Comparative Study on the Effect of Vegetable Based Cutting Fluid and Mineral Oil on Cutting Forces and Surface Roughness during Turning Operation

دراسة مقارنة تأثير سوائل التبريد للزيوت النباتية والزيوت المعدنية على قوى القطع ودرجة خشونة السطح أثناء عملية الخراطة

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الملخص

فى هذه الدراسة تم عمل دراسة مقارنة عمليا لقياس أداء سوائل القطع للزيوت النباتية الصديقة للبيئة (زيت عبادالشمس – زيت الزيتون –زيت جوز الهند- زيت بذر الكتان – زيت الخروع) والتى تم إعدادها ومقارنة الأداء بينها وبين سوئل القطع من الزيوت المعدنية عن طريق قياس خشونة السطح وقوى القطع أثناء عملية الخراطة الطولية للصلب المطاوع كما تم عمل مقارنة بينها وبين نتائج التشغيل الجاف.وقد إستخدمت ظروف قطع مختلفة. جميع الزيوت النباتية التى تم إستخدامها فى هذه المقارنة عند سرعة قطع 955 لفة/الدقيقة وعمق قطع 1 مم ومعدل تغذية 0.08 مم/لفة قللت قيمة قوى القطع والقيم المتوسطة لخشونة السطح بالمقارنة بالزيوت المعدنية وبينت دراسة المقارنة أيضا أنه يمكن إستبدال الزيوت المعدنية بالزيوت النباتية فى جميع حالات التشغيل الناعمة والخشنة وذلك لتقليل المخاطر الصحية التى تسببها سوائل القطع البترولية.

Abstract

Experimental Comparative study on the performances of both new developed environmental friendly vegetable based cutting fluids (sunflower, olive, coconut, linseed, and castor oils) and mineral oil-based cutting fluids during turning processes were reported in this work. Performances of cutting fluids were compared with respect to surface roughness and cutting forces during longitudinal turning of mild steel. Experimental results were also compared with results from dry cutting conditions. Different cutting conditions were used in this study. All vegetable based cutting fluids which were used in this comparison at cutting speed (955 rpm),depth of cut (1 mm) and feed rate (0.08 mm/rev) achieved a decrease in the values of cutting forces and average value of surface roughness compared with using mineral oil. Comparative study showed that mineral oil based cutting fluids can be replaced by the vegetable based cutting fluids in case of roughing and finishing operations, thus reducing the occupational health risks associated with petroleum oils based cutting fluids.

Keywords

Vegetable Based Cutting Fluids, Additives, Cutting Forces, Surface Roughness

Terminology and abbreviations:

MWFs	Metalworking fluids	F_Z	Main cutting force (N)
VBCFs	vegetable-based cutting fluids	F_X	Feed force (N)
Ra	Arithmetic surface roughness	F_Y	Radial force (N)
AISI	American Iron and Steel Institute	**R**	Resultant of cutting forces (N)
CNC	Computer numerical control	**IP**	Institute oF Petroleum (UK)
MRR	Metal removal rate	**V**	Cutting speed (m/min)
rpm	Revolution per minute	**HSS**	High speed steel
N	Cutting speed (rpm)	**DAQ**	Data acquisition
f	Feed rate (mm/rev)		

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1-Introduction

Metalworking fluids are lubricants, which are extensively used in machining and cutting operations. There are several types of cutting fluids, Most of them are mineral oil-based fluids and they help in increasing productivity and quality of manufacturing operations by cooling and lubrication during cutting and forming processes. Due to their advantages, the consumption of MWFs is increasing in machining industry. Despite their widespread use, they pose significant health and environmental hazards throughout their life cycle. It has been reported by Lawal et al. [5], that about 80% of all occupational diseases of operators were due to skin contact with cutting fluids.

