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Performance evaluation of an oil-free cutting fluid in tapping

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Abstract

In the pursuit of sustainable manufacturing methods, reducing harmful substances in industrial processes is essential. This study presents an oil-free metalworking fluid (MWF) formulated with alkylphosphonic acid in a solvent (Patent Unil Opal France, WO 2016 046401). Traditional MWFs often rely on oil-based components, which pose environmental and health risks. The research focused on testing this new formulation, highlighting its lubricating and anti-wear properties. The fluid was tested using the Tapping Torque Test, in accordance with ASTM D8288 - 19, specifically for cutting tapping operations. A series of characterizations were also conducted to evaluate the anti-wear properties of the tested MWF. While deformation tapping is relatively well understood, cutting tapping remains underexplored in the literature. To address this gap, a characterization procedure inspired by established methods for turning was developed. The developed fluid demonstrated performance comparable to that of neat oils in reducing tapping torque and enhancing wear resistance. Additionally, the absence of oil in the formulation significantly reduces the environmental footprint by eliminating the degreasing step. This oil-free formulation could also enable the development of a new generation of water-based lubricants effective for various machining operations. The authors gratefully acknowledge the financial support received for the ECOLUB project and ICE PhD thesis support from the Regional Council of Bourgogne Franche-Comté.

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1. Introduction

Cutting fluids are used during machining to cool and reduce friction between the workpiece and the tool. Traditionally, these fluids are derived from petroleum refining or chemical synthesis. However, their use raises major issues related to health, safety, and the environment. Indeed, cutting fluids can contain potentially harmful chemicals. Prolonged exposure to these fluids can cause skin irritation, respiratory issues, and increase the risk of serious diseases such as certain types of cancer [1], [2], [3].

Since the 1990s, alternatives to traditional cutting oils have emerged, particularly with the development of vegetable oils. These bio-based oils also have the advantage of a higher auto-ignition temperature compared to petroleum-based oils.

However, other technologies are also under development, such as ionic fluids [4], [5], [6] and nanofluids [7], [8].

In 2014, the FEMTO-ST and UTINAM laboratories collaborated to develop lubricants made from alkylphosphonic acids diluted in a hydroalcoholic medium. These molecules have the property of forming self-assembled monolayers through condensation on the metal hydroxide present on the surface of metals [9]. During this friction, a tribochemical reaction occurs in the contact zone, leading to the creation of a material with an infrared signature similar to that of a graphene oxide [10].

These efforts resulted in products marketed through the creation of the start-up Afuludine, aimed at shaping materials in cold processes such as stamping and cutting. Today, studies are being conducted on machining operations, and this article focuses on tapping.

Tapping involves machining threads inside a bore using a tap. This process can be carried out either by deformation, where the threads are formed by the plastic deformation of the material, or by cutting, which produces chips. Cutting tapping involves continuous oblique cutting in a confined space, creating chips.

Cutting tapping is a common technique in industry and is critical because it is generally the final operation. Thus, any defects during this step can lead to the rejection of a complex part. Moreover, this cutting operation requires a limited amount of cutting fluid, which allows us to compare the performance between spraying and immersion in the cutting fluid, potentially altering industrial practices. Finally, cutting tapping allows the use of ethanol solvent, despite being inflammable. However, tapping is a complex technique to study. The cutting is continuous and follows a helical path. Additionally, the tap consists of a series of specific teeth that combine the functions of roughing, intermediate cutting, and finishing into a single tool. This complexity partly explains the lack of literature on the subject [11]. The ASTM D8288-19 standard provides a testing method for cutting fluids, based on the measurement of mechanical forces during tapping. According to this standard, the lower the tapping torque, the better the fluid. However, this standard overlooks the anti-wear properties of cutting fluids, which help minimize tool damage and extend tool life. Therefore, it is necessary to establish a procedure to characterize tap wear in order to effectively compare cutting fluids.

To date, there is no defined standard or procedure to characterize wear during tapping. Some articles address this topic, but each focuses on specific aspects.

For example, Gil del Val studied the wear of the flanks of the tap [11], [12]. It is therefore crucial to develop a procedure for characterizing wear during tapping. To achieve this, inspiration can be drawn from the characterization procedures used for turning, with certain parameters adapted accordingly.

