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Comparison of the Effects of Vegetable Oils such as Castor and Canola Oil and Polyol Esters on the Metalworking Performance of AL 6061 and Al 7075 Metal Alloys by Tapping Torque Method

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Abstract: Machinability of aluminum alloys still represents a challenge due to its tendency to staining and there is a great need for the development of sustainable solutions for lubrication and cooling. Therefore, researchers are performing intensively to obtain an effective way of machining such alloys. Growth of aerospace and automotive industries have increased utilization of these alloys day by day. Working for the development of more economical and environmentally friendly production technologies has gained increased interest to reduce the environmental and health risks and cost factor caused by the widely used flood lubrication. Vegetable oil and polyol esters are biodegradable synthetic base fluids that can be used as a sustainable alternative to petroleum-derived oils in many lubricant applications. In this study, the effects of castor and canola oils and trimethylolpropane trioleate (TMPTO) and trimethylolpropane trioleate complex (TMPCX), neopentyl glycol (NPG) and pentaerythritol tetra-oleate (PE-TO) type polyol esters on the machining performance of Al 6061 and Al 7075 alloys were investigated using the Tapping Torque test method. As a result, in the studies performed with neat fluids, it was determined that PE-TO showed the best performance in Al 6061, while TMP-TO showed the best performance in Al 7075. In addition, it was found that both vegetable oil types showed lower metal working performance than polyol esters in both alloys. Since similar results were obtained in the machining of both alloys, 68% emulsions were formulated with these vegetable oils and polyol esters to compare the machining performance. In contrast to neat machining, On Al 6061, PE-TO showed the most dramatic performance, while canola oil showed the highest performance. Since Al 7075 has harder machining conditions than Al 6061, the emulsion machining performance of Al 7075 alloy improved with the cooling effect of water and gave better results than neat machining.

Keywords: Sustainability, Metalworking fluids, Tapping torque, Vegetable oils, Polyol ester

Introduction

Aluminum alloys are of special interest due to their low density and special mechanical properties in engineering applications in a wide variety of industries such as aerospace, automotive and medicine. Thanks to these properties they also contribute to the reduction of harmful gas emissions into the atmosphere by reducing the weight of the vehicles, thus enabling lower fuel consumption (Carou & Davim, 2021). Aluminum is the most machinable metal on the market since its material properties make it easy to mill, drill, cut and punch. In addition, aluminum machined parts can be strong and durable (Soren et al., 2019). Along with the advantages of aluminum alloys, they also have a major disadvantage, such as a tendency to staining. The tendency of aluminum for easily stain limits the use of conventional metalworking fluids in the processing of these alloys,

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and therefore special metalworking fluids are developed for the processing of these alloys (Canter, 2020). Another disadvantage of aluminum is that it is a ductile material. This feature of aluminum materials results in a large chip-tool contact area during machining, resulting in chips with a high thickness ratio. The formation of the chip-tool contact area and the increase in the chip thickness ratio cause an increase in cutting forces, machining power and heat generation (Ononiwu et al., 2021). In this regard, utilization of metal working fluids is crucial for effective machining of them. Heat generated can be reduced in the cutting zone and excessive friction can be prevented by helping of metal working fluids. As a result, life of mechanical systems can be extended (Çakır et al., 2015). The most common operation using metalworking fluids for machining light alloys is flood lubrication. However, conventional metalworking fluid formulations used in flood lubrication consist of toxic, non-biodegradable, unsustainable and environmentally harmful petroleum-derived products based on mineral oil as base oil (Santhosh et al., 2021). In line with the increasing demand for the use of light alloys in the aerospace, automotive and medical sectors, the environmental and health risks caused by flood lubrication, which is widely used in the processing of these alloys, and the demand for reducing the cost factor have increased the interest in research on the development of more economical and environmentally friendly production technologies. Another reason for the need to develop new products and technologies in the machining of light alloys is the need to produce alternative lubricants that can ensure sustainability due to the depletion of petroleum reserves (Panchal et al., 2021). There are various sustainable feedstocks to produce bio-lubricants. Highly unsaturated or high oleic vegetable oils (HOVOs), low viscosity polyalphaolefins (PAOs), polyalkylene glycols (PAGs), dibasic acid esters (DEs) and polyol esters (PEs) are categories of biodegradable base oils (Nagendramma & Kaul, 2012).

Vegetable oils which have large market share for biolubricants, are abundant and non-toxic feedstocks. They exhibit higher lubricity, higher flash point, lower volatility, and higher viscosity index than mineral oils. Presence of long chain fatty acid and polar groups in the structure of vegetable oil make them suitable for both boundary and hydrodynamic lubrications. Besides their advantages, they have low oxidation stability and their low temperature properties are poor. Thus, they can easily polymerize in the harsh working condition. This situation limits their industrial application (Wickramasinghe et al., 2021). Low viscosity biodegradable polyalphaolefins (PAOs) are another alternative for environmentally friendly lubricants and can be defined as low molecular dimers to tetramers. While low molecular weight causes undesirable high volatility for these fluids, it becomes an advantage at low temperatures where PAOs perform excellently. The absence of polarity of PAOs cause to problems of additive acceptability, but this result in excellent hydrolytic stability. Since PAOs have no double bonds or other reactive functional groups in their structure, oxidative stability of PAO with antioxidant additive is competitive to petroleum-based products.

