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PERFORMANCE EVALUATION OF CUTTING FLUIDS MADE FROM BIO-DEGRADABLE VEGETABLE OILS IN MACHINING OF MILD STEEL

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ABSTRACT
Three vegetable oils, palm oil, shea butter, and groundnut oil, were investigated for use as lubricants in the orthogonal turning of mild steel. The cutting speed was varied while the depth of cut and feed was kept constant; the surface finish was determined using a roughness checker, and the interface temperature was measured using a k-type thermocouple. Tool life and coefficient of friction were determined. Results show improved tool life and good surface finish were obtained at low and medium cutting speeds. Findings show the satisfactory performance of groundnut oil with chip compression of 0.83 at the speed of 300 rpm and that of the shear butter with a maximum temperature of 62°C within the speed range. The cooling effect of the vegetable oils compared favourably with that of the standard soluble oil. The order of performance of the oils was palm oil, shear butter, and groundnut oil, which decreased in order, a performance attributed to their oiliness. The result of this work can be used to source new cutting fluids in cutting operations.
Keywords: *cutting fluid, vegetable oil, tool life, spindle speed, feed rate, chip compression, coefficient of friction*

INTRODUCTION

Machining is a widespread metal shaping process that achieves high precision with good tolerance and surface finish. It is versatile in producing complicated free-form shapes with many features over an extensive size range, which can be made cheaply, quickly, and simply by controlling the path of a standard cutting tool. Another reason for the success of metal machining is the idea of competition to increase productivity, hold market share, and find new markets. These have led to significant changes in machining practice. The changes include machine technology, manufacturing systems, and materials technology. Chip formation is a significant outcome of machining operations, and **c**utting parameters influence the morphology of the chip. The process of chip formation gives a continuous form through crack propagation. Thus, the type and shape of the chip depend directly on the physical and mechanical properties of the machined material. For continuous chip formation, for example, once the chip thickness is known, the stresses and temperature in the work and tool, which influence tool life and quality of machined surface, can be estimated (Childs *et al.*, 2000). Notably, cutting speed, depth of cut, and feed are major parameters influencing chip formation and, hence, the quality of the machined surface. An earlier researcher (Biermann *et al.*, 2024) observed that chip thickness is influenced by lubrication, and adding a lubricant causes the chip to become thinner and reduces the friction between the chip and tool. Investigations have shown that cutting speed and feed have some influence on the cutting force. High cutting speeds increase the chip removal rate while the cutting force is decreased. Also, heat is generated at the chip-tool interface, adversely affecting chip formation mode, cutting force, tool life, and machined surface quality.

Metalworking fluids (MWFs) are used to improve productivity and the quality of machined products through cooling, lubrication, extending tool life, reducing process variability, and preventing corrosion (Lawal *et al.*, 2012); hence, the necessity for continuous search for new and improved machining lubricants to reduce to a minimum the adverse effects encountered in machining. Water is an effective cooling agent that removes heat more rapidly than oil but is a very poor lubricant when used alone and causes rusting. Some essential additives are generally added to transform water into a suitable metalworking fluid (Peterson, 2007).

Due to their advantages, the consumption of MWFs is increasing in the machining industry. Despite their widespread use, they pose significant health and environmental hazards during use, such as skin cancer and soil degradation. Various alternatives such as synthetic, solid, and vegetable-based lubricants, dry cutting, and minimum quantity lubrication (MQL) are being explored as the demand for renewable and bio-degradable lubricants increases (Ponnekanti and Savita, 2012). Cutting speed, temperature variation, and tool life are part of the criteria for orthogonal turning operations and choosing suitable machining lubricant. Machining is an effective method for evaluating metal-forming lubricants because the cutting fluid alters the forces between tool and work, cutting temperature, shear angle, wear, tool life, chip form, and surface finish (Sristi and Zaman, 2024). The cutting fluid reaches the chip/tool interface by diffusing through the distorted structure of the metal and by capillary action. This study evaluates the performance of cutting fluids made from biodegradable vegetable oils in machining mild steel. Specifically, it comparatively assesses the lubricity effects of palm oil, shear butter, and groundnut oil on chip quality, surface finish, coefficient of friction, and tool life in the machining of mild steel. The result is part of sourcing new lubricants as alternative cutting fluids in machining.

