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Test of a new water-based lubricant in turning of 316L stainless steel

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Abstract. In recent years, hybrid manufacturing combining additive and subtractive processes is gaining increasingly importance in the industry. One of the issues related to this association of processes concerns the use of cutting fluids, important to optimize the machining part, but that can strongly affect the additive part by generating pores in the laser metal deposition. The present work deals with the performance of a new ecological cutting fluid that dries just as water, eliminating the need for a cleaning step between the machining and the laser metal deposition. This lubricant is an emulsion mainly composed of water and alkylphosphonic acids known to allow creating a low-friction tribofilm on metals. This study is carried out by comparing the machining performance of this new cutting fluid with two more classical lubricants, a straight oil and a soluble oil. It was found that machining forces and surface roughness were not very affected by the change of the lubrication mode, while the tool wear showed a significant difference between the dry and the lubricated cases. Considering that the performance of all the cutting fluids was very close, it was concluded that the new lubricant has a great potential for machining applications, since it is ecologically more friendly, non-harmful to the operator and does not need a degreasing step.

1. Introduction

As customers and applications become increasingly demanding, new manufacturing methods also emerge to adapt to this new reality. One of the great innovations of the market in recent years has been the development and expansion of hybrid manufacturing machines, able to reduce production time and create customized products [1]. By combining additive (laser metal deposition, LMD) and subtractive (machining) processes, this new method allows the manufacturing of much more complex pieces with a high productivity, but still with a fine surface finish. It means that the advantages of both types of manufacturing are combined in order to optimize the whole process. The 'stair effect', generated by the deposition of powder or wire layers in the LMD-process, is eliminated by machining and finishing the workpiece [2].

However, some challenges are still related to this combination of operations, and one of them is the use of cutting fluids, important to the machining optimization, but which can disrupt the additive part by aggravating one of its weaknesses: the porosity formation. According to Ng et al. [3], the pores are mainly originated by gas bubbles that are trapped with the powder stream. Now considering the presence of a cutting fluid, this tendency to pore formation increases even more. In hybrid machines, as additive and subtractive processes are intercalated, the piece must usually be cleaned before LMD process to avoid this pore formation. Barckhoff [4] also correlated the presence of a cutting fluid with the introduction of gas bubbles, saying that any lubricant on the surface should be removed before the additive part.

Hence, the presence of any cutting fluid remaining from the machining is strongly related with the pore formation in the LMD process. A cleaning step is an option to remove this lubricant, but it implies the introduction of a cleaning stage, which increases the cost and the total process time. The present research work aims to evaluate the performance of a new cutting fluid based on the Self-Assembled-Monolayer (SAM) principle and on a high control of the chemical reaction between the solution and the substrate (grafting of molecules onto the surface). The development of the proposed solution is based on the control of the chemical reaction between specific active molecules and metallic oxidized substrates such as stainless steels. It ensures surface functionalization by using organic molecular assemblies like Ulman et al. [5] previously did, and more especially by using alkylphosphonic acid molecules. These molecules are well known to act as a protective layers formed by chemical reaction with the metal surface due to a fairly high level of chemical activity [6]. Raman et al [7] studied their ability to create a Self-Assembled-Monolayer (SAM) on the surface of an oxidized austenitic stainless steel (316L). In more recent studies [8,9,10,11,12], significant improvement of the tribological behaviour of different substrates (copper, titanium, stainless steels) was demonstrated and assigned to alkylphosphonic acids molecules used as nano-size liquid additives in lubricant, highlighting more especially the formation of low-friction tribofilm during sliding, responsible for the surface protection, Figure 1. The development of a water-based lubricant containing alkylphosphonic acids is now in progress, and the efficiency of grafted tribofilms obtained from fluid additive reaction with metallic parts concerned by the cutting process (part and tool), has to be validated. In this emulsion, acid molecules act as additive, active agent and solvent.

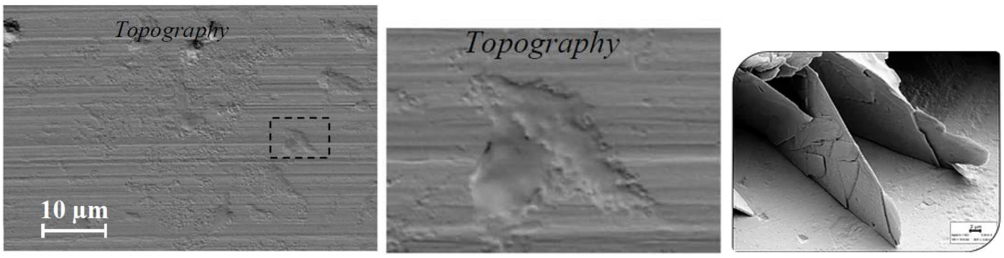

Figure 1 – Observations of tribofilm and SAM anchored on a stainless steel substrate [12]