PAOs are finding increasing use as hydraulic and engine oils, especially in cold climate applications and where hydraulic pressures increase, as they are an attractive option for converting biodegradable lubricants to water in low temperature applications. PAOs are also used as gear lubricants because of their ability to provide lower operating temperatures and lower coefficients of friction, which helps reduce wear. On the contrary of PAOs, polyalkylene glycols (PAGs) have high polarity as they have alternating ether linkages rather than essentially having a hydrocarbon backbone. However, they can be easily contaminated with moisture, resulting in increased solubility in water, which is detrimental for many lubricant applications. The solubility problem of organic additives in PAGs and the incompatibility of PAGs with conventional petroleum-based lubricants are often problematic for this species. For biodegradable PAGs usage, fire resistant fluids are often the best option. The high molecular weight of diesters makes volatility problems negligible and ester bonds provide high solubility power. Branching in alcohol fragments results in very good low temperature performance, but diesters score poorly in final biodegradability tests. For this species, ester linkages are not sterically hindered to restrict hydrolytic decomposition.

Diesters find use in biodegradable hydraulic fluids with long drain intervals, compressor oils turbine oils, and are mixed with PAOs in some synthetic lubricants. Diester fluids have outstanding solubility and cleaning ability. Because of these properties, it can have a negative effect on certain varnish or paint surfaces. This limits the use of dibasic acid esters. The most main area where dibasic acid esters find use is paint and coating applications. At last, but not least, PEs are effective feedstocks. They consist of fatty acids attached to an alcohol and hydrogen atom on the β-carbon atom does not exist in their backbone. PEs are used as environmentally acceptable base fluids in high performance lubricants. PEs have found application in many lubricants due to its very good low temperature behavior, high thermo-oxidative stability of some types, very high viscosity index, good anti-wear and low evaporation properties. The physico-chemical characteristics of PEs indicate that the properties are matching with the conventional base stocks. The development of new synthetic-based base fluids to meet the needs of high-performance lubricants is increasing day by day. As a result, the use of synthetic esters as base fluids has gained great importance in various industrial and military applications. Examples of lubricant types using PEs are engine oils, gear oils, hydraulic oils, compressor oils, pump and turbine oils. Also, PEs are being evaluated for lubricity performance with a view for their application as metal working fluids (Nagendramma & Kaul, 2012). In the literature, these biodegradable base stocks are studied with many parameters as metal working fluids but there is limited study about their comparison of metal working behavior. When abundancy of vegetable oils and advantages of PEs are considered, comparison these two fluids can provide a valuable insight to the literature.

An important parameter in the processing of aluminum is the removal of heat from the friction between the tool and the material. Cooling performance is as important as the lubrication effect, and the cooling/lubrication balance must be maintained when machining these alloys. Heat can be removed by balancing cooling and lubricity. Water can be a good cooling agent due to its high specific heat capacity. However, achievement of homogenized solution is a challenging process due to the dispersion resistance of the oil droplets in the water. In order to formulate the base oil with water in a stable solution, surfactants are used. Surfactants consists of an amphi-hydrophilic group at the water-loving head and an oil-loving lipophilic chain at the hydrophobic tail. The hydrophilic group and the lipophilic chain have a strong attraction to the water and oil, respectively (Wickramasinghe et al., 2020).

There are various performance tests for metal working fluids. Lubricity behavior of metal working fluids can be investigated with Tapping Torque test method. It is a favorable method as bench scale test and combines qualitative and quantitative techniques. Tapping is a metal machining process to cut or form threads in a pre-drilled hole in a metal specimen which can be made of various metals while lubricating the contact zone between tap and hole wall by a metalworking fluid. Finally, a torque value to cut or form a thread is obtained. Smaller torque values indicate better metal working performance (Demmerling, & Söffker, 2020). In this study, metal working performance of vegetable oils and PEs were evaluated with Tapping Torque test method. Al 6061 and Al 7075 series were selected as the metal sample to be machined.

In this study, machining performance of the castor and canola oils and trimethylolpropane trioleate (TMPTO) and trimethylolpropane trioleate complex (TMPCX), neopentyl glycol (NPG) and pentaerythritol tetra-oleate (PE-TO) type PEs on the Al 6061 and Al 7075 alloys were investigated using the Tapping Torque test method. In addition, to investigate the effects of water input on cooling performance in these fluids, emulsions with 30% water content were formulated with these vegetable oils and PEs using alkyl polyglycol ether (C16:18 ethoxylated/propoxylated fatty alcohols) emulsifier.