Theoretical Background

The depth of cut t_1, existing before the formation of the chip, changes into the thickness t_2 after the chip has been generated. Hence, the chip thickness ratio or chip compression λ can be computed as

$$\lambda = t_2/t_1 \qquad (1)$$

Further analysis (Obi, 1997) will show that the coefficient of friction μ, occurring between chip and tool, is given by

$$\mu = \frac{\ln \lambda}{\pi/2 - \alpha} \qquad (2)$$

where

α = rake angle of the tool

To avoid failure by fatigue in a typical tool lifetime, tool material and geometry should be selected to maintain maximum tensile stress caused by the cutting forces, and the chosen cutting parameters, such as feeds and speeds, are within the limit of the temperature increases in the tool. Tool life prediction is important for tool management, and Taylor's tool life equation, though old, is still widely used for this work. An approximate equation due to Ojolo and Ogunkomaiya (2014), given in equation 3, is used to compute tool life.

$$T = L \times 60/Nf \qquad (3)$$

Where,

N (RPM) = cutting speed in Revolutions per minute

f = feed rate in Millimetre per revolution

L = Length of effective cut

T = Tool life in seconds

Chip-tool Interface Temperature

One of the goals of temperature measurement in machining is to quantitatively measure the heat energy distribution throughout the cutting region, which is difficult because of the high temperatures. Tool failure caused by fracture disrupts the machining process so suddenly that conditions are chosen to avoid this. The heat sources in machining include shear deformation and friction between the tool and workpiece and between the tool and chip.

However, measuring the average temperature at the chip/tool contact is sufficient. In this work, the average temperature was measured using a K-type thermocouple arrangement developed by Dhar and Islam (2005), as shown in Fig. 1. It was mounted on the tool-work interface junction, and the temperature was read off a calibrated digital multimeter.

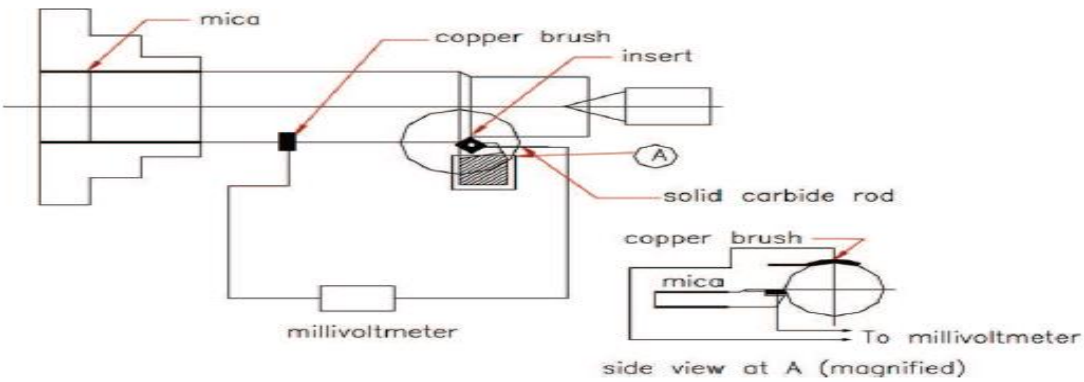


Fig.1: K-type thermocouple for temperature Measurement (Dhar and Islam, 2005)

It is also important to note that lubricants play a vital role in machining, such as the cooling effect to ameliorate high temperatures on the tool and workpiece, ensure the production of smooth surfaces of the work, reduce friction, and prolong tool life. A good lubricant would generate the best among these criteria. In this work, three local oils are applied separately to determine their order of acceptability as machining lubricants through their cooling effects, chip compression, coefficient of friction, and surface finish.

MATERIALS AND METHODS

The investigation used mild steel samples soaked in palm oil, shea butter, and groundnut oil, with soluble oil as a control. Obi *et al.* (1998) determined the trace elements of these oils, which are shown in Table 1.