2. Experimental set-up

2.1. Samples

The tapping was performed in open bores made of stainless steel 316L, with a length of 20 mm, a width of 10 mm, and an internal diameter of 8.5 mm. The internal diameter was measured using a caliper, with values ranging from 7.44 to 7.46 μm . The stainless steel 316L was ordered from Lugand Aciers (Appendix A). This steel has a measured hardness of 329 ± 11.6 HV.

2.2. Tap and tapping machine

These bores were then tapped fixed in a tool holder collet mounted on a dynamometer, and tapped using a Technispiro Roscomat 200 pneumatic tapping machine (Fig. 1).

The taps used are Walter Tool Prototex X-pert M, M20213-M10 taps, made of HSS steel (Appendix A). These taps can tap to a depth of three times the thread diameter, then 30 mm in this case. They are specifically designed for materials with long

chips, such as stainless steels. The machined thread has a pitch of 1.5 mm, with a 6Hx tolerance class.

The tap has a B-type conical entry with five active teeth and three flutes. Each tooth has a different geometry. To identify these teeth, it is important to be able to reference the tap. This can be done by using the "M" logo present on each tool; the flute beneath this "M" is called flute 1, and the others are numbered clockwise. The cutting angle corresponding to the second active tooth of each flute can then be determined based on the results from the radius measurements of the cutting edges.



Fig. 1. Experimental set-up and pictures of the tap.

2.3. Lubricants

A lubricant called here ECOTAP, based on ethanol and alkylphosphonic acid, as described in [13], was used. For synthetic cutting fluids, Vascomill 10 neat oil was used. This is a synthetic ester-based oil suitable for tapping, with a viscosity of 10 mm^2/s at 40°C, a density of 0.9 g/cm^3 , a pour point of -48°C, and a flash point of 202°C. The soluble oil used was Hangsterfers S-500 CF. This soluble oil is suitable for tapping and stainless steels, with the manufacturer recommending dilution in water to achieve a 10% concentration.

2.4. Tapping procedure

Before starting any test, the cylinders and taps were degreased in a 30°C acetone bath using ultrasound for 5 minutes. The workpiece holder was degreased with a cloth soaked in ethanol. The setup was cleaned between each fluid. The bore was then mounted in the workpiece holder and tightened, after which the workpiece holder was filled with the fluid being studied. Data acquisition was initiated before starting the tapping process. Once the tapping was complete and the tap removed from the bore, the rotation direction was reversed to extract the tool.

The tool life criterion employed in these experiments was the ability of the tool to tap 28 pieces without any teeth breaking. This criterion does not account for thread quality or adherence to dimensional tolerances. In the literature, tool life is commonly defined as the number of parts machined before exceeding the manufacturer's specified tolerances [12]. However, this definition is generally applied to scenarios where a tool machines hundreds of parts, leading to gradual tooth wear - a condition not observed in this study.

In our investigation, the primary limiting factor was the breakage of one or more teeth. All experimental configurations were repeated at least three times, and tests straight oil and ECOTAP always conducted to a stable result, while tests involving dry machining always conducted to a premature tool breakage. Tests with soluble oil were repeated 4 times because of a massive tooth breakage during the first one.

2.5. Dynamometer and data processing

The torque, axial force, and tangential force were measured using a Kistler 9272 dynamometer (Fig. 1), connected to a Kistler 5070 amplifier, a National Instruments acquisition card, and Labview software. The sampling frequency was set to 1 kHz. The dynamometric device has a natural frequency of 20 kHz. Despite the setup reducing this frequency, it is estimated to remain far from a quarter of the natural frequency, ensuring reliable measurements. Additionally, the Kistler 9272 dynamometer has a sensitivity of 0.2 N·m for torque and 0.01 N for axial and tangential forces.

To analyze the data, torque (Mz) was plotted as a function of time. As illustrated in Fig. 2, a typical torque curve for a tapping operation shows an initial rapid increase in torque, followed by a steady rise caused by the tap pushing chips and the guide section engaging with the newly formed threads. The tapping process concludes with a sharp increase in torque, immediately followed by a rapid decrease. This final torque spike is attributed to the removal of chips in front of the tap's cutting edges, constrained by a burr at the bore outlet formed during sample preparation. To focus on the continuous tapping phase, this final peak was excluded from the data analysis.