This new generation of lubricants can offer a technical answer for improving manufacturing processes with several advantages compared to classical solutions: they need less cleaning steps after machining, need no chemical treatment when replacing, and are non-harmful to the operator. All these factors justify a study of the application of this new cutting fluid in hybrid manufacturing. It is made here by analyzing their performances in turning. First of all, based on the work of Nur et al. [13], straight turning is carried out in different conditions by varying the cutting parameters, i.e. cutting speed, feed and depth of cut. Results are compared through machining forces and surface roughness. The second step consists of accelerated tool-life tests of 15 minutes. Flank wear Vb and resultant average roughness Ra are quantified and presented. Then, based on this experimental configuration, a discussion about the different tested lubricants and their efficiency is proposed.

2. Turning experiments

2.1. Experimental setup

All the experimental tests were performed on a Doosan Lynx 220Y, a 4-axis CNC lathe with a maximum spindle motor power of 15 kW and a maximum spindle speed of 6000 rpm.

The workpieces were made from AISI 316L, an austenitic stainless steel widely used in additive manufacturing. The turning inserts used were made from tungsten carbide and coated with three layers of TiCN, Al2O3 and TiCN. The tools are designated as ISO CCMT09T304 and ISO CCMT09T308, with nose radius of 0.4 and 0.8 mm, respectively. The coating thickness and the cutting edge radius, measured with a numerical microscope, were, respectively, of about 5 and 50 µm.

The viscosity was measured with a rotational viscometer Haake 550 for a temperature from 20°C to 100°C (the presented values are average values for a shearing rate from 500 to 1300 s^{-1}).

The following lubricants were employed for comparison in turning:

- Dry machining, in order to get the reference of the worst case in machining.
- Straight oil (Castrol CARECUT ES 2), in order to get the reference of the best case in machining, even if it is not a good solution for hybrid manufacturing (density: 855 kg/m^3 at 20°C, viscosity: 3.39 MPa.s at 100°C) .
- Soluble oil (Jeffacool Poly-Shape), with an oil concentration of 5%, one of the lubricants currently recommended for hybrid manufacturing (density: 978 kg/m^3 at 20°C, viscosity: 0.63 MPa.s at 100°C).
- Water-based lubricant (AFULudine AFO7), based on active molecules dissolved in alcool and then mixed in water (emulsion with 7% concentration of alkylphosphonic acids) (density: 971 kg/m^3 at 20°C, average viscosity at 500 s^{-1} or higher: 0.81 MPa.s at 100°C).

2.2. Cutting conditions

Based on the material and the tool manufacturer's recommendations, the turning conditions for the first group of tests (straight turning in finishing and roughing) were defined as shown in Table 1. For each operation, there are then nine combinations of parameters, and all of them are doubled.

Table 1 - Cutting conditions in straight turning

	Cutting speed Vc [m/min]	Feed rate f [mm/rev]	Depth of cut d [mm]
Finishing tests	120 - 200 - 300	0.10 - 0.15 - 0.20	0.5
Roughing tests	120 - 200 - 300	0.10 - 0.20 - 0.40	1

For the tool-life tests, based on the respective ISO standard [14], it was decided to work with a cutting speed of 200 m/min, a feed of 0.1 mm/rev and a depth of cut of 1 mm.

2.3. Comparison criteria

The machining forces were recorded by a dynamometer (KISTLER 9129AEO) connected to a multichannel amplifier (KISTLER 5070) in order to turn the dynamometer output signal into readable data. All the three components were studied, but in order not to overload this article, only the results for the cutting force, the most important between them, will be detailed. In any case, the results follow the same trends in all three directions.

The surface roughness was measured with a surface profilometer over a length of 10 mm of the machined workpiece. The parameter chosen to compare the cutting fluids was Ra, average roughness.

Finally, the tool wear is analyzed using a numerical microscope (KEYENCE VH-ZST) whose amplification goes from 20 to 2000x. Following the ISO standard, the criteria Vb, the flank wear, is used to evaluate the tool wear.

3. Results

3.1. Cutting forces and roughness

This section presents the results obtained after all the tests and the analyzes with all the mentioned cutting fluids. Firstly, a good repeatability was verified for the doubled tests – the difference was less than 10% for all the cases. Besides, it has been observed from dry cutting tests that the results follow the expected trends: the cutting speed has no great influence on the forces and surface roughness, while a variation in the feed generates a visible change in these resulting parameters. This is in accordance with the results obtained in similar tests carried out by Nur et al. [13].