Method

Materials

In the present study castor and canola oils and trimethylolpropane trioleate (TMPTO) and trimethylolpropane trioleate complex (TMPCX), neopentyl glycol (NPG) and pentaerythritol tetra-oleate (PE-TO) type polyol esters were used and their physicochemical properties were given in Table 1. Also, alkyl polyglycol ether (C16:18 ethoxylated/propoxylated fatty alcohols) emulsifier was used in the emulsions formulated with these vegetable oils and polyol esters. Castor oil and canola oil were supplied from Kim-paş A.Ş and Oleo Kimya, respectively. Trimethylolpropane trioleate (TMPTO) supplied by Oleon. TMP Complex ester (TMPCX) was supplied from Temix Oleo. Neopentyl glycol dioleate (NPGDO) was supplied from Oleon. Neopentyl glycol dioleate (NPGDO) was supplied from Oleon. Pentaerythritol tetra-oleate (PE-TO) was supplied from Oleon. Alkyl polyglycol ether (C16:18 ethoxylated/propoxylated fatty alcohols) emulsifier was supplied from Solvay.

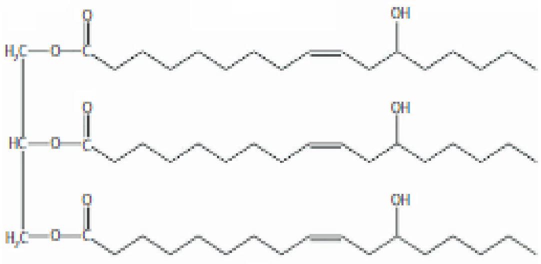
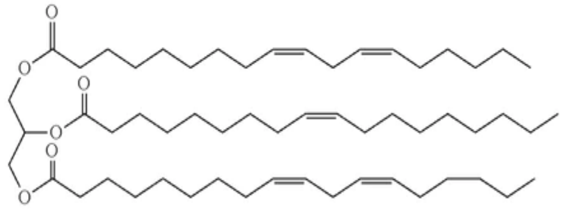
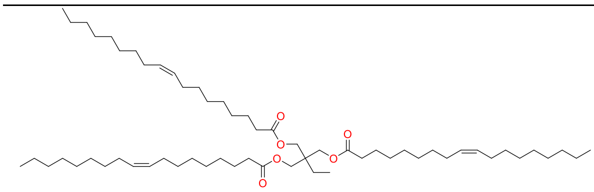
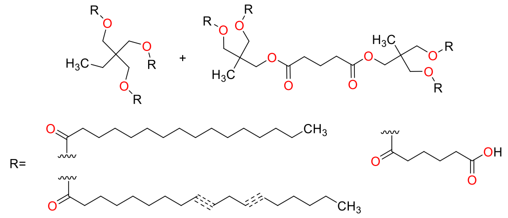
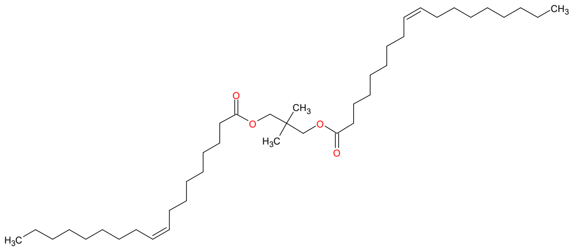
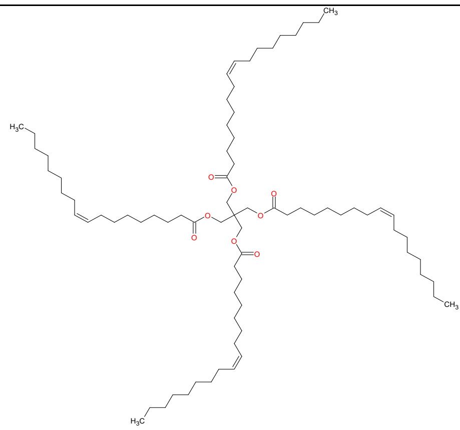
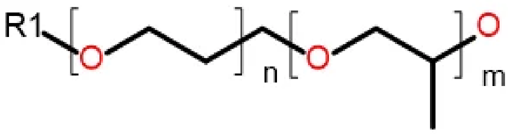
Table 1. Physicochemical properties of used compounds in the study.

Test Parameter	Test Method	Castor Oil	Canola Oil	TMPTO	TMPCX	NPGDO	PE-TO
Kinematic Viscosity (40℃, cSt)	ASTM D 445	160	46	46	70	23	65
Kinematic Viscosity (100℃, cSt)	ASTM D 445	15	10	9,2	12.5	6	14
Viscosity Index	ASTM D 2270	93	212	187	180	228	225
Flash Point (℃)	ASTM D 92	172	≥ 190	≥ 270	300	≥ 250	≥ 280
Pour Point (℃)	ASTM D 97	≤-21	≤-18	≤-42	-33	≤-18	≤-25

Molecular structure of compounds

Molecular structure of used compounds in the study was shown in Table 2.

Table 2. Molecular structure of used compounds in the study.

