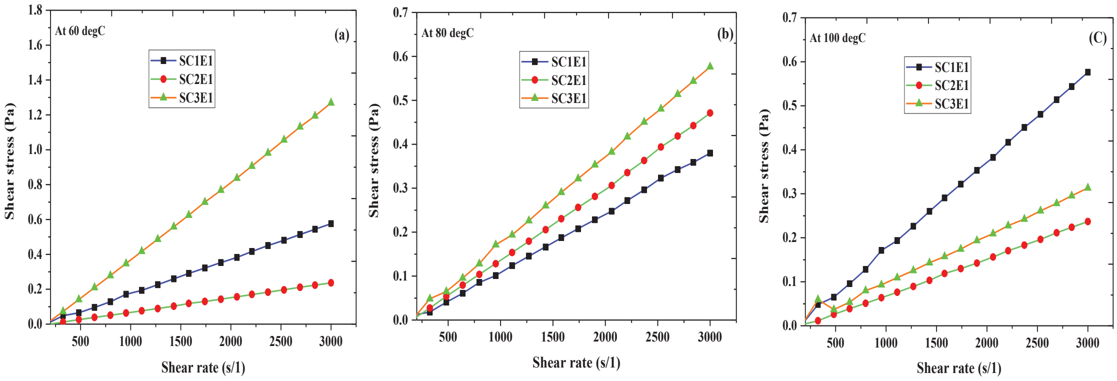


Fig. 7 Shear stress vs shear rate at (a) 60, (b) 80 and (c) 100 ^{0}C of SC1E1, SC2E1 and SC3E1

It is important to know the behaviour of cutting fluid because various metalworking processes involve different operating range of temperature and shear rate. Figs. 7 (a-c) shows the effect of shear rate on shear stress of SC1E1, SC2E1 and SC3E1 at 60, 80 and 100 ^{0}C respectively. The rheological behaviour of all the emulsions was similar. All the cutting fluids shows near Newtonian behaviour ($n =1$) at 60 ^{0}C (Fig. 7 (a)), 80 ^{0}C (Fig. 7 (b)) and 100 ^{0}C (Fig. 7 (c)). Newtonian behaviour can be confirmed by the linear variation of shear stress with shear rate. Therefore, it can be said that all the emulsions are able to maintain Newtonian behaviour at higher temperature.

Figs. 8 (a–c) illustrates the effect of shear rate on viscosity of SC1E1, SC2E1 and SC3E1 at 60, 80 and 100 ^{0}C respectively. At 60 ^{0}C, viscosity of SC1E1, SC2E1 and SC3E1 are 0.33, 0.36 and 0.44 Pas, respectively. At 80 ^{0}C, viscosity of SC1E1, SC2E1 and SC3E1 are 0.13, 0.16 and 0.21 Pa.s, respectively. Furthermore, with increase in temperature, the viscosities of SC1E1, SC2E1 and SC3E1 are 0.07, 0.08 and 0.110 Pas, respectively at 100 ^{0}C. Increase in temperature showed a reduction in viscosity. It can be fact that attributed to oil molecules can overcome a threshold energy barrier and occupy the adjacent vacant site due to thermal activation [16]. SC3E1is expected to provide better lubrication compared to SC1E1 and SC2E1 as it has showed relatively higher viscosity.

3.6 Iron chip corrosion

ASTM D4627 defined break point as the weakest concentration of cutting fluid tested, which shows no rust stain on the glass fiber filter paper. As per standard, the rate of corrosion is graded from 1 to 10, where 10 is highly corrosive, 5 represent medium corrosion and 1 stands for non-corrosive cutting fluids.

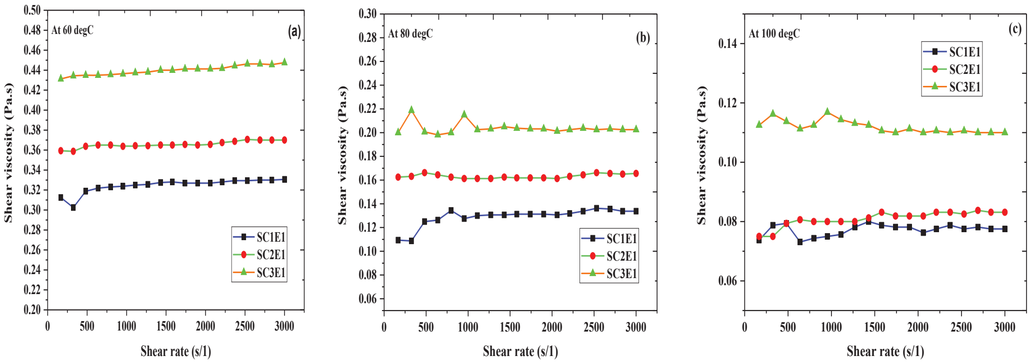


Fig. 8 Shear viscosity vs shear rate at (a) 60, (b) 80 and (c) 100 ^{0}C SC1E1, SC2E1 and SC3E1

After corrosion test, results with several concentrations of SC1, SC2 and SC3 was shown in Table 8. Results shows that the amount of rusting reduces with the increase in concentration of cutting fluids. For SC1 less rusting was observed as compared to SC2 and SC3 for all concentrations. It confirms that the SC1 having HLB value 9 has better anti-corrosion properties with respect to SC2 and SC3 based cutting fluids having HLB values 13 and 16. This may be attributed to the effect of the number of terminal amine and hydroxyl groups present in CI and surfactant having HLB value 9.

