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EVALUATING THE PERFORMANCE OF ENVIRONMENTALLY FRIENDLY AND MINERAL OIL-FREE CUTTING FLUIDS: A COMPARISON OF FULLY SYNTHETIC, SEMI-SYNTHETIC AND HEAVY-DUTY EMULSIONS

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ABSTRACT

The paper aims to determine the relative lubricity environmentally friendly of the Fully Synthetic (FS) Cutting Fluids (CF) group and a bio-based emulsion and compare technical performance to Semi-Synthetic (SS) and Heavy-Duty Emulsions (HDE) groups. In the final section of the paper, the environmental impacts of the three CF groups are discussed and the method of calculation is described to compute their (GHG) emissions using a case study.

The experiments were performed using a precision CNC machine by incorporating a rotating dynamometer attached to the rotating spindle to enable direct measurement of torque and thrust force exerted by the tap at low spindle speed to machine aerospace engine components in Titanium alloy (Ti-6AL-4V) under simulated field performance conditions.

The paper describes insights into the factors affecting process variability covering the tool, material, preparation, and environmental factors, and ranks their effects. It also demonstrates the impact of GHG on the environment which can be reduced by using bio-based Metal Working Fluids (MWFs) rather than mineral-based.

In total eight different CFs (two of the CF Heavy Duty Emulsion (HDE) , two Synthetic, two Semi-Synthetic and two non-mineral oil) were compared and analysed against a known industry benchmark(BM). The initial findings in this paper, although focused on freshly mixed CFs products, suggest the non-mineral oil product can perform equally well or some cases even better.

1.0 Introduction

Cutting fluids are used in metalworking processes to provide cooling and lubrication. However, the health, safety and environmental issues are of concern. Exposure of CF, for example, if it encounters the skin, inhaled, or enters the body it can cause health issues. Also, CF can have environmental impact due to the hazardous additives, waste, and disposal issues. With current attention and government regulations, industries are forced to reduce the amount of this impact. According to [1], Mineral-based CFs which are hazardous for storage and disposal, require a special physical or chemical treatment by an environmental protection agency (EPA) to remove the toxic components inside the CF before disposal. For instance, the European Union alone consumes about 320,000 tonnes per year of CFs within one year and two-thirds of it needs to be disposed of [2] It is estimated that the cost of CFs, including purchasing, preparation, maintenance, and disposal is approximately 16% of the total machining costs of a product. The disposal cost of CFs can be up to two to four times the purchasing costs because the CFs are not biodegradable and require expensive treatment before disposal[1].

A European Union regulation concerning the Registration, Evaluation, Authorisation, and restriction of Chemicals came into force on 1st June 2007, replacing several European Directives and Regulations with a single system (European Commission, 2020). This regulation was adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals while enhancing the competitiveness of the EU chemicals industry and establishing procedures for collecting and assessing information on the properties and hazards of substances [3].

Currently, there are wide-scale evaluations of the use of MWFs in machining, to reduce the number of lubricants in metal removal operations. According to [2] there has been interest in using dry machining which eventually met with success in the field of environmentally friendly manufacturing. However, these are less effective when higher machining efficiency, better surface finish quality and severe cutting conditions are required, therefore, it was suggested vegetable oils would be a viable alternative to petroleum, considering the subject of performance, cost, health, safety, and environmental points of view [2].

Also found that although the major advantages of the new developed vegetable-based CFs are high biodegradability and environmentally friendly while providing the same or better performance than mineral-based CFs, and the vegetable oils are potential CFs as an alternative to mineral based or conventional CFs. However, the disadvantages of vegetable oils are low thermal and oxidative stability, Vegetable oils freeze at higher temperatures as compared to the mineral oil and poor corrosion protection.

Apart from the health and safety issues for those who work with the of CFs, the disposal of these fluids can have a negative impact on the environment and present a hazard to the health of individuals exposed to them. The cost of treatment is high and fluid disposal can cause air and soil pollution, and surface water and ground contamination. [4] According to [1] the widespread use of petroleum based CFs cause significant environmental pollution throughout their life cycle.

Over the years, the focus on CFs has shifted from biodegradability to renewability in order to protect the environment. Due to the many negative effects that CFs have on health and the environment, there is a need to develop more wide spread use of CFs that are sustainable, effective, environmentally friendly, minimise waste streams and can be easily treated and disposed.

