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The effect of an organic pentasulfide EP additive in turning and milling operations

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ABSTRACT

Because a cutting fluid could be equally used for different cutting operations, this study proposed to investigate the behavior of a well-known extreme-pressure additive (pentasulfide) in both turning and milling operations of a steel workpiece. The experimental approach is based on the coupling of mechanical tests (turning, milling, and tribological tests) with physico-chemical characterizations (Auger Electron Spectroscopy and X-Ray Photoelectron Spectroscopy) of the friction surfaces (chip and tool). In the case of milling, it was shown that the presence of a pentasulfide additive has a beneficial effect on the specific cutting energy (k_c) and flank wear (V_b). These results are correlated with the presence of iron sulfides (FeS and FeS_2) on the flank face of the cutter mill and on the chip face in contact with the mill. No such additive effects are found in case of turning. A lubrication model is proposed for the case of milling based on an indirect lubrication of the tool/workpiece and tool/chip contacts due to the transfer of iron and its reaction with sulfur compounds to produce iron sulfides. Because milling is a discontinuous cutting process, this lubrication mechanism is much more efficient than that observed in turning. Indeed, the tool faces are re-fed iron sulfides each time they leave the workpiece.

1. Introduction

When performing severe cutting operations, such as turning and milling, a cutting fluid is used for different reasons. First, it contributes to chip evacuation. Second, due to its coolant capacity, the fluid plays an important role in the removal of heat from the contacts. Another reason to use a fluid is to improve the tribological behavior of the different contacts (tool rake face/chip and tool flank face/workpiece). Finally, the fluid is considered based on its lubricating ability obtained due to the additives it contains. Because of European regulations, the use of chlorinated or leaded compounds is no longer allowed. Sulfur additives, which are well known for their extreme-pressure properties, remain good candidates but need to be formulated with a very low concentration of sulfur. The development of efficient cutting fluids compatible with environmental regulations is the actual goal of lubricant manufacturers. To reach that objective, a better understanding of the action mechanism of sulfur-containing additives for different cutting operations is needed because the same lubricant could be used equally for different cutting operations.

External turning with a carbide insert and *milling with a solid carbide tool* are two different machining techniques with different specificities, as described in Fig. 1. During a turning path, the tool is always engaged with the workpiece (continuous cutting), whereas this is not the case for cutting edges during a milling operation (discontinuous cutting). In the latter, the cutting edges enter the material intermittently. The cutting geometries of the tools used in these two machining operations are also different [1]. In turning, the cutting insert has a negative rake angle, and the tool workpiece contact is convex on the flank face. In contrast, the solid milling cutter has a sharp edge and a positive rake angle, and the tool/workpiece contact is concave, which induces an accentuated contact in the flank face compared to turning.

Despite these differences between the turning and milling configurations studied, the two machining techniques both induce chip formation, generate great mechanical stress on the workpiece material and produce a high temperature. During the metal-cutting process, the tool is in contact with the material in two different areas: with the workpiece (tool flank face/workpiece contact) and with the chip (tool rake face/chip contact). Does the lubricant come into these interfaces? This is important to consider regarding the tribological role of the lubricant. As A. Mallock mentioned in 1881–82 [2]: “Lubricants seem to act by lessening the friction between the face of the tool and the shaving, and the

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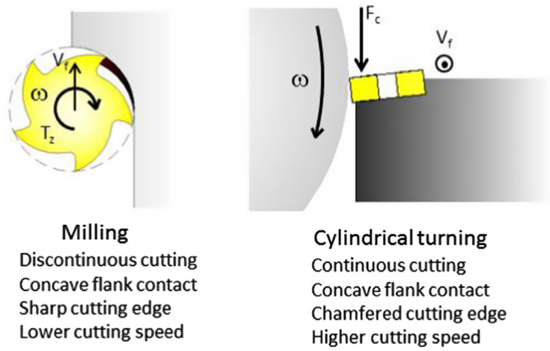

Fig. 1. Milling and turning specificities.

Table 1
Workpiece materials used for machining test.

