Experimental characterization of friction coefficients at the tool-chip-workpiece interface in cutting: Evaluation of lubrication efficiency of mineral oil

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Summary The characterization of friction coefficients at the tool-chip-workpiece interface remains an issue. This paper presents a new experimental set-up able to simulate similar tribological phenomena as the ones occurring at the tool-chip-workpiece interface. Especially, this system aims to reach contact pressures up to 3 GPa and sliding velocities between 0 to 1000 m/min, and to obtain an open-tribosystem (continuous regeneration of the tool-workmaterial contact). This system has been applied to the characterization of the tool-chip-workpiece interface during the cutting of an AISI4140 treated steel with TiN coated tools. Two environments have been tested: dry cutting, lubrication with a basic mineral oil. The effect of the mineral oil has been investigated.

1. INTRODUCTION

Many efforts are being undertaken to develop advanced machining processes using no coolant in order to eliminate problems associated with the cutting fluid management: waste generation, machining cost, parts cleaning, recycling of chips, health hazard, etc… However, the large majority of cutting operations till uses cutting fluid since manufacturing procedure and machines cannot be modified easily without a detailed technical and economical analysis. It is usually admitted that the basic functions of a cutting fluid are to provide cooling and lubrication and thus reducing the severity of the contact processes at the cutting tool-chip-machined surface interfaces [1] and to assist also in chips removal. However, the selection of the type of the cutting fluid for a particular machining operation is often based upon recommendations of sales representatives without clearly understanding the real mechanisms of their action. The basic attitude in industry consists in trying the new fluid in the machine without being able to control a large number of parameters such as application conditions, temperature, etc. So conclusions of such tests are often hazardous.

Another way of testing consists in using laboratory cutting tests in order to compare some macroscopic measurements such as forces and torque. One the most popular tests is the tapping torque test (ASTM D-5619), or the drilling test (ASTM A830-85) [2]. These methods may compare several fluids for a couple of materials (cutting tool substrate / workmaterial) but can neither provide the modification of the friction coefficient, nor explain the tribological mechanisms at the interface. It is basically a statement: better or worse. The conclusion is valid for the investigated cutting operation but it is not possible to extend them to other cutting conditions or to another cutting process (example: milling). So other authors have proposed to transpose this method to other cutting processes. For example, Cakir [3] and Jayal [4] use forces measurement to compare cutting fluids in turning whereas [5] investigated the influence of cutting fluids in mechanical actions in milling.

A huge number of authors prefer making wear tests to evaluate the performance of cutting fluids (example: [5-6]). Such tests are expensive, time consuming and very sensitive to little variation of any parameter.

However, all these cutting investigations do not enable to provide a full understanding of cutting fluid action, since each cutting operation induces specific tribological conditions at the tool-workmaterial interface. Moreover these tribological conditions are not predictable accurately in the current state of the art. So there is a great lack of elementary knowledge on metal machining tribology, which prevents intelligent decision-making in cutting fluid selection.

Based on this statement, a lot of laboratories have tried to use a more fundamental approach through elementary tribological tests. However, the problem is that the tribological conditions supported by the cutting fluid at the tool-workmaterial interface (contact pressure up to 3 GPa, temperature up to 800°C since Trent [1]) are not simulated by current laboratory tests. Usually, many properties, characterized by standard tests (viscosity, flash points, pH, etc.), relate to the cutting fluid maintenance rather than to the tribological characteristic of the metal cutting system. Different tests are also applied to evaluate metalworking fluids: the Pin and Vee method (ASTM D2625-94), the four balls wear test (ASTM D-4172), pin on disc test, etc… However, it is impossible to correlate these tests with the performance of the cutting fluid in metal cutting. The major problem is that, in rubbing tests, the continuous sliding contact occurs by cyclic reintroduction of the same surface element from the counter-material. On the contrary, after the strong plastic deformation occurring in the primary shear zone, a freshly formed surface made of workmaterial slides against the tool in the secondary shear zone as shown in Fig.1. Based on this statement, various researchers have developed specially designed tribometers in order to enable pins to rub a fresh surface [7-8] (Fig.2). However these tribometers have been used to characterize the influence of sliding velocity, contact pressure and cutting tool coatings, but they have never been applied to investigate the influence of cutting fluids.