Table 1: Trace Elements in the vegetable oil samples (Obi, 2000)

	Trace elements in samples (µg/g)		
Element	**Palm oil**	**Shea butter**	**Groundnut**
Al	31.000	44.010	19.350

Trace elements in samples (μg/g)			
Element	Palm oil	Shea butter	Groundnut
Ca	80.800	74.750	29.890
Ci	29.600	60.350	11.910
Cu	1.430	2.011	1.790
Mg	28.100	26.890	7.320
Mn	0.940	1.690	0,470
Na	29.600	72.760	17.450
V	0.065	0.0671	0.039

The cutting tool was of tungsten carbide with a 10° rake angle, 9° clearance angle, and 1.5mm nose radius with a 10mm tool overhang. A lathe machine of Model Metalx WARSZAWA, Serial No. TUE40-9800 was used. The soluble oil was applied directly to the tool-workpiece interface, while the vegetable-based oils were applied using a small plastic can. The mild steel rod, with a diameter of 75 mm and length of 120mm, purchased from scientific equipment dealers, was used for this work. Its chemical composition is given in Table 2.

Table 2: Elemental composition of low carbon steel (%) (Faci, 2017)

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al	Mg
0.215	3.350	1.316	0.102	<0.100	0.029	0.015	0.022	0.012	0.130	0.014

The rod was mounted on the lathe and machined at a constant feed rate and depth of cut of 0.8 mm/rev and 1.5 mm, respectively, at 100, 150, 200, 250, and 300 rev/min speeds, using soluble oil as a cutting fluid. Excessively high turning speeds were avoided because, at high speeds, there is less time for the heat generated to be conducted through the workpiece. Moreover, the lubricating performance of the oils can only best be evaluated at low speeds, which helps avoid the splashing of the oils during machining and maintains uniform film over the chip-tool interface (Obi, 1997). The temperature of the work-tool interface at each speed was measured, the chips collected and their thicknesses measured with a micrometer screw gauge, the chip compression and coefficient of friction were computed using equations 1 and 2, respectively (Obi, 1997), and the tool life with equation 3. The average of four chip thickness measurements was used to compute the chip compression in each case. The surface roughness of the machined surface after each operation was determined using a roughness checker *(Taylsurf subtronic)* with a sampling length of 1cm. The process was repeated for the vegetable-based oils; the results are recorded in Table 3. The mild steel used in this work was used by Faci (2017)

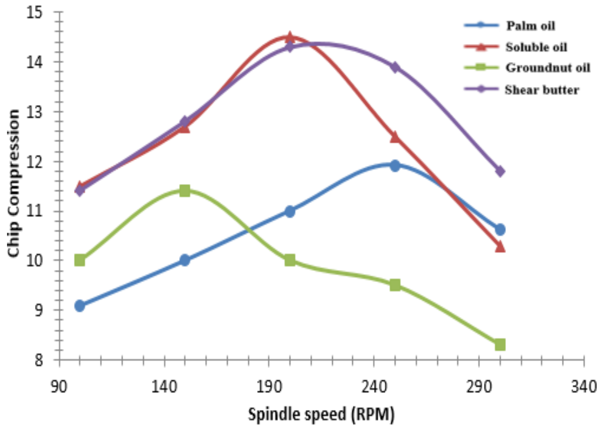
RESULTS AND DISCUSSION

Table 3 presents the results of chip thickness, temperature, surface roughness, chip compression, coefficient of friction, and tool life at varying spindle speeds.

Table 3: Measured chip thickness, temperature, and surface roughness and computed values of compression and coefficient of friction

Machining Lubricant	Spindle speed (RPM)	Thickness of chip (t)(mm)	Chip compression (λ)	Chip-tool temperature (°C)	Surface Roughness (μm)	Tool Life (min)	Coefficient of friction (μ)
Palm oil	100	0.42	9.09	58.3	2.00	57.7	0.32
	150	0.40	10.00	65.0	1.40	56.37	0.29
	200	0.38	11.00	63.9	1.20	41.38	0.28
	250	0.38	11.92	69.3	1.25	32.04	0.27
	300	0.40	10.62	73.9	1.20	12.65	0.25
Soluble oil	100	0.45	11.50	57.0	2.20	0.33	0.33
	150	0.44	12.70	61.0	1.75	0.30	0.30
	200	0.42	14.50	65.0	1.40	0.28	0.30
	250	0.40	12.50	70.0	1.40	0.27	0.28
	300	0.42	10.30	75.0	1.25	0.26	0.27