Steel designation	Experiment	Ultimate strength (MPa)	Metallurgical structure
C45	Turning	800	Ferrito-pearlitic
25 MnCrMoSiVB 5	Turning	1000	Bainitic
	Orthogonal cutting		
42 CrMoV 4	Milling	1080	Bainitic

difficulty is to see how the lubricant gets there". Since then, various authors have proposed lubricant penetration mechanisms in the chip/tool interface considering the following three assumptions:

- *The lubricant is in a liquid or gaseous form and fully penetrates the chip-tool interface*: If the cutting speed does not exceed 20 m/min, a lubricant liquid film could be formed inside the contact of the chip with the tool and protect surfaces against adhesion [3]. For higher cutting speeds, it is suggested that the lubricant acts through its vapor form.
- *The lubricant is in a liquid or gaseous form and penetrates partially into the chip-tool interface*: The lubricant protects the contact surfaces in its range of penetration. Different authors, including Williams, Godlevski and Liu [4–6], have proposed models considering the penetration of liquid or gaseous forms of lubricants in the chip/tool contact through capillaries. The effect of cutting speed has also been discussed [7].
- *The lubricant is in a liquid or gaseous form and cannot penetrate into the chip-tool interface*: This can be encountered under continuous cutting conditions and with very high cutting speeds. According to De Chiffre [8,9], the lubricant flow therefore acts by reducing the contact area between the chip and the tool. Different mechanisms could contribute to this reduction in the contact area. First, the contamination of the tool rake face by the lubricant at the exit of the chip/tool contact could reduce adhesion and thus reduce the contact area. Then, the cooling of the external chip face by the lubricant could contribute to a stronger curvature of the chip, which would also lead to a reduction in the contact area.

It is interesting to note that none of these models takes into account the effect of lubricant additives. Furthermore, it would be necessary to know if discontinuous cutting in milling affects the lubrication process, especially because cutting fluids are actually not really optimized specifically for a milling or a turning application. Additionally, if the cutting continuity affects the lubrication effect, the model of lubricant penetration mechanisms should be reformulated.

In a previous work [1], different sulfur-based molecules have been tested in milling operations. The molecule of interest in this work will be a pentasulfide compound because it has shown good tribological properties in milling.

Thus, the aims of this work are as follows:

(1) To compare the efficiency of the same cutting fluid containing a pentasulfide additive in both turning and milling operations.
(2) To understand the possible action mechanism of this molecule in both machining techniques.

2. Materials and methods

The originality of the experimental methodology proposed here is the coupling of both mechanical and physico-chemical experiments: mechanical tests, such as 3D turning, milling and tribological tests, as well as physico-chemical characterizations (XPS and AES) of the different friction surfaces are carried out.

For the machining experiments, force and wear measurements are performed, and different parameters defined in the ISO standard [10–12] are calculated to quantify the efficiency of the lubricant. These results are then correlated with surface analyses (XPS and AES) of the friction surfaces (tool and chip).

Then, a tribological test is proposed in two different controlled environments (presence of pentasulfide and under Ultra High Vacuum). Even if it is not possible to obtain contact conditions that are exactly identical to those obtained during cutting operations, the objective is to focus on the physico-chemical effect of additives on friction. In-situ analyses of friction wear tracks are carried out to investigate the origin of friction and the wear reduction mechanism.

All materials, lubricants, equipment characteristics and conditions of use are detailed in the following.

2.1. Materials and lubricant

Different steels are used as workpiece materials for machining to adapt to machining test constraints. Information relative to these materials is presented in Table 1. For the turning test, 25 MnCrMoSiVB 5 low-alloy steel is chosen with C45 carbon steel to evaluate the cutting fluid performance under softer conditions. The 42 CrMoV 4 low-alloy steel, with a similar hardness to that chosen for turning, is used in the milling experiments.

Concerning the lubricants, two types of fluids are tested: a pure base oil and the same base oil formulated with a sulfur additive. The base oil, noted PBO, is a chemically non-active paraffinic base oil. The cutting fluid contains an organic pentasulfide, noted ADDS1 in the following, and formulated at a concentration of 1 wt% of sulfur in PBO. This additive was chosen from different sulfur additives based on its good performance in milling applications [1].

2.2. Settings of turning experiments

The turning experiments are conducted on a 2-axis CNC lathe. A conventional lubrication system with an external nozzle oriented to the tool rake face and a flow of up to 10 L/min is used. A 9121 Kistler (Winthertur, Switzerland) dynamometer is used to measure the cutting forces during machining. This instrument allows the measurement of the F_c, F_f and F_p forces, as defined by the standard [10]. The average cutting forces are calculated during steady state conditions. The specific cutting energy (k_c) represents the energy needed to remove a given volume of workpiece material. From the mean cutting force, the specific cutting energy