Conventional CFs can be classified into three main categories, which depend on how much oil they contain before dilution, as shown in table 1.

Table 1: Three main CFs classification as referenced by ASTM E2523-13. 2018.

Category	Standard Terminology
Semi-Synthetic	Mineral Oil, often Ester based. Metalworking fluid that generally contains >20 % water and <50 % petroleum oil and functional additives.
Heavy Duty Emulsions	Ester based or Mineral oils. Emulsion - Relatively stable mixture of two immiscible liquids.
Fully synthetic	Oil free. Metalworking fluid that contains no oil and forms a true solution (no micelles) when mixed with water

It has been a lot of published works on the machinability of high strength titanium alloys such as Ti-6Al-4V are more prone to tool breakage due to seizure in the workpiece, especially in threading small diameter blind holes [5] [6] [7] [8] [9] [10] [11] [12][13]

2.0 Experimental setup

The experiments were performed using CNC DMG MORI Evo40 5-axis machining centre incorporating a 4-component Kistler rotating dynamometer. A tool holder collet clamped to an Emuge synchronous tapping chuck set. The soft synchronous chuck was secured to the RCD which in turn is secured to the machine spindle by an HSK 32A adaptor to enable direct.

The measurement of torque and thrust force on a rotating tool during cutting processes the experimental set up as shown in figure 1. The measuring time was 20 seconds, the sample rate was 100 Hz each (which takes the sample every 0.001 from a second).

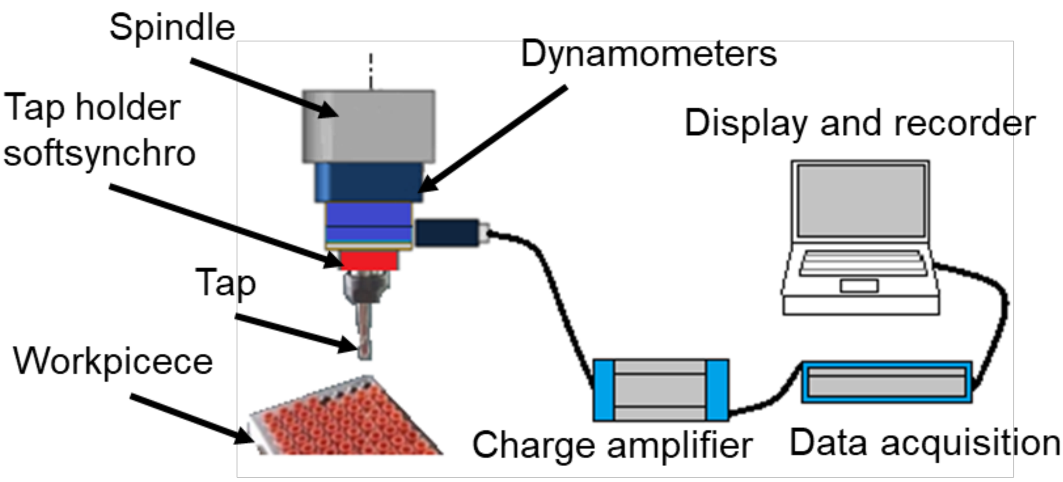


Figure 1. Experimental set up

Coordinate-measuring Machine (CMM) was used to check the diameter of the holes which were precision drilled to a tolerance of 5.500 and 5.520 mm (client standard) and between 5.460 and 5.560 (ASME standard) for the CFs shown in figures 3.

The cutting parameters for the drilling are speed v 60 mm/min. The temperature, relative humidity and Brix% were measured and recorded; this was performed at least once every time before any testing. The workpiece material is Ti-6Al-4V (grade 5) alloy rectangular block with dimensions of 168 x 72 x 20 mm. All the workpiece material used for the tests were from the same manufacturing batch. The chemical composition of the workpiece is shown in Table 2.

Table 2: Workpiece Materials Chemical composition of Ti-6Al-4V (grade 5) alloy.

Chemical composition	Al	V	Fe	C	N	H	O	Ti
Weight (%)	6.48	4.06	0.2	0.08	0.009	0.015	0.13	balanced

The tap tool used is uncoated HSS-E-P. The dimensions and characteristics details are shown in figure 2. The chemical composition can be seen in table 3.