Machining Lubricant	Spindle speed (RPM)	Thickness of chip (t)(mm)	Chip compression (λ)	Chip-tool temperature (ºC)	Surface Roughness (μm)	Tool Life (min)	Coefficient of friction (μ)
Groundnut oil	100	0.38	10.0	61.0	2.40	0.34	0.34
	150	0.37	11.4	64.0	2.20	0.32	0.32
	200	0.45	10.0	67.5	1.75	0.30	0.30
	250	0.46	9.50	70.0	1.40	0.28	0.28
	300	0.43	8.30	72.0	1.20	0.27	0.26
Shea Butter	100	0.32	11.4	53.0	1.40	105.83	0.35
	150	0.35	12.8	55.1	1.20	93.57	0.35
	200	0.34	14.3	62.0	1.20	82.36	0.32
	250	0.35	13.9	60.0	1.00	76.37	0.30
	300	0.37	11.8	58.0	0.60	68.38	0.28



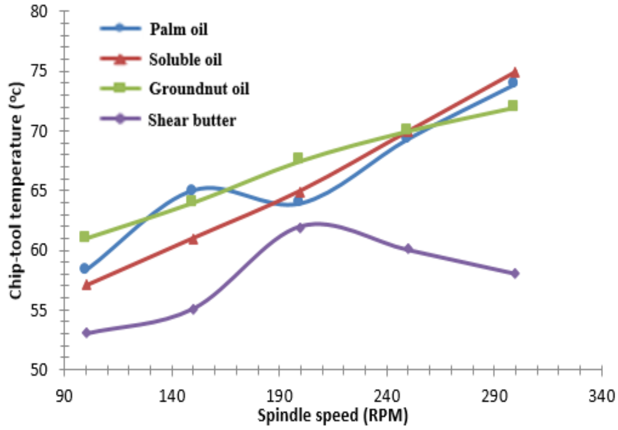


Figure 2: Variation of chip compression with speed. **Figure 3: Variation of chip tool interface temperature with the speed**

Fig. 2 shows the variation of chip compression with speed. The profile shows a slight rise in chip compression with speed, followed by a general drop as the speed increases. The changing values of the cutting angle, formation of built-up-edge, and variation of coefficient of friction cause the variation in chip compression. Obi (2000) has shown that with an increase in cutting speed, chip compression is first reduced to a minimum and then increased to reach a maximum, after which it drops again and varies slightly at high speeds. Another investigation (Obi, 1997) has shown that the reduction of chip compression with speed indicates a reduction of cutting force, power consumed, and reduction of temperature, which depends on the cutting fluid used. Groundnut oil performs better than the rest of the cutting fluids with chip compression of 0.83 at 300 rpm. Fig. 3 shows that the chip-tool interface temperature increases with the speed of machining. Previous authors have shown that the temperature generated was due to the primary shear of the workpiece, average temperature rise due to the rake face of the tool, and heat due to friction between the tool and the workpiece and between the chip and the tool and that this heat increases with cutting speed. At low cutting speeds, the principal factor affecting chip-tool interface temperature is the deformation at the shear zone, while at high cutting speeds, the tool-chip friction. Theoretical analysis of the plane strain deformation of metal showed that energy deformation when converted to heat, increases the temperature. The rise in temperature is due to the heat generated at the primary shear plane and friction between chip and tool and between tool and workpiece, which increases with speed. Obi (2000) has shown that cutting forces decrease with speed, and since heat is the product of force and velocity, more heat is generated with increasing speed. Among the oils investigated, shear butter performed better than the rest, with a maximum temperature of 62ºC within the speed range tested. It was followed respectively by groundnut oil (70ºC), palm oil (70.9ºC), and soluble oil (75ºC).