 CASTOR OIL	 CANOLA OIL
 TMPTO	 TMPCX
 NPG- DO	 PE-TO
 Alcohols, C16-18, ethoxylated propoxylated	

Machining performance of castor and canola oils and trimethylolpropane trioleate (TMPTO) and trimethylolpropane trioleate complex (TMPCX), neopentyl glycol (NPG) and pentaerythritol tetra-oleate (PE-TO) type polyol esters and their emulsion forms were investigated by Tapping Torque Test. Composition of samples was given in Table 3. In Tapping Torque Test, Al 6061 and Al 7075 series were used and test was carried out with 14.4 nm depth and 800 rpm.

To understand of the machining performance of the neat fluids and their emulsion forms, a tapping torque test was conducted in Labtap G8 (Microtap, Munich, Germany). The material used for the machining was a Al 6061 and Al 7075 with pre-drilled holes as shown in Figure 1. A TTT-Al 6061-M6F and TTT-Al 7075-M6F tools, size M6 with 69 helical channels per test plate was used for each fluid. The cutting fluid was poured in the holes to lubricate them during the tapping process at 800 rpm, with a 14.4 mm length of thread and each tapping process was repeated 3 times.

Table 3. Composition of samples by mass percentage, numbers in parentheses represent mass percent

Sample No	Sample Composition	Sample No	Sample Composition
1	Castor Oil (100:0)	7	Castor Oil+Water+Em (68:30:2)
2	Canola Oil (100:0)	8	Canola Oil+Water+Em (68:30:2)
3	TMPTO (100:0)	9	TMPTO+Water+Em (68:30:2)
4	TMPCX (100:0)	10	TMPCX+Water+Em (68:30:2)
5	NPG (100:0)	11	NPG+Water+Em (68:30:2)
6	PE-TO (100:0)	12	PE-TO +Water+Em (68:30:2)

Tapping Torque Test

Figure 1. Tapping torque test system

Figure 2 shows the tapping process graphically where: (a) shows the beginning of the forming; (b) indicates the torque increasing and the tool penetrating the workpiece as a result of increasing contact surface between the workpiece and the tool; (c) implies the tool forming with all its chamber teeth until the length's thread is achieved and (d) indicates the beginning of the reversal of the forming tap to bring the tool to the initial position. Consequently, the forming performance results of the fluids were determined averaging the tapping torque values (N·cm) in the 0 to 14,4 mm range of form.

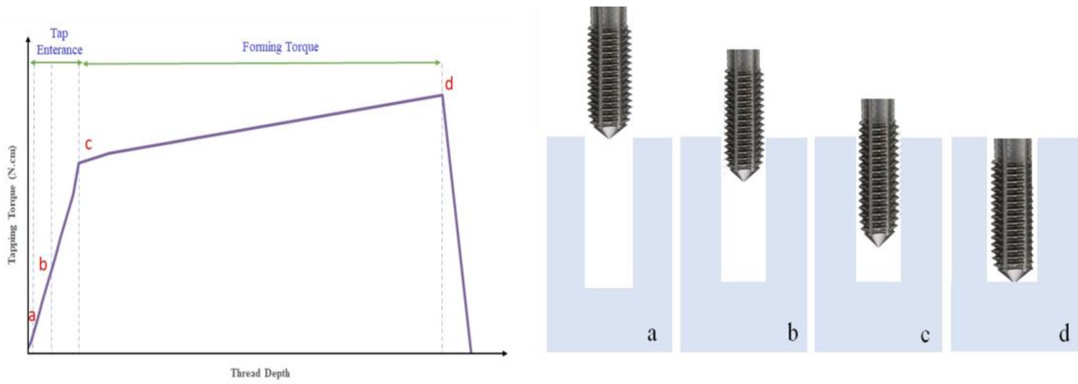


Figure 2. Graphical illustration of the tapping process and different positions of the tap during working. (a) beginning of the forming, (b) tool penetrating on workpiece, (c) teeth entering the chamber completely and (d) beginning of the reversal of the forming tap.

Results and Discussion

Tapping torque test results of samples on Al 6061 series were shown in Table 4. In addition, as shown in Figure 3 torque applied versus depth of cut graphs of each sample were obtained. It was determined that Pentaerytritol Tetraoleate (PE-TO) exhibited the best processing performance on the Al 6061 alloy, the processing performances of other polyol esters (NPG-DO, TMP-TO, TMP-CX) and canola oil were close to each other and they performed better than castor oil.

Table 4. Tapping torque test results of neat fluids for Al 6061 series.