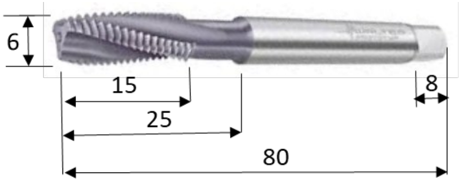


Figure 2 The PARADUR TI 234164-UNF1/4 tap tool for titanium. (Dimensions in mm)

Table 3: HSS-Co AISI materials chemical composition.

C%	Si%	Mn%	P%	S%	Co%	Cr%	Mo%	V%	W%
0.88-0.96	≤0.45	≤0.4	≤0.03	≤0.03	4.5-5	3.8-4.5	4.7-5.2	1.7-2	6-6.7

The tool used for drilling is Solid carbide twist drill (DC150-05-05.500A1). The cutting parameters for the tapping experiments are speed 2.39 m/min (120 rpm) and the thread length 9.52 mm.

3.0 Experimental results and discussion

3.1 Drilled holes

Prior to the tapping operation, holes need to be drilled; it is very important for the size of the holes to be accurate in order not to have an effect on the forces during tapping. The hole sizes must be within the limits according to the ASME and client standards.

Figure 3 shows the limits for diameter for all the holes before tapping. The ASME Standards is ± 60 µm and the client Standards is ± 20/0 µm.

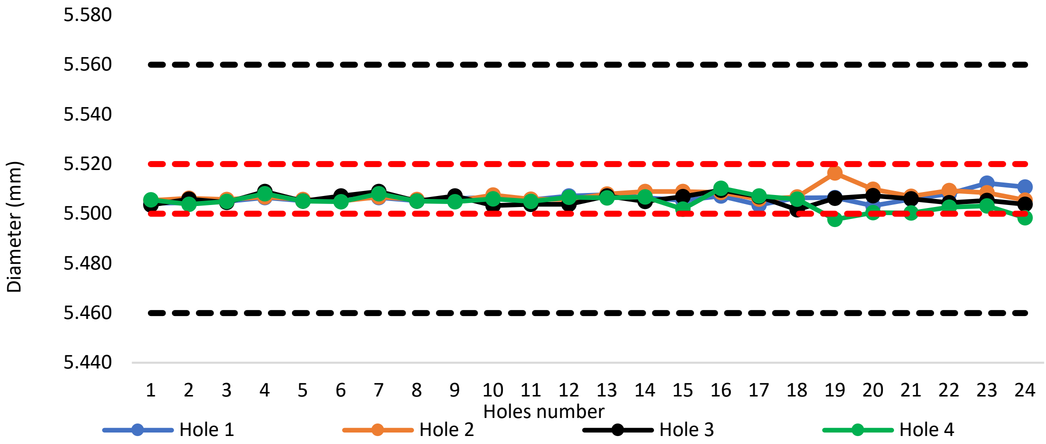


Figure 3 Diameter vs number of holes.

3.2 Cutting Fluids

The CF is one of the most important factors in machining operations that affects surface finish, forces etc. The primary function of lubricating oil is to reduce friction between the tool and workpiece, which in turn decreases cutting forces and the tool wear [14]. HOwever, the most important effect a CF can have is that on the environment. Presently, companies not only have to choose a CF that gives the best performance but also CFs that are from the environmentally friendly category. In order to find which CF is the most effective in producing the lowest torque and thrust forces in the tapping process using titanium, 8 CFs were used. Two CFs from each type, synthetic, semi-synthetic, heavy-duty cooling, and non-mineral oil, table 4 shows Seal number, category and description.

Table 4: The category and description of are CFs were testes.

Category	HDE1- HDE2	FS1 – FS2	SS1 – SS2	M5 – M6
Code	A6 – F5	B5 – K4	E4 – J5	M5 – M6
Description	Mineral oil 50-60%	Fully Synthetic	Mineral oil <50%	Mineral oil free

3.3 Torque curve for the forward and reverse with the benchmark

The semi-synthetic oil CF, SS1(E4) is used in figure (4) to show the results for the torque curve for the forward and reverse thread cycles with the (BM) CF. In this example, both the CF SS1(E4) and the BM start at the same point until the steady state section (A) which is between 1.5 and 3.5 seconds. In this area the BM outperforms the semi-synthetic CF SS1(E4) which has higher torque forces, and the BM CF even outperforms SS1(E4) in section B (between 4 and 6 seconds) for the reverse thread cycle.