3.7 SRV

The coefficient of friction (COF) versus time for SC1E1, SC2E1 and SC3E1 showed in Fig 9 (a). All the samples have shown sudden increase in COF and reduced gradually over time. The sudden increase in COF was relatively lower for SCE3E1 compared to other samples. This could due to higher viscosity of SC3E1. The wear scar dia of the test ball was measured after SRV test and showed in Fig 9 (b). Relatively, SC3E1showed lower wear scar dia. This could be due to the higher viscosity of SC3E1 compared to SC1E1 and SC2E1.

Wear depth values of the test disc after SRV test was shown in Fig 9 (c) for SC1E1, SC2E1 and SC3E1. The lower wear depth was noticed for SC3E1 compared to SC1E1 and SC2E1. This could be due to higher viscosity of SC3E1 compared to SC1E1 and SC2E1.

3.8 Reichert test

Fig 10 (a) shows the frictional force generated versus time during Reichert test. Results showed that SC1E1, SC2E2 and SC3E1exibits similar friction behaviour. This can be attributed to the presence of same EP additives in all the three samples. Fig 10 (b) explains the temperature raise versus time during Reichert test. SC1E1 showed lower temperature generation compared to SC2E1 and SC3E1. This can be attributed to the fact that SC1E1 has relatively lower viscosity compared to SC2E1 and SC3E3.

Table 8. *Corrosion grades for soluble cutting oil emulsions*

Cutting fluid	Composition concentration of Cutting fluid (%)		Corrosion grade after 24 hr at 25^{0}C
	Soluble oil (%)	Tap water (%)	Oil separated/cream separated (ml)
SC1E1	5	95	3
SC1E2	10	90	3
SC1E3	15	85	2
SC1E4	20	80	2
SC2E1	5	95	5
SC2E2	10	90	5
SC2E3	15	85	4
SC2E4	20	80	4
SC3E1	5	95	5
SC3E2	10	90	5
SC3E3	15	85	4
SC3E4	20	80	4

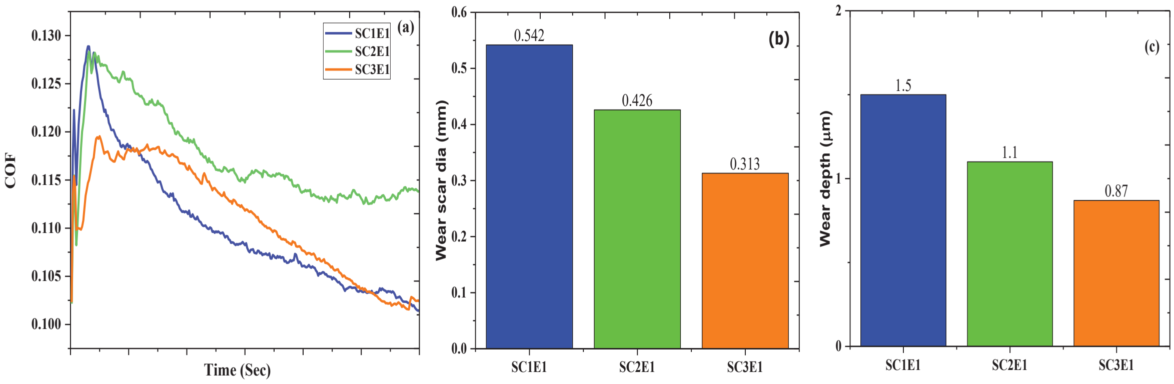


Fig. 9 (a) COF for SC1E1, SC2E1 and SC3E1 at 40 ^{0}C, (b) Wear scar of the ball after SRV test and (c) Wear depth of the disc after SRV test

The measured wear area for SC1E1, SC2E1 and SC3E1 after Reichert test was showed in Fig.10 (c). The measured wear area was relatively lower for SC3E1 compared to SC1E1 and SC2E1. This may be due to higher viscosity which result in thick lubrication film between the frictional contacts.