Vegetable oils are highly attractive substitutes compared with petroleum-based oils because they are environmentally friendly, renewable, less toxic and readily biodegradable. Consequently, VBCFs are more potential candidates for use in industry as lubricants/MWFs. Many investigations are in progress to develop new bio-based cutting fluids from various vegetable oils available around the world. Because of environmental concerns and growing regulations over contamination and pollution, the increase in need for biodegradable lubricants and renewable is highly expected. [5]

2- Literature Review:

Krahenbuhl [1] reported that VBCFs were viable alternative to petroleum-based metalworking fluids due to the following reasons: (i) vegetable oils provided a lubricating film layer, which helped to improve workpieces quality and overall process productivity reducing friction and heat generation, (ii) vegetable oil possess higher flash point, which give opportunities for an increase in MRR, because of the reduction in smoke formation and fire hazard during machining process.

Lawal et al. [2] experimentally studied the performance of cutting fluids developed from four vegetable oils and comparing results with soluble oil and dry cutting in turning of mild steel. Temperature was considered to evaluate the performance of the cutting fluid developed from each vegetable oil.

Ojolo et al. [3], experimentally determined the effect of some straight biological oils (groundnut oil, coconut oil, palm kernel oil and shear butter oil) on cutting forces during turning of three materials (mild steel, aluminum and copper) using a tungsten carbide tool. Their results showed that bio-oils were suitable as metalworking fluids, but the effects of the bio-oils on cutting force were material dependent.

Babur Ozcelik et al [7] studied the performances of three VBCFs which developed from crude sunflower oil, refined sunflower oil, refined canola oil and commercial semi-synthetic cutting fluid. Results were compared in terms of tool wear, thrust force and surface roughness during drilling of AISI 304 austenitic stainless steel with HSS tool. Experimental results showed that canola based cutting fluid gave the best performance due to its higher lubricating properties with respect to other cutting fluids at the constant cutting conditions (spindle speed of 750 rpm and feed rate of 0.1 mm/rev).

Sharafadeen Kunle et al [8] evaluated the performances of palm oil and groundnut oil in comparison with that of mineral oil-based cutting fluid during machining operation of mild steel. Temperature of the workpieces and their chip formation rates using these vegetable oils as cutting fluids under different cutting speeds, feed rate and depth of cut, were compared with that of mineral oil and dry machining. Based on their results, groundnut oil and palm oil were being recommended as viable alternative lubricants to the mineral oil during machining of mild steel.

3- Preparation of Vegetable Oils.

Vegetable oils primarily consist of triglycerides, which are glycerol molecules with three long chain fatty acids attached at the hydroxyl groups via ester linkages. It is reported [4] that triglyceride structure provides desirable qualities for boundary lubrication. It is due to their long and polar fatty acid chains, which provide high strength lubricant films that interact strongly with metallic surfaces, reducing both friction and wear. The polarity of fatty acids produces oriented molecular films, which provides oiliness and imparts anti wear properties.

3.1 Additives.

Five different vegetable oils and one commercial mineral oil were used. The vegetable oils were linseed, sun flower, castor, olive and coconut oil. These oils were prepared at the first time in the laboratory of research center of Misr Petroleum Company, Egypt. Many chemical substances were added to vegetable oils to make suitable cutting fluid. The main additives were emulsifiers, biocides, extreme-pressure, corrosion inhibitors and oiliness agents. When emulsifiers were mixed, they disperse the oil in the water and form a stable oil to water emulsion. The emulsion causes the oils to cling to the work piece during machining. Emulsifier particles scatter light, giving the fluid a milky and opaque appearance. Table 1 show typical additives which were used for emulsifiable cutting oils.

3.2 Evaluation Tests for Vegetable Cutting Fluids.

The aim of these evaluation tests to ensure that water mix metal working fluids should remain stable during using it at different temperature degrees and should not readily permit corrosion of equipment with which they come into contact. The following tests were done according to IP standard:

a. Determination of thermal stability of water mix metal working fluids - IP 311.

b. Determination of stability of water mix metal working fluids - IP 263/70.

c. Determination of frothing characteristics of water mix metal working fluids - IP312.

d. Determination of cast iron corrosion characteristics of petroleum products-IP 125.