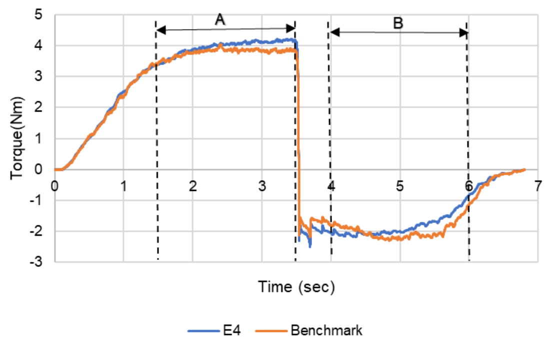


Figure 4 Torque curve SS1(E4) and BM for forward and reverse thread cycle.

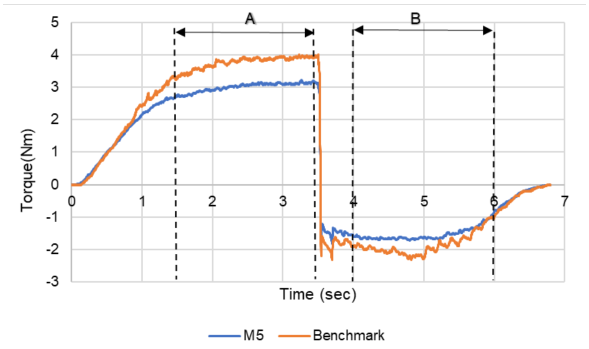


Figure 5 Torque curve M5 and BM for forward and reverse thread cycle

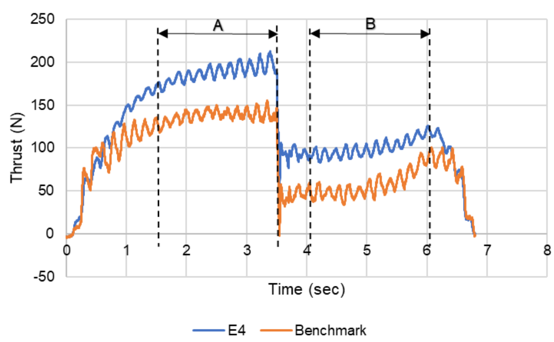
In the second example, M5 CF, which is the non-mineral oil, is used for the results in figure 5. The graph shows the torque curve for the forward and reverse thread cycle. The results for the M5 CF clearly outmatched the BM for both sections A (which is between 1.5 and 3.5 seconds) in steady state region, where it can be seen the BM CF is approximately. 4 Nm whereas the M5 CF is at 3 Nm, and B (which is between 4 and 6 seconds).

From both examples used in figures 4 and 5 for the torque forces, for the semi-synthetic oil CF SS1(E4) and non-mineral CF M5, it is clearly demonstrated that one of the CFs performs better than the BM CF, which is M5, and the other CF which is inferior in its performance as compared to the BM CF is the semi-synthetic oil CF SS1(E4).

3.4 Thrust curve for the forward and reverse with their benchmarks.

Using the same examples for the CFs, the semi-synthetic oil SS1(E4) and the non-mineral oil M5, the results for the thrust curve for both forward and reverse thread cycle are compared with BM and shown in figures 6 and 7.

Figure 6 shows the results for the semi-synthetic cutting oil SS1(E4) and the BM for the thrust curve for both the forward and reverse thread cycles. By observing the steady state section, A, which is between 1.5 and 3.5 seconds, and section B, which is between 4 and 6 seconds, the BM CF is at approximately 150 N at A, the steady state section for the forward thread cycle, and for the reverse thread cycle it is at 50 N. While for the semi-synthetic cutting oil SS1(E4), it is at 200 N for A, the steady state section for the forward thread cycle and at100 N for the reverse thread cycle. The thrust forces are worse for SS1(E4) than the BM. Once again, the thrust forces are higher for SS1(E4) than the BM, which means that the BM CF outperforms the semi-synthetic oil CF SS1(E4).



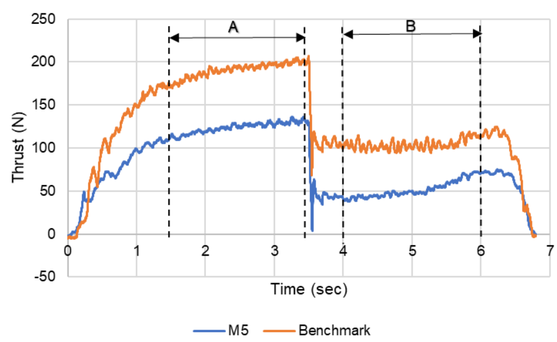


Figure 6 Thrust curve SS1(E4) and BM for forward and reverse thread cycle.