Test plate	Test method	1	2	3	4	5	6
Al 6061 (800 rpm, d 14,4mm) (Nm)	BLN 105	161.1	142.5	140.2	141.2	144.3	136.1

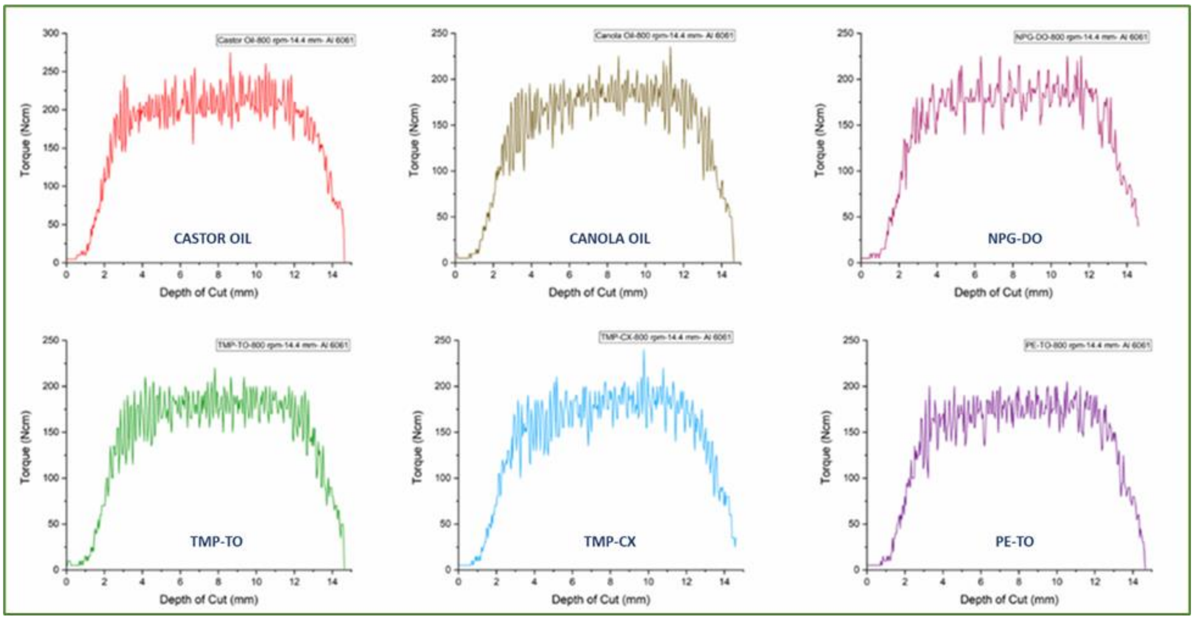


Figure 3. Tapping performance graphs of vegetable oils and esters on Al 6061.

Tapping torque test results of samples on Al 7075 series were shown in Table 5. In addition, as shown in Figure 4 torque applied versus depth of cut graphs of each sample were obtained. In the tests performed on Al 7075, it was determined that all fluids showed the same processing performance results as the tests on Al 6061, that is, PE-TO showed the best processing performance, the processing performances of other polyol esters (NPG-DO, TMP-TO, TMP-CX) and canola oil were close to each other and all these fluids performed better than castor oil.

Table 5. Tapping torque test results of neat fluids for Al 7075 series.

Test plate	Test method	1	2	3	4	5	6
Al 7075 (800 rpm, d 14,4mm) (Nm)	BLN 105	252.4	232.2	226.8	231.3	239.4	225.9

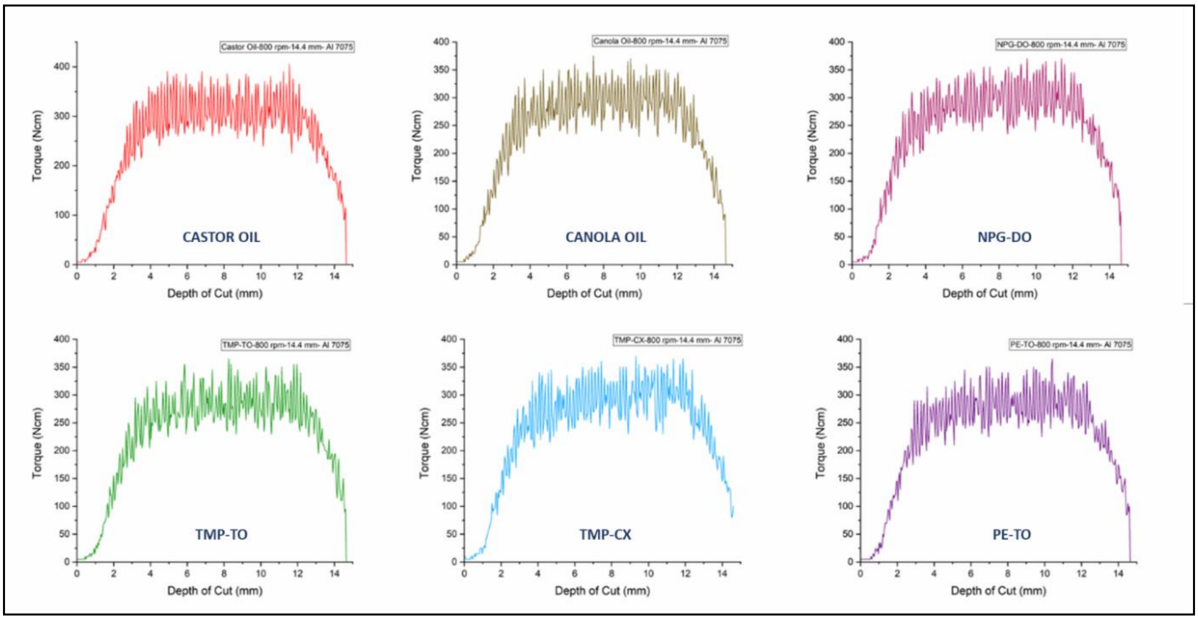


Figure 4. Tapping performance graphs of vegetable oils and esters on Al 7075.