After doing this analysis for all fluids and noticing the same tendency, it was decided to work only with the average values for each feed, disregarding the influence of the cutting speed. By proceeding in this way, Figures 2(a), (b), (c) & (d) show the results for the analyzed parameters.

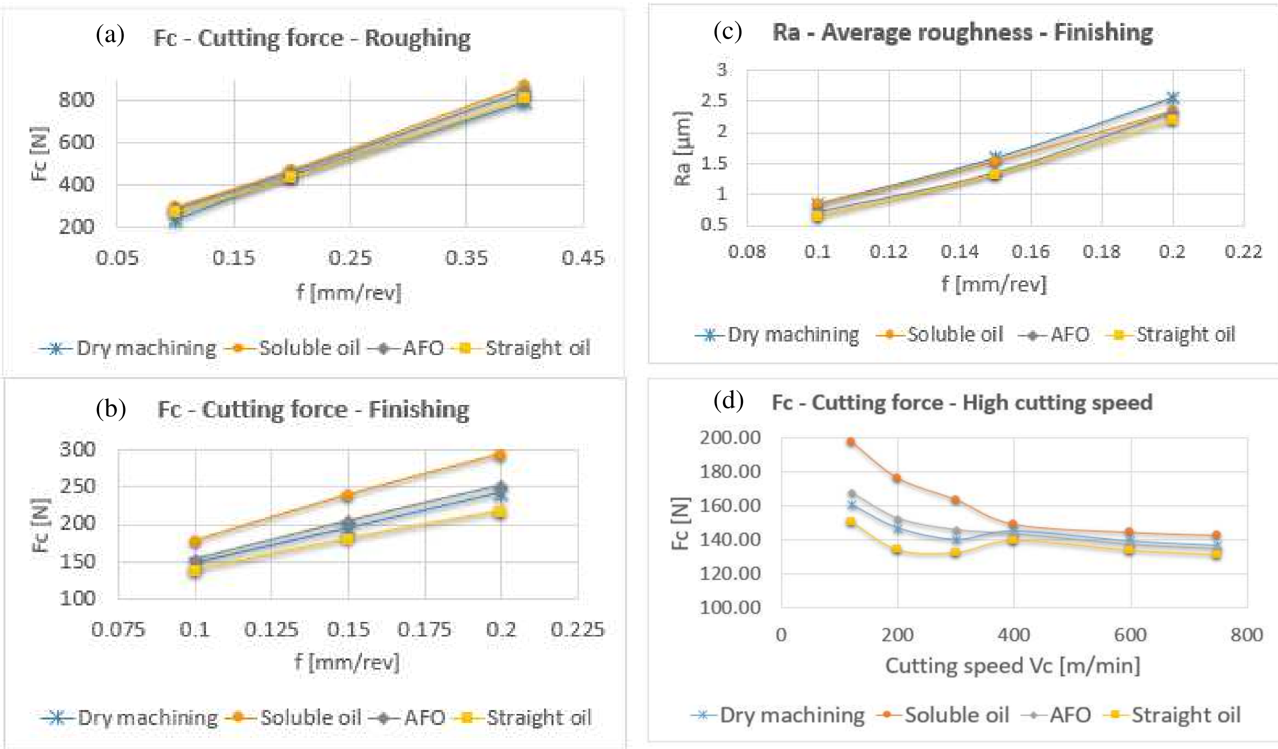

Figure 2 – Obtained results in turning of 316L steel with different lubricants

As it can be observed, the differences between the results are not so significant (exception made for the soluble oil in finishing). For the surface roughness, the expected trends can be effectively verified, with the straight oil having the best performance and the dry machining case the worst. However, a more notable difference was expected for all the parameters, at least between the dry and the lubricated cases. At high cutting speed conditions (400, 600 and 750 m/min), the differences were even smaller, as shown in Figure 2(d).

These results lead to the conclusion that the chosen tool is very well suited to the range of tests and that the friction effects (reduced by the cutting fluids) are very small compared to the forces to remove the material. Because of this, a change of the cutting fluid does not affect the overall result so noticeably.

3.2. Tool wear

Figure 3 shows the tools wear images obtained after 15 minutes of machining with each one. It is possible to notice that the dry machining case presents a much more pronounced wear. The Figure 4 confirm this tendency by comparing, respectively, the flank wear value Vb and the final average roughness Ra. The results obtained with the water-based SAM lubricant (AFO7) are close to results obtained with straight oil concerning wear and close to soluble oil concerning resultant roughness.