Figure 7 Thrust curve M5 and BM for forward and reverse thread cycle.

The results for the non-mineral CF, M5 were also compared to those of the BM CF for the thrust forces, for both the forward and reverse thread cycles and are shown in figure 7. By observing both section A (1 and 3.5 seconds) and B (4 and 6 seconds), the BM CF is at approximately 200 N at A, the steady state section for the forward thread cycle, and at 100 N for the reverse thread cycle. The non-mineral CF M5 is at 125 N at A, the steady state section for forward thread cycle, and for the reverse thread cycle it is at 50 N. M5 outperforms the results of the BM.

It has been demonstrated that M5, which is the mineral free CF outperforms the BM CF for both the torque and thrust forces, and SS1(E4) the semi-synthetic oil CF underperforms for both the torque and thrust forces. Therefore, it can be concluded that non-mineral oil CF exceeds on its performance in comparison with the semi-synthetic oil CF.

3.5 Overall of cutting fluids against the same benchmarks.

The next section presents figures 8 to 11, which show the results for an average of 3 tests for each of the 8 CFs against the same BM. The graphs show results taken for the steady state section for forward and reverse thread cycles A and B respectively. The cutting in area A was between 1.5 and 3.5 seconds, while for area B the cutting was between 4 and 6 seconds. The tests for the 8 CFs and the BM were all performed on the same day for torque and thrust forces.

The graph in Figure 8 shows the results for forward torque in the steady state section for all the 8 CFs against the BM CF. All of the CFs outperform the BM CF apart from SS1(E4) semi-synthetic oil CF which gives worse results, and HDE1(A6) heavy duty oil CF has very similar results as the BM CF. The best performing CFs are M5 and M6 which are both non-mineral oil CFs.

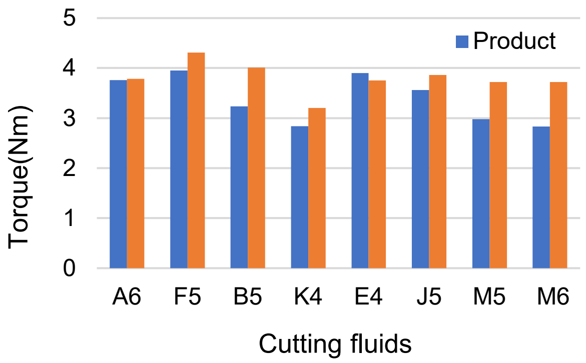


Figure 8 Average forward torque results for 8 CFnd 8 BM fluids

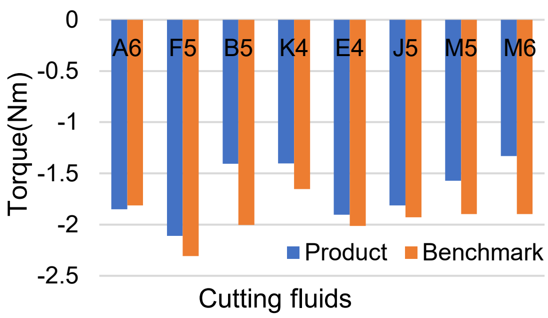


Figure 9 A reverse torque results for 8 CFs and 8 BM fluids

Figure (9) shows the results, which are demonstrated in minus, for the reverse torque results for section B, which is between 4 and 6 seconds. The results show that all the CFs outperform the BM except for HDE1(A6) heavy duty oil CF, which shows almost equal performance. The best performing CFs are synthetic oil CF; (FS1(B5)), non-mineral oil CFs; M6 and M5, once again, 2 out of the 3 best performing CFs are M5 and M6 which are the non-mineral oil CFs.

The results for the forward thrust for all the 8 CFs compared with the BM CF, which were performed on the same day for each test are shown in figure 10, for the steady state section, where cutting was between 1.5 and 3.5 seconds. The 4 CFs, which perform better than the BM, are synthetic oil CFs; FS2(K4), FS1(B5) , mineral oil CFs; M5 and M6. The worse performing CFs are SS1(E4) and SS2(J5) worse than BM as shown in figure 10, semi synthetic oil CFs, while HDE1(A6) and HDE2(F5) heavy duty oil CFs perform almost the same as the BM, the two out of the best three are non-mineral oil CFs which are M5 and M6.