4. Experimental Works.

The experiments were carried out on a conventional center lathe. Sixty three samples of mild steel have been machined through original fixation. The work pieces were firmly held on a 3-jaw chuck of the machine. The cutting tool was mounted on a tool holder on the upper plate of a dynamometer. The dimensions of samples

Table 1: Additives in VBCFs:

Additives	Type (example)	function
1-Base emulsifier	Petroleum sulphonates	Improve wetting of parts, disperse oil in water
2-Co- emulsifier	Ethoxylate compounds	Disperse oil in water
3-Biocides	Glokill 77	Reduce microorganisms
4-Extreme-pressure additives	Neat sulphur	Lubricate under pressure
5-Coupling agents	Hexylene glycol	Improve the solubility of the various additives in the cutting fluids
6-Corrosion inhibitors	Amine borates	Prevent part or tool corrosion
7-Oiliness agents	Sulphated castor oil	Increase film strength

and cutting conditions which were used are shown in an experimental plan in table 2. Each group of samples was turned at three different spindle speeds, three different feed rates and three different cutting depths. The spindle speeds were 460, 955, and 1200 rpm, the feed rates were 0.1, 0.08 and 0.08 mm/ rev, and cutting depths were 0.5, 1.0, 0.2 mm depth respectively. The spindle speeds and feed rates were selected from the recommended standard tables of the materials to avoid excessive tool wear and failure. Each group of samples has been done at dry machining using six types of cutting fluids. One of these types is commercial mineral oil-based cutting fluid and others types of VBCFs which were developed on the first time in Egypt in the research center of Misr petroleum oils Company. The samples were machined by using a neutral tool with 60 degrees approach angle and with a variable cutting speed, feed rate and depth of cut. The compositions of the work piece materials used for experimentation are given in table 3.

Table 3: Chemical Composition of the mild steel sample (wt. %). [8]

Element	Average content
Fe	97.68
C	0.24
Si	0.20
S	0.01
P	0.004
Mn	0.737
Ni	0.106
Cr	0.01
Mo	0.001
V	0.0006
W	0.0065

5. Cutting Force Measurements.

Turning operation generated three perpendicular cutting force components. a carbide tip tool TNMG 160412 was used. Flood coolant condition was used. Flow rate for all cutting fluids was chosen as 3 liter/min with ratio (1:20) oil to water concentrate according to standard methods These three forces were measured with a Kistler 9257B piezoelectric type multi-component dynamometer with a top plate 100 x 170 mm up to 10 kN. The dynamometer is mounted on the carriage

Table 2: experimental plan of 21 samples of each group.

No of groups	No of samples	Lubrication type	Cutting conditions	Dimension of samples
Group 1	21	Dry Mineral oil Sunflower oil Olive oil Coconut oil Linseed oil Castor oil	**Condition 1 (Roughing)** N = 460 rpm f = 0.1 mm/rev d = 0.5 mm V ≈ 60 m/min	29.3 φ mm × 110 mm lengths and 28 φ mm× 95 mm length.
Group 2	21	Dry Mineral oil Sunflower oil Olive oil Coconut oil Linseed oil Castor oil	**Condition 2 (Finishing)** N = 1200 rpm f = 0.08 mm/rev d = 0.2 mm V ≈ 120 m/min	32 φ mm × 110 mm lengths and 28 φ mm× 95 mm length.
Group 3	21	Dry Mineral oil Sunflower oil Olive oil Coconut oil Linseed oil Castor oil	**Condition 3** N = 955 rpm f = 0.08 mm/rev d = 1 mm V ≈ 95 m/min	31.5 φ mm × 110 mm lengths and 28 φ mm× 95 mm length.

of the lathe by fixture as shown in Fig.1, this fixture was machined on CNC milling machine. The measuring chain with DAQ system is shown in Fig.2, while schematic diagram of the experimental set-up is shown in Fig.3. Forces data were saved on a personal computer, acquired via a DAQ card and Kistler dynoware software.

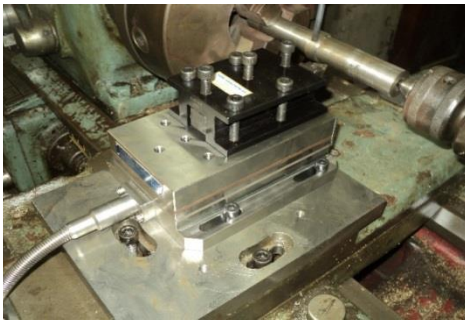


Fig. 1: Mounting of dynamometer on carriage of lathe.