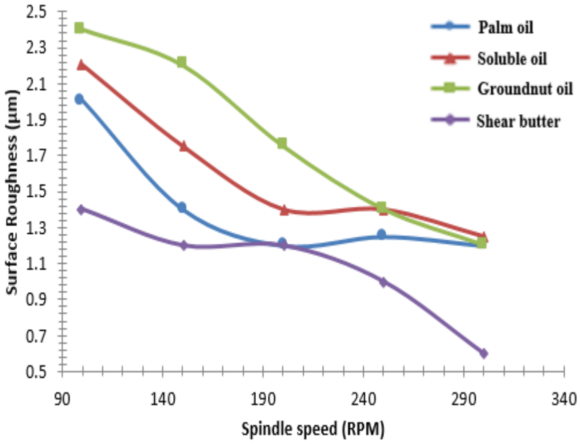


Figure 4: Speed-Temperature Characteristics of the oils

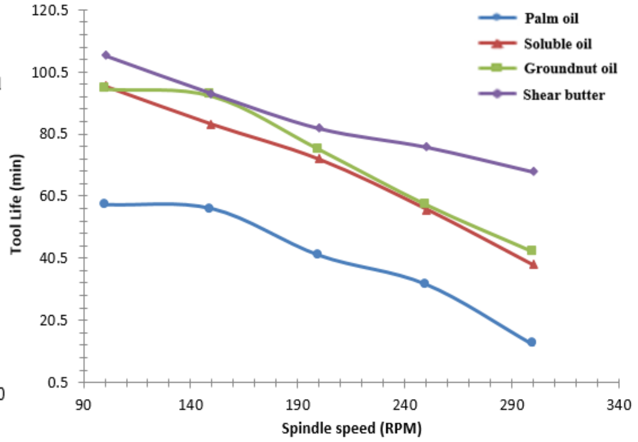


Figure 5: Effect of cutting speeds on Tool Life using the oils

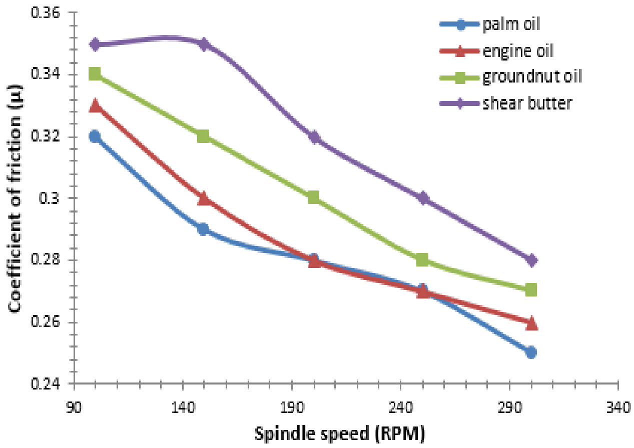


Fig 6: Effect of cutting speeds on the coefficient of friction.

The improvement of surface roughness with speed is shown in Fig 4. Built-up-edge (BUE) formation occurs at low speeds and offers a way of relieving some strains that occur at low speeds but at the expense of worsening the cut surface finish. The BUE reduces and disappears at higher speeds, improving the surface finish. Cutting fluid reduces the BUE to a size commensurate with the feed, reduces the contact area between tool and workpiece, and reduces the tool forces so that power consumption is reduced and temperatures lowered, resulting in improved tool life. As the cutting speed increases, a limit is reached above which the BUE is not formed. The shape of the tool changes, and the surface finish improves as the BUE disappears. There was a slight surface quality deterioration with palm oil at high cutting speeds. Previous authors summarized the reason for the lowered effectiveness of cutting fluids at high cutting speeds: the cutting fluids fly off the chip at high cutting speeds, the reaction time for the formation of a chemical compound is too short, and the time for convection of heat developed at high cutting speeds is too short. Fig. 5 is the variation of cutting speed with tool life. It is observed that tool life improves with speed. Thermal damage to tools occurs because of temperature increases. As tool damage, by wear or fracture, increases the surface roughness and the accuracy of the machined surface deteriorates, it is necessary to adopt an inflexible criterion to evaluate tool material machining capabilities, such as temperature variation with speed. Fig. 6 is the variation of speed with a coefficient of friction. The adiabatic shear band is generated during machining due to the workpiece's viscoelastic behavior, leading to the workpiece's deformation. Subsequently, chips are formed by cracking and plasticization following high-pressure stresses. With increasing cutting speed, the shearing bands become more intense, reducing the width between the segments and fragments due to localized deformation in the primary shear zone and increased temperature. Mechanical properties decrease in the cutting zone by reducing resistance to plastic deformation, which causes chip shearing. Forces decrease with increased cutting speed due to reduced friction between chip and tool, hence the shape of Fig. 6.

Physiochemical characteristics of oil that enhance their performance

The properties of vegetable oils that enhance their performance in machining operations include the presence of fatty acids (Ajala, 1982), which are effective as boundary lubricants due to a chemical reaction between the polar head of the acid molecule and the surface they react with, to produce the adsorbed layer which is sufficiently thick to separate the surfaces thereby reducing friction. The presence of surface-active agents such as *stearic* acid and halogens like chlorine help to reduce the surface energy and increase its wetting power or oiliness. Ajala (1982) has shown that *shea butter* contains 35% by weight of *stearic* acid compared to groundnut and palm oil, with percentage stearic contents of 4.5% and 4%, respectively. Also, Obi (2000) has shown that *shea butter* contains 60.35 μg/g of *chlorine*, *groundnut oil* 11.91μg/g, and *palm oil* 29.60μg/g. These properties have contributed to the satisfactory performance of these vegetable oils in machining.