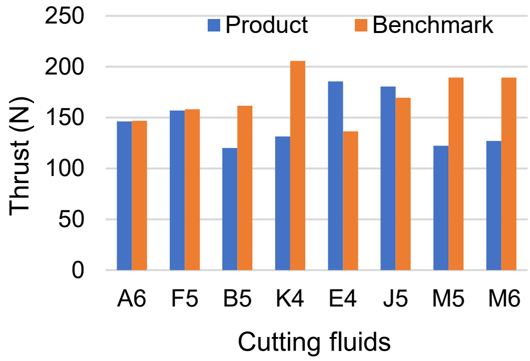


Figure 10 average forward thrust results for 8 CFs and 8 BM fluids.

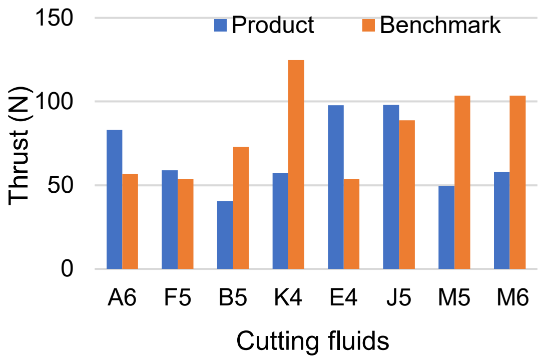


Figure 11 average reverse thrust results for 8 CFs and 8 BM fluids.

The reverse thrust results for section B (between 4 and 6 seconds) are illustrated in figure 11. CFs(K4) FS1(B5) synthetic oil CFs, non-mineral oil CFs, M5 and M6, perform well against the BM CF, while heavy duty oil CFs; HDE1(A6), HDE2(F5), SS1(E4) and semi synthetic oil CFs; SS2(J5) semi synthetic oil CFs give worse performing results when compared to the BM, once again the two out of the best three CFs are the non-mineral oil CFs which M5 and M6.

3.6 Impact on Greenhouse Gas (GHG) Emission.

Environmentally, the ecosystem is affected largely because of (GHG) from burning of fuel in manufacturing and services activities. A case study at the Institute for Innovation in Sustainable Engineering, University of Derby which compared Life Cycle Assessment of mineral oil-based and bio-based MWFs demonstrated that the disposal of coolants and raw materials have the biggest impact on GHG emissions in the machining process life cycle. The work was carried out using two generic MWF products: one formulated from mineral oil one from a renewable (Rapeseed). The study is framed around process (activity) data obtained from tapping Ti64 alloy workpieces in regard to performing CFs appraisals for client.

Table 5: The activities CO2e emission for rapeseed oil and mineral oil.

Rapeseed oil			
Activities		CO2e emission factor	kg CO2e
Raw Material (oil)	70 kg lubricant per year)	-0.3620 kg Co2e / kg	-25.3
Water	Tap water (530 kg)	0.0004 kg Co2e / kg	0.2
Tool	High speed steel usage (57 kg)	4.91 kg Co2e / kg	279.5
Process	100 RPM * 3 N.M (179 kW.h)	0.27 kg Co2e / kW.h	48.3
Disposal (Coolant)	Treatment of biowaste, industrial composting (600 kg)	0.0599 kg Co2e / kg	35.9

Disposal (Tap tool)	Scrap steel, (57 kg)	0.0084 kg Co2e / kg	0.5
	Mineral oil		
Activities		CO2e emission factor	kg CO2e
Raw Material (oil)	70 kg lubricant per year)	1.07 kg Co2e / kg	74.9
Water	Tap water (530 kg)	0.0 kg Co2e / kg	0.2
Tool	High speed steel usage (76 kg)	4.91 kg Co2e / kg	372.7
Process	100 RPM * 3 N.M (239 kW.h)	0.27 kg Co2e / kW.h	64.4
Disposal (Coolant)	Treatment of biowaste, industrial composting (600 kg)	2.85 kg Co2e / kg	1710
Disposal (Tap tool)	Scrap steel, (57 kg)	0.008 kg Co2e / kg	0.6

In a production environment, the case study assumes aerospace working patterns of operating two shifts typically attaining 38% machine utilisation over one year. One full coolant change per annum and maintenance top ups.
Each tap tool, weighing 19 g, is assumed to have a 5-minute life cycle with 5 tap regrinds, thus reducing the number of tap replacements and allowing the same process time for drilling. Activity emissions factors as shown in table 5.