Fig. 2: DAQ system (charge amplifier, data acquisition card and laptop)

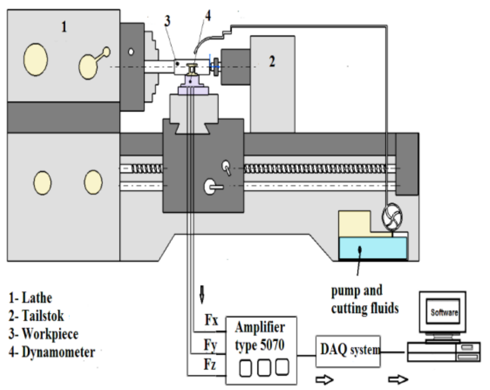


Fig. 3: Schematic diagram of the experimental set-up

It is universal and easy to use, and it is particularly suitable for force measurements with dynamometers or single and multi-component force sensors. For signal analysis, dynoware offers online visualization of curves measured, together with useful calculation and graphics function. Fig.4, shows signal shape which obtained from the dynamometer. In addition to simple configuration of the main measuring instruments, it supports individual documentation of the measurement, as well as storage of configuration and measured data. The signal sampling frequency was selected as 50Hz for most measurements.

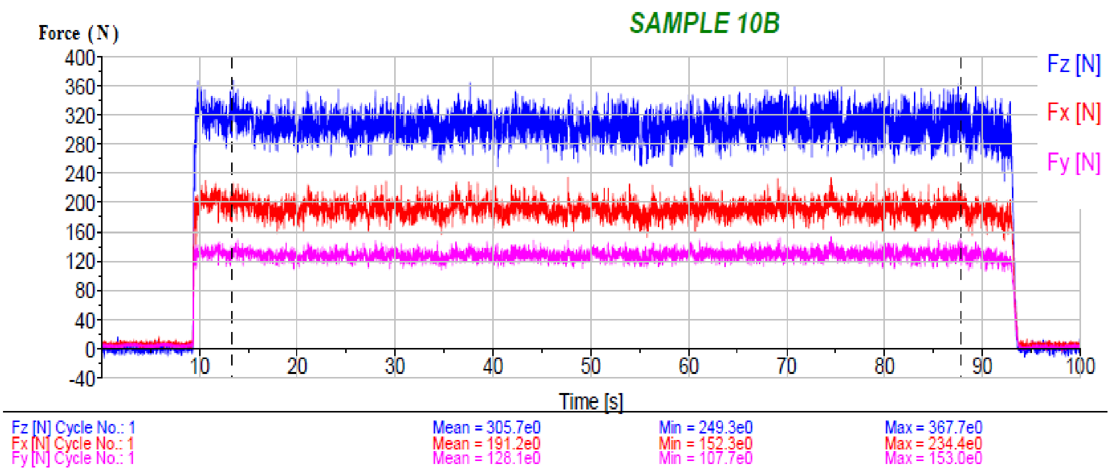


Fig. 4: Signal curve for one of the samples of olive based cutting fluid at N=955 rpm, f=0.08 mm/rev, d=1 mm

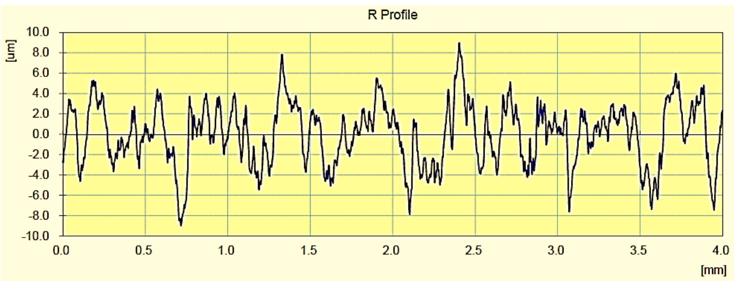
6. Surface Roughness Measurements.