Table 6. Tapping torque test results of emulsions for Al 6061 series

Test plate/Test condition	Test method	7	8	9	10	11	12
Al 6061 (800 rpm, d 14,4mm) (Nm)	BLN 105	143.7	115.3	144.6	153.5	165.3	182.2

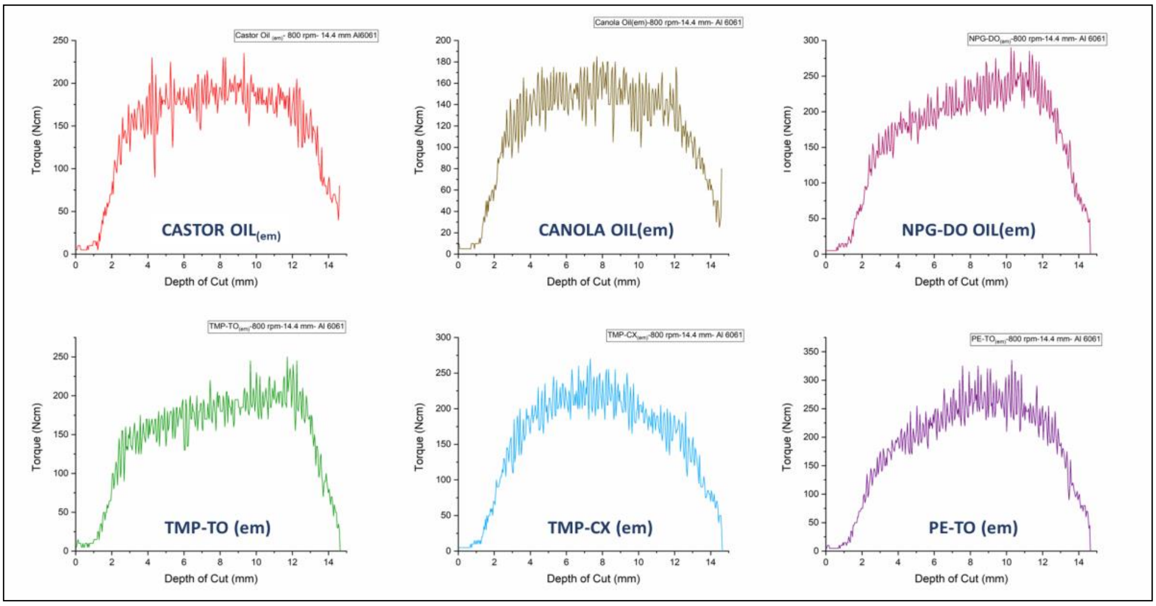


Figure 5. Tapping performance graphs of emulsion forms of vegetable oils and esters on Al 6061.

Table 7. Tapping torque test results of emulsions for Al 7075 series

Test plate/Test condition	Test Method	7	8	9	10	11	12
Al 7075 (800 rpm, d 14,4mm) (Nm)	BLN 105	225.3	207.4	218.3	221.6	215.8	209.9