For comparison purposes, the average tapping torque recorded during the tests was used. This value was calculated by averaging the torque measurements between the beginning and the end of the process. The uncertainty was determined using the standard deviation of the collected data.

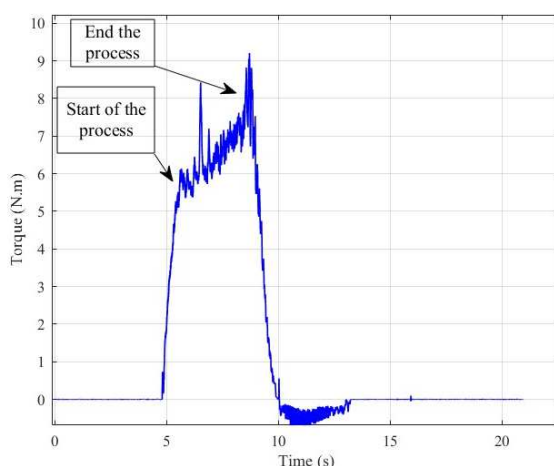


Fig. 2. Evolution of torque during tapping.

2.6. Flank wear

During machining, the upper part of the tooth comes into contact with the machined surface, causing flank wear [14]. Unlike in turning, flank wear in tapping appears to be more

gradual and uniformly distributed across the width of the tooth. Drawing inspiration from the work of Gil del Val [11], the width of the flank wear zone was measured. To achieve this, a Keyence VHX-5000 digital microscope was used with a magnification of x300 to precisely observe the worn zone. Ten profiles of the worn zone were then traced to determine its mean width, with a regular spacing, according to the corresponding norm ISO 3685 [15]. The same procedure was applied to the second tooth of each flute.

3. Analysis and results

3.1. Tool life

During tapping, only two of the tested fluids allowed systematically machining of all 28 parts in acceptable machining conditions: ECOTAP and neat oil.

Tool breakage was observed at the latest on the 8th part when tapping without lubrication, and on the 9th part when using soluble oil during the first test. In both cases, the breakage was severe and affected multiple teeth, as illustrated in Fig. 3 (a). For teeth on flute 1 to 3 when machining with soluble oil, the cutting edge was quickly worn irregularly by chipping, and some cracks appeared beneath the edge (Fig. 3 (b)), conducting to an accelerated stepback of the edge, and then a reduced depth of cut. Since tool life is the most critical criterion for a cutting fluid, dry machining was excluded from further characterizations, and the case with soluble oil has to be analyzed differently, especially when considering flank wear, because the local depth of cut is more limited for teeth flutes 1, 2 and 3.

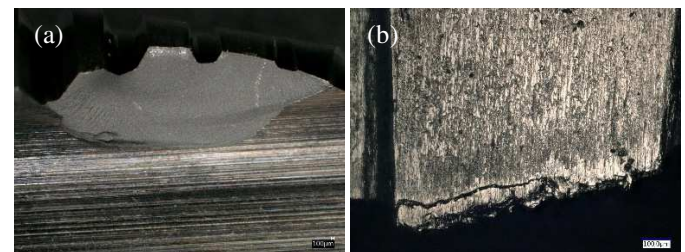


Fig. 3. Tool failure in tapping with soluble oil: (a) a broken tap (x30) ; (b) chipping of the cutting edge and crack propagation (x300).

3.2. Monitoring of mechanical actions

For taps that machined using ECOTAP and neat oil, the average torque stabilized after tapping the first three parts, suggesting that approximately three parts are required for the tools to break in. Moreover, no significant increase in torque was observed, which could indicate the absence of tool degradation.

It can be seen in the Fig. 4 that neat oil produces a slightly lower tapping torque compared to ECOTAP. Thus, neat oil reduces friction more effectively than ECOTAP. It should be noted, however, that lower friction does not always mean lower wear.

It is also observed that the average tapping torque slightly increases with use. For ECOTAP, between the first and the 28th part, there is an increase of 1 N·m, corresponding to a 15% rise. For neat oil, the average torque increases by 0.18 N·m, which represents a 2.7% rise.