Activity emissions factors are obtained from established referenced sources which have been identified and used to compute GHG (Kg Co2e) using the equation:

GHG (Kg Co2e) = activity x emissions factor

The GHG Emission data for each activity are illustrated in figure 12. For all the activities the rapeseed oil outmatches the mineral oil.

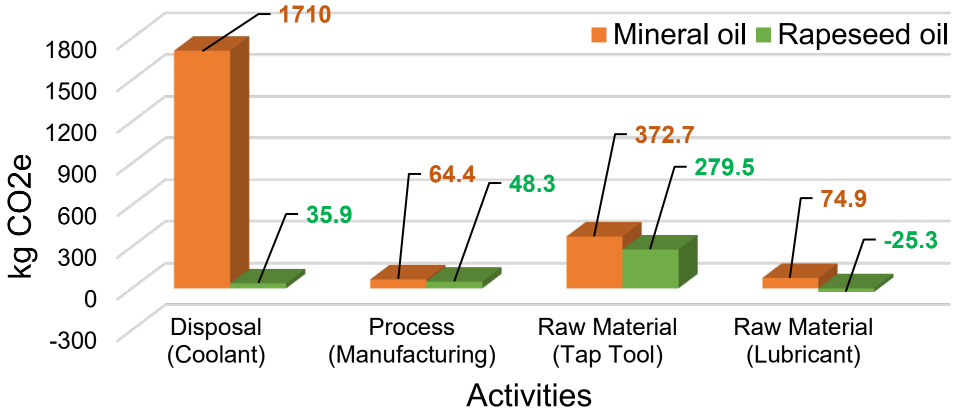


Figure 12 Greenhouse Gas Emission (GHG) vs activities.

The mineral oil was compared to the rapeseed oil for each activity, and the results for the GHG. The performance of the mineral oil falls behind that of the rapeseed oil for every activity apart from the raw material (water) where it is equal to the rapeseed oil.
Therefore, with current practice, for one process and one machine tool, a total GHG emission over one year of mineral oil is 2222.8 kg CO2e, with a potential of being reduced to 339.1 kg Co2e using rapeseed oil.

4.0 Conclusion

In this paper, 8 different CFs were evaluated, for the forward and backward thread cycle for torque, M5 and M6, both of which are non-mineral oil CFs, produced the best results. For the backward thread cycle for torque, the best performing CFs are M6 than FS1(B5), M5 and M6, two on mineral oil.

The semi synthetic oil CFs SS1(E4) and SS2(J5) showed the highest thrust values with regards to the thrust forward thread cycle, the synthetic oil CFs FS1(B5) and FS2(K4) outperformed the BM cutting oil.

The non-mineral oil CFs category which are M5 and M6 exhibited the best results. The worse results for the thrust reverse thread cycle were displayed by the semi synthetic oil CFs SS1(E4) and SS2(J5), and the heavy-duty oil CFs HDE1(A6) and HDE2(F5) compared to the BM CF. The worst were shown by FS1(B5) and FS2(K4) synthetic oil CFs and M5 and M6 non-mineral oil CFs category.

In general, the best performing category was the non-mineral oil CFs which produced lower forces than the synthetic CFs, while the semi synthetic CF produced higher forces than the heavy-duty CFs. Therefore, it can be concluded that the non-mineral oil CFs category exceeds in performance as compared to the other categories.

It was found that the non-mineral oil can outperform other CFs, categories non-mineral oil produces lower forces hence uses lower energy. Hence, the mineral oil free CFs can be used as CFs which perform better than other CFs and also have the benefit of being clean for the environment. Consequently, it is beneficial to a greener environment.

The rather limited case study on GHG which indicates for all process activities, the level of GHG can be reduced to 1883.7 kg Co2e per year by using bio-based renewables rather than mineral oil. This rather limited case study illustrates the impact of disposal of coolant and raw materials for tools as having the biggest impact on GHG emissions in the machining process life cycle.

5.0 Acknowledgement

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