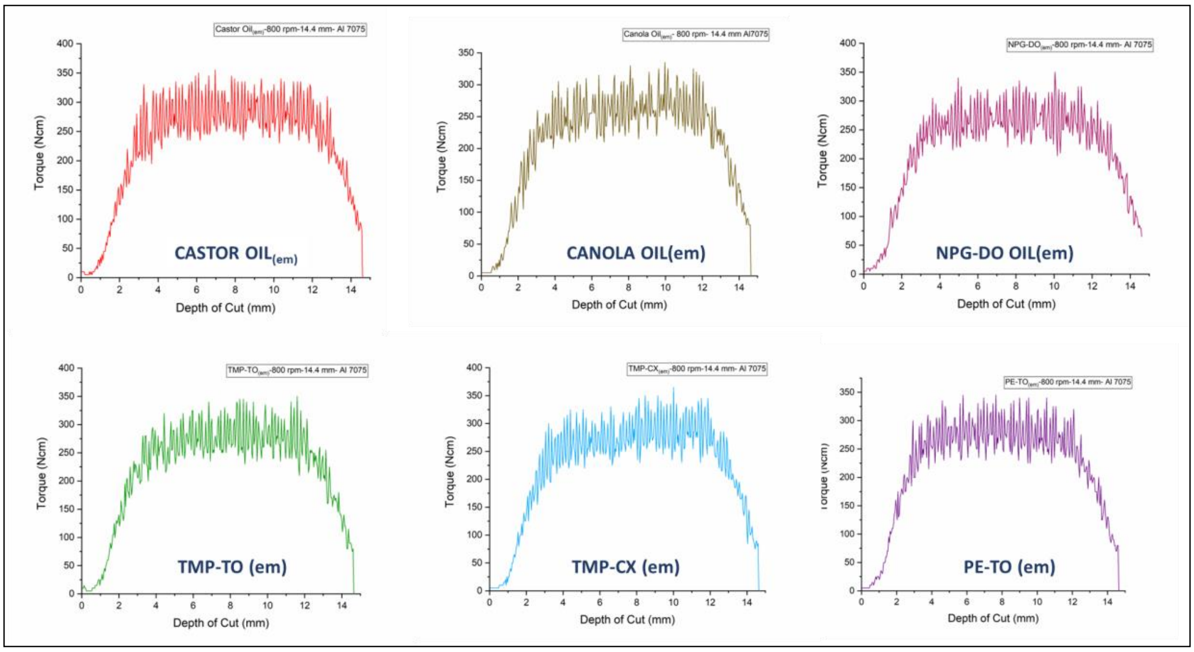


Figure 6. Tapping performance graphs of emulsion forms of vegetable oils and esters on Al 7075.

As a consequence of similar results in aluminum processing performances, 68% emulsions of vegetable oils and esters with water with a constant emulsifier ratio were prepared and tested on aluminum alloys to determine the difference in processing performances and to measure the effect of water input on cooling performance. In the emulsion tapping tests performed on Al 6061, PE-TO emulsion exhibited the worst and very low performance, contrary to the test result applied to the pure liquid. Similarly, Neopentyl glycol emulsion also showed low tapping performance. The tapping performance of TMP-TO, on the other hand, remained unchanged and stable. Canola oil showed the highest performance. Tapping torque test results of emulsions on Al 6061 series were shown in Table 6. Also torque applied versus depth of cut graphs of each sample were shown in Figure 5.

Since Al 7075 has harder machining conditions than Al 6061, the emulsion machining performance of Al 7075 alloy improved with the cooling effect of water and gave better results than neat machining. Furthermore, torque applied versus depth of cut graphs of each sample were obtained. Test results of 68% emulsions of vegetable oils and esters were given for 7075 series in Table 7 and performance graphs were shown in Figure 6.

Conclusion

Machining performance of castor and canola oils and trimethylolpropane trioleate (TMPTO) and trimethylolpropane trioleate complex (TMPCX), neopentyl glycol (NPG) and pentaerythritol tetra-oleate (PE-TO) type polyol esters and their emulsion forms were investigated by Tapping Torque Test. It was determined that Pentaerytritol Tetraoleate (PE-TO) exhibited the best processing performance on the Al 6061 alloy and machining performance of samples was found as follows from best to worst: PE-TO > TMP-TO > TMP-CX > NPG-DO > Canola oil > Castor oil. Tapping torque test result graphs for neat liquids performed on the Al 6061 series are shown in Figure 7.

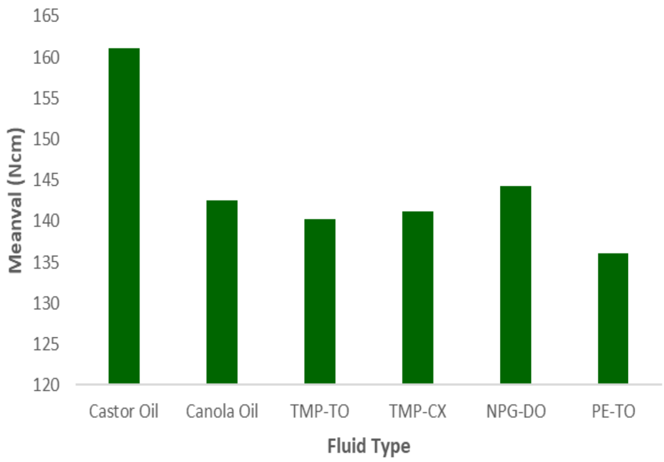


Figure 7. Tapping performance graphs of vegetable oils and esters on Al 6061.

In tests performed on Al 7075, similar machining performance results were obtained with Al 6061. Tapping torque test result graphs for neat liquids performed on the Al 7075 series are shown in Figure 8.

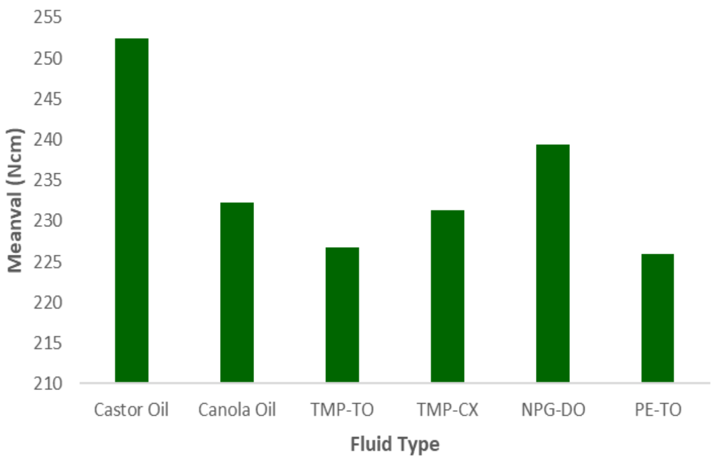


Figure 8. Tapping performance graphs of vegetable oils and esters on Al 7075.