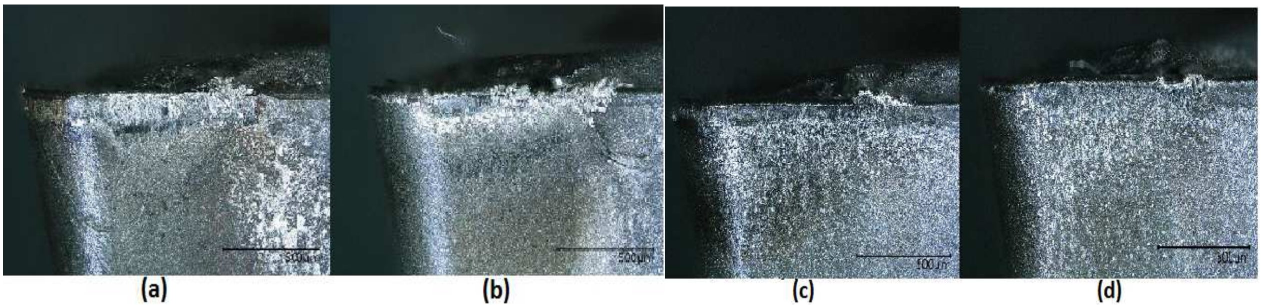

Figure 3 - Flank wear for: (a) Dry machining; (b) Straight oil; (c) AFO; (d) Soluble oil

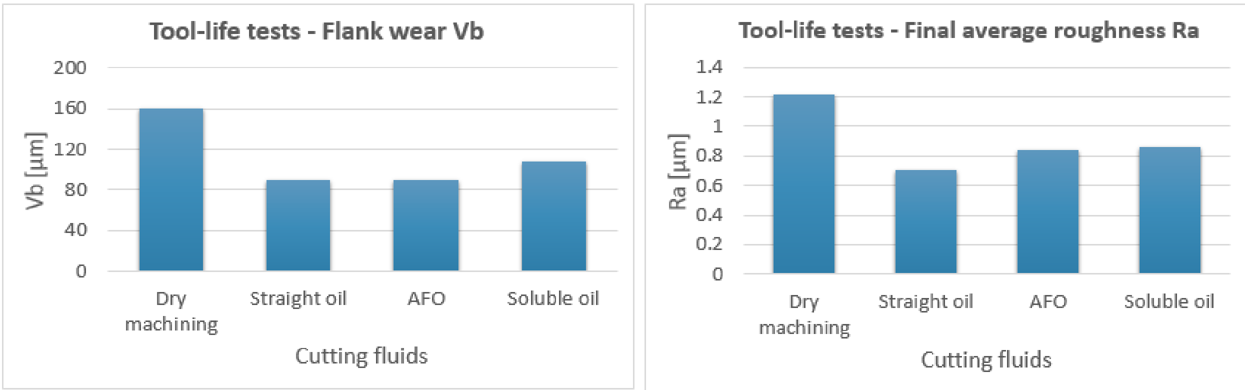

Figure 4 - Comparison of the flank wear Vb and final average roughness Ra

4. Conclusions

In the present work, a comparison between the machining performances of some cutting fluids was carried out. The main goal was to study a new application for a SAM water-based lubricant, in hybrid additive and subtractive processes, as it presents the advantage of drying by itself, not requiring a degreasing step between the operations. Various machining tests were performed in order to situate its performance in turning of 316L steel in relation to some other lubrication solutions and some conclusions can be drawn from the obtained results:

(1) It was found that for the initial cutting parameters chosen for straight turning, the results were not greatly influenced by the lubrication mode, even considering the dry machining case. As explained, it means that the tool insert used was very well adapted to the tests conditions and that the friction effects, reduced by the use of a lubricant, did not have a great influence on the global result compared to the forces to cut the material.

(2) On the other side, as expected, the tool-life tests results showed a clear difference between the dry and the lubricated cases, proving that the use of a cutting fluid significantly increases the tool life. Considering the three cutting fluids, the flank wear Vb presented similar values for all of them, with a slight advantage toward AFO and the straight oil.

(3) Considering that the turning performances are quite similar, other parameters can be analyzed in order to choose the best cutting fluid to apply in hybrid manufacturing machines. The environmental risks associated with the elimination of the fluids are lower. Of course, straight oil and soluble oil are part of the problems related to the contamination of soil, water and atmosphere. The harmfulness of cutting fluids for people who come into contact with them has to be taken into account too. The straight oil and the soluble oil require additional precautions, because they can cause problems like cutaneous pathologies or even cancers. Finally, a water-based and oil free lubricant does not require a degreasing step after machining, and can potentially dry easily by heating.

Some other tests must be carried out to confirm if these trends are maintained using other cutting parameters and performing other operations (milling and drilling, for example). However, the present results are already a promising indication that the water-based SAM lubricants can be an interesting option in hybrid manufacturing, as well for the production of non-polluted parts (e.g. medical device).

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