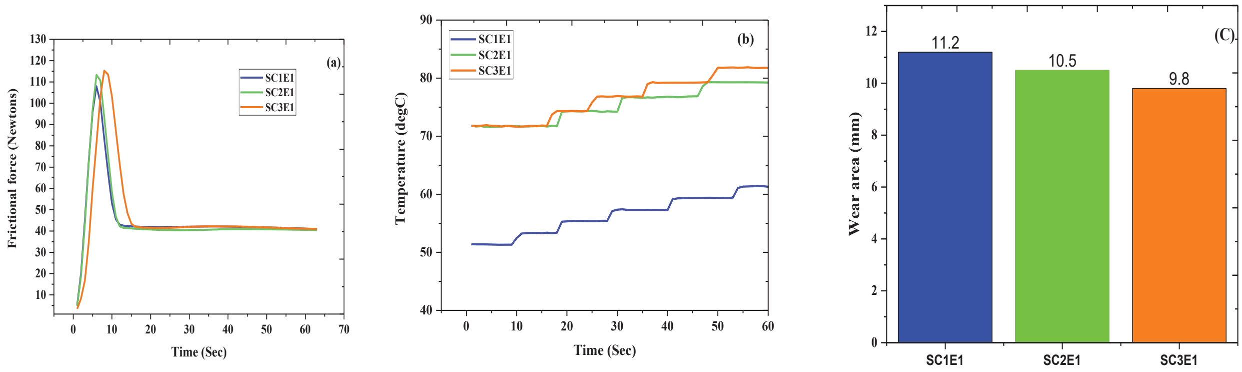


Fig. 10 (a) Frictional force for SC1E1, SC2E1 and SC3E1 at 40 ^{0}C, (b) Temperature generation during testing and (c) Wear area of the cylinder after test

3.9 Machining experiments using cutting fluid emulsion

The effect of cutting speed on cutting force, surface roughness and cutting temperature during machining operation was shown in Fig. 11 (a), Fig. 11 (b) and Fig. 11 (c) respectively. From Fig .11 (a) it was found that relatively SC3E1 showed lower cutting force at higher speed. This could be due high viscosity of SC3E1 and formation of lubricant film.

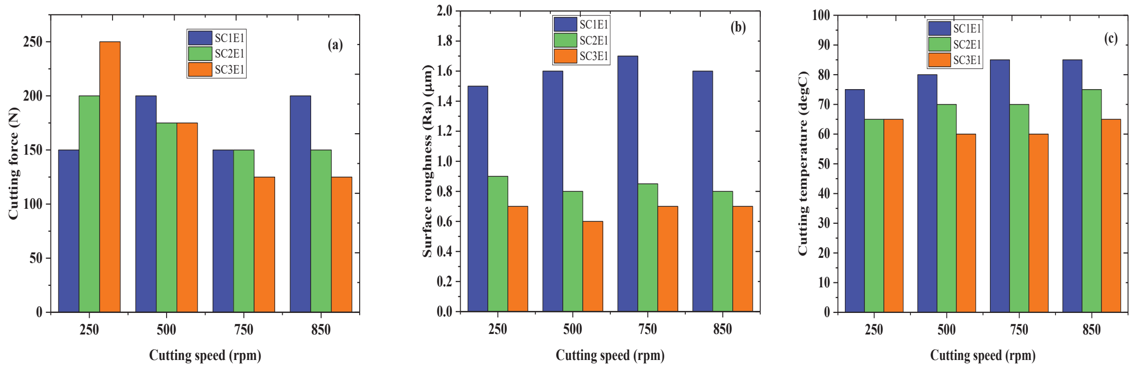


Fig. 11 Effect of cutting speed on (a) cutting force, (b) Surface roughness and (c) Surface temperatures

It was observed from Fig .11 (b) the work piece surface roughness after machining with SC3E1 was lower as compared to SC1E2 and SC2E3. This could be due to the lower cutting force generated at higher speed in case of SC3E1

. The raise in temperature was low for SC1E1 compared to SC2E1 and SC3E1 [Fig.11(c)]. This may be due to lower viscosity of SC1E1.Result showed that the performance of SC3E1 is superior to that of SC2E1 and SC3E1 in terms of both surface roughness [Fig.11. (c)] and cutting force. This is attributed to (i) better lubricating ability of SC3E1 because of its high viscosity as compared to SC1E1 and SC2E1 and (ii) high viscosity oils are expected to have better thermal conductivity and specific heat capacity [17].

4. CONCLUSION

The effect of incorporation of emulsifier having different HLB value viz., 9, 13 and 16 in castor oil based soluble cutting oil was studied. The variation in HLB value of emulsifier did not change the pH and viscosity. Soluble cutting oil having HLB value of 16 showed better thermal stability as observed in TGA analysis. Further, the effect of varying content of water on emulsion properties of soluble cutting oil was studied. A better emulsion stability was noticed 95:5 ratio of water and soluble cutting oil (containing emulsifier with HLB value of 9). Reduced content of water increased the corrosion resistance. All cutting fluid emulsion exhibited Newtonian behaviour at both low and high temperature. The emulsion prepared with soluble cutting oil containing emulsifier of HLB value of 16 showed good tribological and machining performance.

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