In the tapping tests of emulsions performed on Al 6061, the PE-TO emulsion showed the worst and very poor performance, contrary to the result of the test for pure liquid. Machining performance of samples was found as follows Canola oil > Castor oil > TMP-TO > TMP-CX > NPG-DO > PE-TO. Comparison graphs of tapping performance of neat and emulsion forms of vegetable oils and esters on Al 6061 are shown in Figure 9.

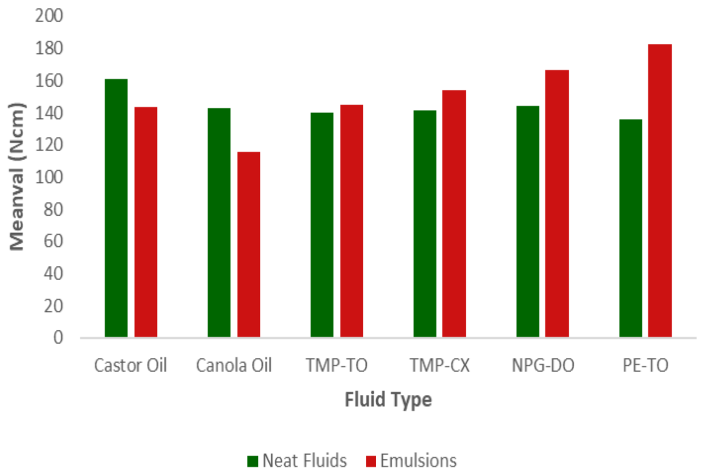


Figure 9. Tapping performance of emulsion forms of vegetable oils and esters on Al 6061.

Since Al 7075 has harder machining conditions than Al 6061, the emulsion machining performance of Al 7075 alloy improved with the cooling effect of water and gave better results than neat machining. Comparison graphs of tapping performance of neat and emulsion forms of vegetable oils and esters on Al 7075 are shown in Figure 10.

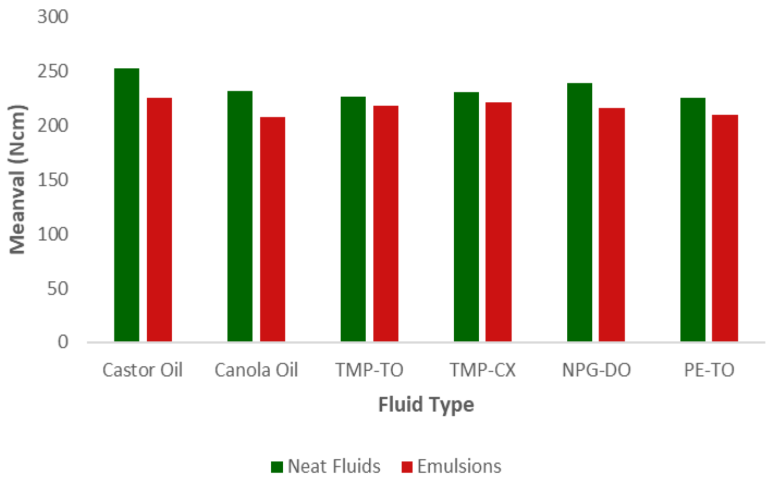


Figure 10. Tapping performance of emulsion forms of vegetable oils and esters on Al 7075.

The present study was carried out to investigate the effects of vegetable oils such as canola and castor oil and polyol esters on the machining performance of Al 6061 and Al 7075 type aluminum alloys, and based on the above results, the following inferences can be made:

1. In the tests carried out using vegetable oils on Al 6061, it was observed that the test results of emulsions with water input were better, on the contrary, using polyol esters on Al 6061, the test results of emulsions with water input were worst. The reason for this is that the heat generated at the tool-workpiece interface during neat machining with vegetable oils is quite high compared to polyol esters and the cooling effect is provided by the water input. The reason for the negative effect of water input on metalworking performance in polyol esters used in the tests performed on Al 6061 is that neat machining is sufficient to remove the heat occurring at the tool-workpiece interface and lubrication performance is required, not cooling.
2. Since Al 7075 has harsher machining conditions than Al 6061, the emulsion machining performance of the Al 7075 alloy has improved due to the cooling effect of the water, giving better results than neat machining. For this reason, the performances of neat machining of vegetable oils and esters on Al 7075 were found to be poor, unlike emulsions, and cooling performance was needed. In contrast, machining performance has improved due to the cooling effect of the water content in emulsions.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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