In manufacturing industries, especially for metal cutting, surface finish of machined parts is extremely important in determining the quality. Surface finish is important in terms of tolerances because it reduces assembly time and avoids the need for secondary operations. Besides, good-quality turned surface is significant in improving corrosion resistance, fatigue strength and creep life [6]. The surface roughness for the entire 63 sample were measured using a surface roughness tester (Mitutoyo Surf test SJ-201) showed in Fig.5. It is a stylus type surface roughness measuring instrument developed for shop floor use. The SJ-201 is capable of evaluating surface texture with a variety of parameters according to various national and international standards. Cut-off length and number of readings for each sample were selected as 0.8 mm and 3 reading, respectively. These measurements were repeated three times and the average values were used for analysis.

Measurement processes were made in parallel with sample axis. The roughness

Fig. 5 - Surface roughness tester.

Results were displayed digitally/ graphically on a computer, and output is saved as excel printed sheet. The stylus of the SJ-201 detector unit traced the minute irregularities of the work piece surface. Surface roughness was determined from the vertical stylus displacement produced during the detector traversing over the surface irregularities. The Arithmetic Mean Deviations of the profile Ra of the each sample piece was noted down as a surface roughness measurement. Some examples of the surface roughness profile generated by the tester were shown in Fig.6.



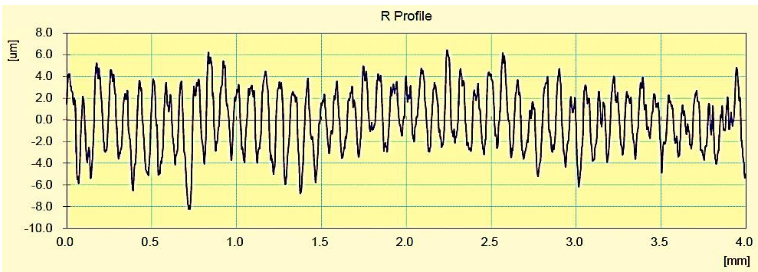


Fig. 6 – Surface roughness profiles which were generated from Mitutoyo Surf test SJ-201.

7. Results and Discussions.

Three samples were used in both dry machining and for each cutting fluids to determine the average values of both cutting forces and Ra. Cutting forces were measured during cutting operations using the dynamometer while the surface finish was measured afterwards by the surf test in a laboratory.

7.1 Group 1.

Variations of cutting forces with different cutting fluids on mild steel at 0.5 mm depth of cut, 0.1 mm/rev feed, and 460 rpm cutting speed are shown in Fig.7. Average values of Ra by using dry cutting, mineral, and five different VBCFs on mild steel during turning operation at these cutting conditions are shown in Fig.8.

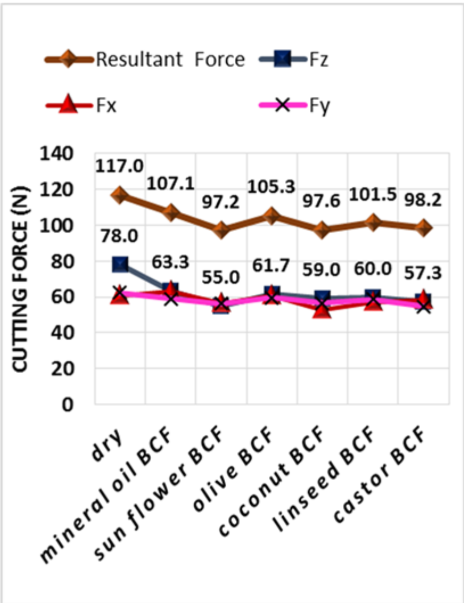


Fig. 7: Variation of cutting forces with different cutting fluids for group 1

Quantitative comparisons of VBCFs with respect to the commercial mineral oil and dry cutting for the resultant cutting force R and Ra are shown in Table 4. Performances of VBCFs with respect to mineral oil can be listed in decreasing order of the surface roughness in Table 4. Negative values of Ra percent indicated percentage improvements of VBCFs for the rest, and the negative percentage for cutting force indicated the decreasing of value of cutting force, and vice versa. Observations from Fig.7, 8 and Table 5. can be as follows:

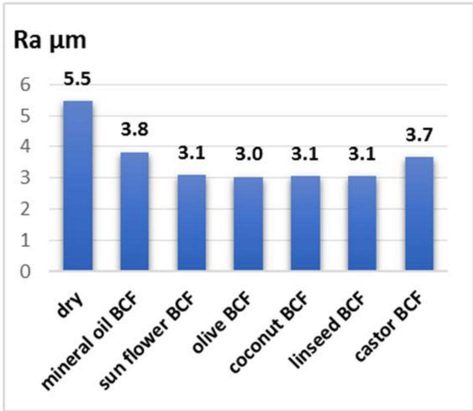


Fig. 8: Average value of Ra for dry, mineral, and five different VBCFs for group 1.

a. All cutting fluids (mineral and vegetable oils) which were used under these cutting conditions achieved a decrease in the cutting forces and surface roughness compared with dry cutting, therefore improvement in cutting operation results.

b. All vegetable BCFs which were used in this comparison achieved a decrease in the values of the cutting forces compared with using mineral oil.

c. All the used vegetable BCFs which achieved a decrease in the average values of surface roughness Ra with respect to using mineral oil and dry cutting.

d. Olive BCF achieved a decrease in the value of Ra by a large percent 45.45% compared with dry cutting and by 21.05% compared with mineral oil.

e. The lowest value of cutting forces were obtained by using sun flower BCF. The average value of R was 97.2 N and decreased by 9.24% compared with using mineral BCF.

f. Sunflower BCF, coconut BCF, and linseed BCF achieved good percentage improvement for average value of the Ra, and it was 18.42 % compared with mineral oil.

g. The lowest percentage of Ra was obtained when using olive BCF. The average value of Ra was 3 µm and decreased by 21.05% compared with using mineral BCF. On the other hand it achieved less percentage for R, and it was 1.68 % compared with mineral oil.

h. Figure 7, shows that there was no significient deference between the cutting forces Fx and Fy at these cutting conditions.

7.2 Group 2.

Cutting forces were measured when vegetable oils were used and compared with which were obtained by using mineral oil and dry cutting through these cutting conditions. Variations of cutting forces with different VBCFs on mild steel are shown in Fig.9, while the average values of Ra by using dry cutting, mineral, and five different VBCFs are shown in Fig.10. Quantitative comparisons of VBCFs with respect to the commercial mineral oil and dry cutting against the cutting forces and Ra are shown in Table 5 (5).

7.3 Group 3.

In finish cutting conditions during the turning operation, maximum cutting velocity 1200 rpm, minimum feed rate 0.08 mm/rev and 0.2 mm depth of cut were used. Variation of cutting forces through using different VBCFs are shown in Fig.11. The average values of Ra by using dry cutting, mineral, and five different VBCFs were shown in Fig.12. Quantitative comparisons of VBCFs with respect to the commercial mineral oil and dry cutting for the cutting forces and surface roughness were shown in Table 6.

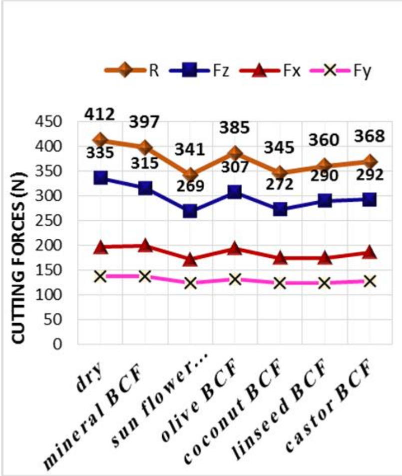


Fig. 9: Variation of cutting forces with different VBCFs for group 2.