These measurements were reproduced with similar trends, showing a tapping torque 0.54 N·m higher for ECOTAP than for neat oil. Neat oil exhibits better lubricating properties than ECOTAP; however, the difference between the two is limited and the use of ECOTAP increases globally the tapping torque by 13% only compared to straight oil.

Soluble oil generates more torque than ECOTAP (about 28%) and neat oil, and a less regular wear of teeth, with higher chipping and stepback of the cutting edge, and even cracks initiation and propagation (Fig 3 (b)). The phenomenon is initiated on first teeth of first flute and then propagates to over flutes step by step when compensating the depth of cut modification due to edge stepback.

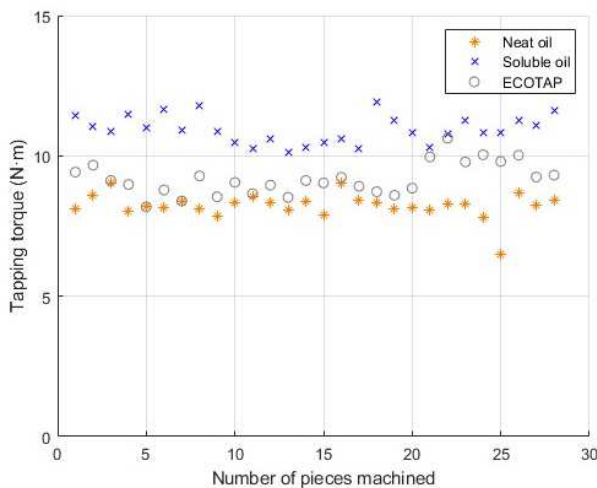


Fig. 4. Evolution of the tapping torque as a function of the lubricant used.

3.3. Flank wear

Fig. 5 illustrates the evolution of the average flank wear width for the three flutes of each tap, depending of the lubricant used. Unlike the cutting face wear, flank wear is characterized by a regular progression for neat oil and ECOTAP. For soluble oil, the stepback of cutting edges of first teeth modifies the depth of cut and distorts the results. This third case is then difficult to compare with the two others in term of flank wear. The cutting edge stepback should be added to this value for each case but this quantity was really difficult to evaluate technically after each tapping test.

It is observed that ECOTAP consistently exhibits a narrower wear band compared to neat oil. On average, for the three flutes, the worn band width is $44.6 \pm 9.3 \mu\text{m}$ for ECOTAP, compared to $67.8 \pm 14.4 \mu\text{m}$ for neat oil. Thus, the use of ECOTAP reduces flank wear by 35 % compared to neat oil. These results were reproducible, consistently showing a narrower wear band for ECOTAP

To lower friction, lubricants are typically formulated with oil and extreme pressure additives, such as ZDDP [16], [17], which form an adherent coating that separates the two metallic surfaces. In the case of ECOTAP, friction generates a third-

body lubricant composed of carbon [10], which also separates the two metallic surfaces and reduces friction-related forces [13]. Therefore, in the context of tapping and flank wear, this new type of lubricant, such as ECOTAP, demonstrates superior anti-wear properties.

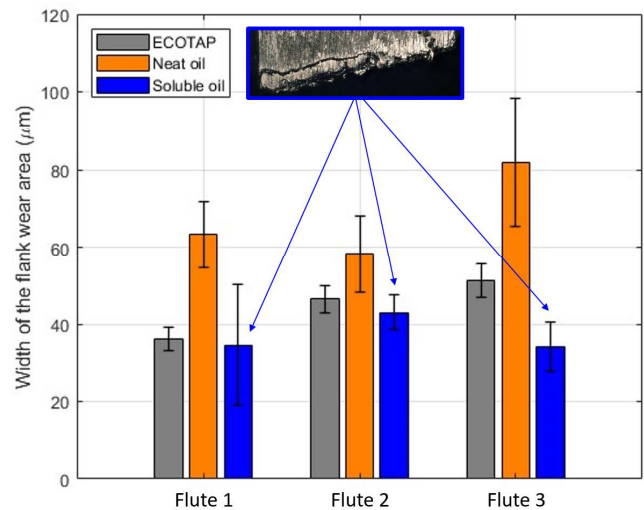


Fig. 1. Width of flank wear area as a function of the lubricant used.