Conclusion

This study evaluates the performance of cutting fluids made from biodegradable vegetable oils in machining mild steel. It comparatively assesses the lubricity effects of palm oil, shear butter, and groundnut oil on chip quality, surface finish, coefficient of friction, and tool life in the machining of mild steel. The findings show that the cutting speed significantly affects the quality of turning of mild steel. Also, the lubricants improve the cutting tool's life, with a better surface finish for machining at low and medium cutting speeds. This implies ecology-friendly vegetable-based oils could successfully replace soluble oils as cutting fluids.

It is therefore recommended that the adoption of shea butter and groundnut oil as a metalworking fluid in metal cutting operations such as turning and other machining operations because of their high thermal conductivity and oxidative stability be encouraged; also, the oxidative stability of the vegetable oil-based cutting fluid could be improved using nature-friendly, uncomplicated and less-mineralized solution antioxidant to cater for the problem of the chlorinated, sulphured and phosphorus-based types used which are known to cause health issues to operator typical to mineral based oils.

REFERENCES

Ajala, A. O. (1982). Investigation of the major characteristics of some vegetable oil used in Nigeria. An Unpublished M.Sc. Thesis, Ahmadu Bello University, Zaria, Nigeria.

Biermann, D., Saelzer, J., Bergmann, B., Schenzel, J., Menze, C. J., Gerken, J. F., Wolf, T., Denkena, B., Möhring, H-C., and Zabel, A. (2024). Fundamental characterization of lubrication effects through various cooling lubricants in the chip formation zone. *Production Engineering*, 1-13.

Childs T., Maekawa K., Obikawa T., and Yamane Y., (2000). Metal Machining: Theory and Applications. First Edition. John Wiley and sons inc., New York, USA.

Dhar, N. R., S. Islam, M. Kamruzzaman, and T. Ahmed. The Calibration of Tool-Work Thermocouple in Turning Steels. National Conference on Industrial Problems on machines and mechanisms, 24th -25th February 2005.

Faci, N.D. (2017). Mechanical and Corrosion behaviour of low carbon steel in crude oil inhibited by some extracts of *Acacia nilotica (*Gum Arabic tree) plant. An unpublished M. Sc. Thesis, Ahmadu Bello University, Zaria.

Lawal, S.A., Choudhury, I. A. and Nukman, Y. (2012), Application of vegetable oil-based metalworking fluids in machining ferrous metals—A review. International Journal of Machine Tools and Manufacture, 52: 1- 12.

Mallock, A. (1881-82). The action of cutting tools. Proc. Roy. Soc. London, 33, pp. 127-139

Obi, A. I. (1997). Use of local oil as cutting fluids for aluminum and brass. Nigerian Journal 0f Technical Education, 14(2), pp. 98-111.

Obi, A. I., A.K. Oyinlola and Aku S.Y. (1998). The effect of locally produced vegetable-based oils on tool wear and thickness of chips in the drilling of mild steel. Nigeria Journal of Physics, 9, pp. 30-37

Obi, A. I. (2000). Lubricity Assessments of Vegetable-Based oils in some metal forming processes. An Unpublished Ph.D. Thesis, Ahmadu Bello University, Zaria, Nigeria.

Ojolo, S. J and Ogunkomaiya, O. (2014). A Study of Effects of Machining Parameters on Tool Life. *International Journal of Materials Science and Applications.* Vol. 3, No. 5, pp. 183-199. doi: 10.11648/j.ijmsa.20140305.19

Petterson, A. (2007), “High-Performance Base Fluids for Environmentally Adapted Lubricants”. Journals of Tribology International 40: 638-645.

Ponnekanti N., and P. Savita (2012). Development of eco-friendly/biodegradable lubricants: An overview. Renewable and Sustainable Energy Reviews, 16, pp. 764-774

Sristi, N. A., and Zaman, P. B. (2024). A review of textured cutting tools’ impact on machining performance from a tribological perspective. *The International Journal of Advanced Manufacturing Technology*, 1-35.