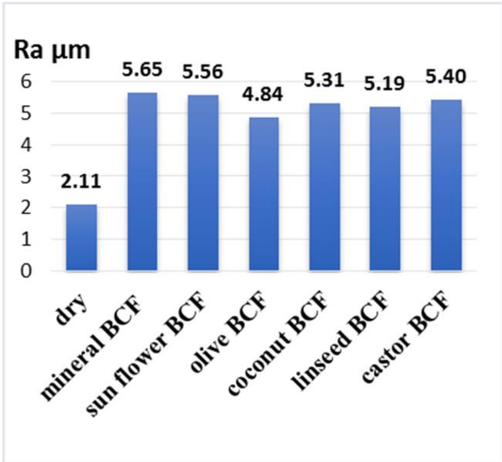


Fig. 10: Average value of Ra for dry, mineral, and five different VBCFs for group 2.

Table 5: Percentage comparisons of the R, Fz and Ra between mineral and vegetable BCFs and dry cutting.

Vegetable BCFS	percentage comparison of the cutting force with respect to mineral BCF and dry cutting				
	Mineral BCF			*Dry cutting*	
	Cutting force Fz (%)	Resultant R (%)	Ra (µm) (%)	Cutting force Fz (%)	Resultant R (%)
Mineral BCF	0	0	0	-6.05	-3.62
Sun Flower BCF	-14.7	-14.03	-1.59	-19.86	-17.14
Olive BCF	-2.63	-2.80	-14.33	-8.53	-6.46
Coconut BCF	-13.75	-12.95	-6.01	-18.97	-16.12
Linseed BCF	-8.03	-9.4	-8.14	-13.6	-12.68
Castor BCF	-7.30	-7.15	-4.42	-12.91	-10.51

Observations can be as follows:

a. All the used vegetable BCFs decrease the values of cutting forces compared with using mineral oil and dry cutting, therefore improvement in cutting operation results.

b. All the used vegetable BCFs decrease the average values of Ra with respect to using mineral oil.

c. The lowest values of cutting forces were obtained by using sun flower BCF. The average values of R and Fz were decreased by 14.03% and 14.7 % respectively compared with using mineral BCF, on the other hand it achieved less percentage improvement for average value of Ra, and it was 1.59 % compared with mineral oil.

d. Coconut BCF achieved good results on the cutting forces compared with mineral BCF. The R and Fz were decreased by 12.95% and 13.75% respectively.

e. The lowest average value of Ra was obtained by using olive BCF. It was 4.84 µm and decreased by 14.33 % compared with using mineral BCF which was 5.65 µm. on the other hand it achieved less percentage improvement in the average value of R and it was 2.8% compared with mineral oil.

7.3 Group 3.

In finish cutting conditions during the turning operation, maximum cutting velocity 1200 rpm, minimum feed rate 0.08 mm/rev and 0.2 mm depth of cut were used. Variation of cutting forces through using different VBCFs are shown in Fig.11. The average values of Ra by using dry cutting, mineral, and five different VBCFs were shown in Fig.12. Quantitative comparisons of VBCFs with respect to the commercial mineral oil and dry cutting for the cutting forces and surface roughness were shown in Table 6.

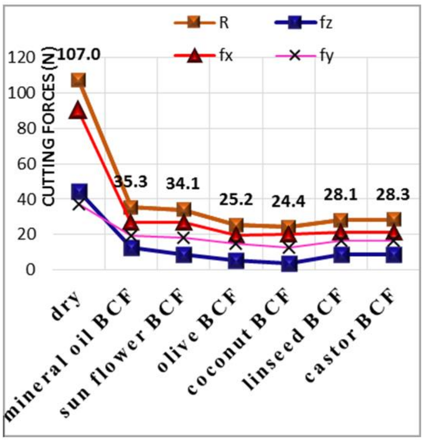


Fig. 11: Variation of cutting forces with different VBCFs on mild steel for group 3.