3.4. Tribo-chemical observations

Fig. 6 shows a SEM image of the tribofilm formed by the ECOTAP fluid, with the associated EDX spectra. The following local atomic compositions can be determined:

- Zone 1 (tribofilm): 48% carbon, 35.7% oxygen, 6.4% phosphorus and 9.4% iron
- Zone 2 (tap): 7.4% carbon, 57.65% oxygen, 0.6% phosphorus and 34.28% iron

The phosphorus and carbon peaks are typical of molecules of alkylphosphonic acids. These results clearly show the presence of these molecules on the surface, at the level of the black clusters observed.

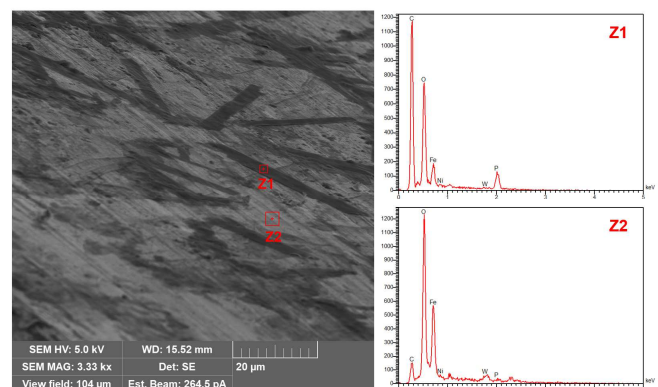


Fig. 6. MEB observation and EDX spectra of clearance surface of a tap after machining with ECOTAP fluid.

Regarding the tribochemical aspect, it is consistent with observations made by Colas et al. [10]. In this paper, various lubricants are tested for fretting, and the authors use Raman spectroscopy to show that the tribofilm formed from

alkylphosphonic acids has a structure similar to that of graphene oxide.

However, it was difficult to reproduce these measurements exactly on the tap. The tribofilm is not present uniformly across the entire surface, and it was not possible to find such a clear signature on the tool, probably due to its geometry and size. It would be interesting to repeat these experiments on a tool with a simpler geometry in order to confirm these observations, for example in planing.

4. Conclusion

The developed method allows for the comparison of different lubricants in tapping by testing the lubricating and anti-wear properties of cutting fluids. It can be concluded that the formulation developed from alkylphosphonic acid exhibits performance similar to that of neat oil in term of tool life; a lower flank wear but with a higher tapping torque.

However, this fluid demonstrates significantly better tool life than soluble oil, with less cut material adhesion on rake and clearance faces of the tool. These results are consistent with the ones obtained in turning with a first water emulsion version of this alkylphosphonic acid based lubricant [18]. In addition to what it is observed in turning, more chipping and cracking is also observed with soluble oil in tapping, leading to a stepback of the cutting edge, local modifications in depth of cut, and even possible flute's breakage.

Finally, for machining operations requiring a higher volume of lubricant, where energy dissipation is critical, it will be necessary to switch to a different solvent (like water) in order to obtain a non-flammable fluid. However, the molecules tested in this study were not water-soluble. To make these molecules soluble, the length of their carbon chains could be reduced, or surfactants could be added. It would also be interesting to compare vegetable oils in these tests, as they are increasingly occupying a significant share of the market.

Moreover, it is necessary to deepen the understanding of tool wear mechanisms in order to determine to what extent they vary depending on the lubricants used. Finally, previous studies on alkylphosphonic acids in dry friction [10], [13] have provided a better understanding of the mechanisms involved during contact. However, it is likely that these mechanisms differ when they are in solution.

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Appendix A. Composition of considered materials

Chemical composition % m/m (NF EN 10088-1)	Tool (HSS-E)	Workpiece (316L)
Co	5.45	
W	3.03	
V	1.01	
Cr	3.95	16.5 – 18.5
Mo	3.00	2 - 2.5
Fe	82.56	62.29 – 68.31
C	~ 1	0.01 – 0.03
Mn		2
Si		1
Ni		10 – 13.5
N		0.1
S		0.03
P		0.05

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