From results illustrated in Fig.11, 12, and comparison table 6, concluded the following:

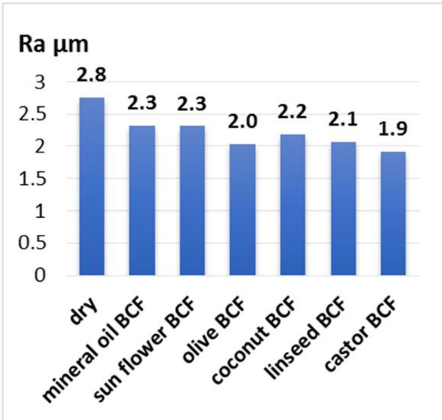


Fig. 12: Average value of Ra for dry, mineral, and five different VBCFs for group 3.

a. It is clear from Fig.12 that the average values of Ra of vegetable oils were less or sometimes equal to the average values of Ra of mineral oil. This means that the vegetable oil can also be used as a lubricant, due to its lubricity and cooling action.

b. It is clear from Fig.11 that the neat cutting forces which were measured by using vegetable oils were less than the cutting forces from mineral oil.

c. All vegetable BCFs achieved a decrease in the average values of Ra compared with using mineral BCF and dry cutting, therefore improvement in cutting operation results.

d. The lowest value of the cutting forces was obtained when using coconut oil compared with mineral oil. The average value of R was decreased by 30.88% and 77.45 % compared with mineral oil and dry cutting respectively. On the other hand it achieved less percentage improvement for the average value of Ra, and it was 4.35 % compared with mineral oil.

e. Olive oil achieved good results in the cutting forces and the average value of Ra compared with mineral BCF, so that the resultant force was decreased by 28.61%.

f. The lowest average value of surface roughness was obtained by using castor oil. The average value of Ra was 1.9 µm, so that decreased by 17.4 % and 32.14% compared with using mineral oil and dry cutting respectively.

e. For finish cutting, the surface roughness of vegetable oils was better than of dry cutting for mild steel with carbide tip, and the resultant cutting forces were decreased to one third of the cutting force of dry cutting.

8. Conclusion:

1. The use of vegetable oils as new metal cutting fluids in reducing the cutting forces and improving the surface finish at different cutting conditions during turning operation gave good competitive results compared with mineral oils.

2. This comparative study showed that mineral oil based cutting fluids can be replaced by the VBCFs, thus reducing the occupational health risks associated with petroleum oil BCF. These were utilized to develop biodegradable lubricants for various industrial applications. The trend was extended to formulate environmental friendly metal working fluids.

Table 6: Percentage comparisonsof the R and Ra between mineral, vegetable BCFs and dry cutting.

Vegetable BCFs	**percentage comparison of the cutting force with respect to mineral BCF and dry cutting**			
	Mineral BCF		Dry cutting	
	Resultant R (%)	Ra (µm) (%)	Resultant R (%)	Ra (µm) (%)
Mineral BCF	0	0	-67.00	-17.86
Sun flower BCF	-3.40	0	-68.13	-17.86
Olive BCF	-28.61	-13.04	-76.45	-28.57
Coconut BCF	-30.88	-4.35	-77.45	-21.43
Linseed BCF	-20.40	-8.70	-73.74	-25
Castor BCF	-19.83	-17.40	-73.55	-32.14

3. By increasing cutting depth the surface roughness of dry cutting was better than of using cutting fluids for mild steel with carbide tip and this result need analysis in the future work. On the other hand the surface roughness of vegetable oils is better than of dry cutting for finish cutting, and the resultant cutting force was decreased to one third value of cutting force of dry cutting.

4. All vegetable BCFs which were used in comparison at cutting speed 955 rpm, depth of cut 1 mm and feed rate 0.08 mm/rev achieved a decrease in cutting forces compared with using mineral oil and dry cutting, therefore improvement in cutting operation results. All vegetable BCFs achieved a decrease in the average values of surface roughness with respect to using mineral oil.

5. The government should introduce a legislation encouraging the use of cutting fluids based on vegetable oils which offers better cutting performance and at the same time free from environment disposed, and storage problems.

Moreover, the use of cutting fluids based on vegetable oils can bring forth considerable reduction in the quantities of petroleum products imported.

6. Although prices of mineral oil products are lower compared with the market prices of vegetable oil products, but biodegradability, safety and health of operators, availability, renewability, and numerous benefits have made them more suitable and economical to use. Furthermore, the recent economic reality in most countries due to high prices of petroleum products is also a motivating factor for the present work because petroleum BCFs are themselves limited resources.

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