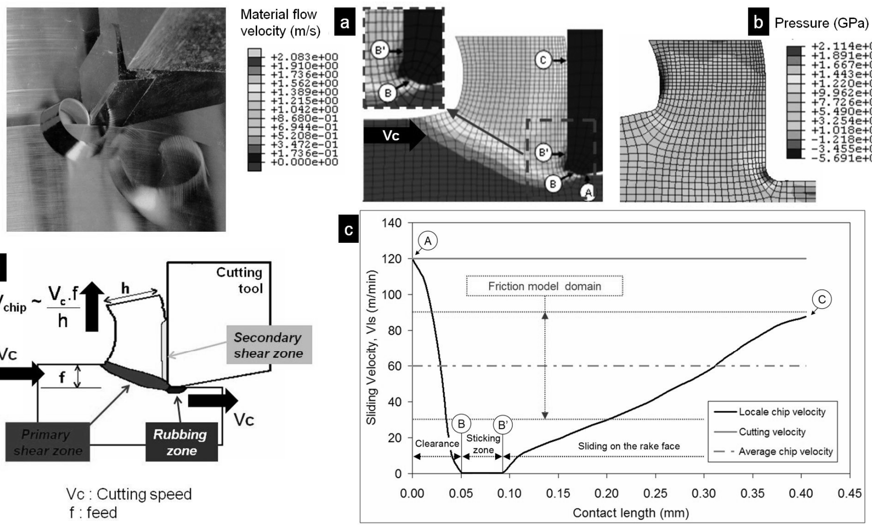

Fig. 1. Evolution of the sliding velocity and of the contact pressure along the tool-workmaterial interface in the case of a AISI316L machining operation at a cutting speed of 120 m/min [8]

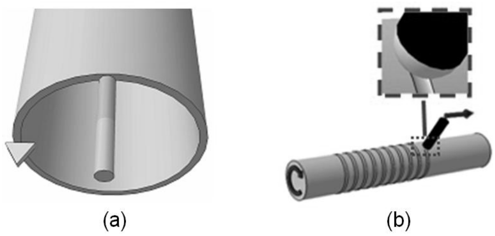

Fig. 2. Tribometers developed to characterize friction coefficient at the tool-workmaterial interfaces (a) Tribometer developed in [7]; (b) Tribometer developed in [8]

So, there is no evident method to investigate the influence of cutting fluids in machining and to provide a clear analysis and quantification of the various mechanisms occurring in each zone reported in Fig.3.

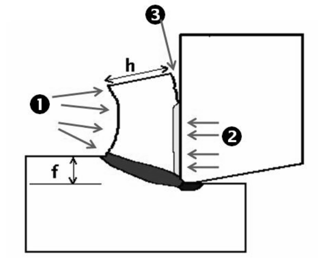

Fig. 3. Influence of cutting fluid in various zones

Without making extensive investigations, it possible to imagine the following actions:

- A cooling of the chip backsurface at 1, resulting in curl increase, which reduces the tool-chip contact length [9]
- A promotion of plastic deformation in the primary shear zone (see Fig.1) due to the pressure of cutting fluid applied in zone 3 [10-11]
- A contamination of the secondary shear (zone 2) from zone 3, by physical phenomena (adsorption, capillarity, vibration, etc.) leading to a decrease of friction coefficient and adhesion in the secondary shear zone. This idea supported by [12-13] but is rejected by [14] due to the very high contact pressure in the secondary shear zone (up to 3 GPa). Other authors, as [15], propose an intermediate explanation. They assume that workmaterial fills out even the microscopic valleys and hills at the beginning of the tool-chip contact area, which does not enable the cutting fluid to be present. At the rear of the contact, far from the cutting edge, the decrease of contact pressure should enable the penetration of cutting fluids through capillarities (Fig. 4). Then the cutting fluid may react with the chip to reduce friction. It is imagined that the maximum penetration results from a balance of two opposing transport mechanisms: the motion of the chip carrying the liquid out of the contact and the pressures driving them in (Fig. 5)
- A contamination of the secondary shear zone (zone 2) from zone 3, by chemical phenomena (chemisorption, evaporation, chemical reaction, etc.) leading to a decrease of friction coefficient and adhesion in the secondary shear zone. The evaporation theory is supported by [13], whereas the chemical reaction and chemisorption is supported by [16-17].

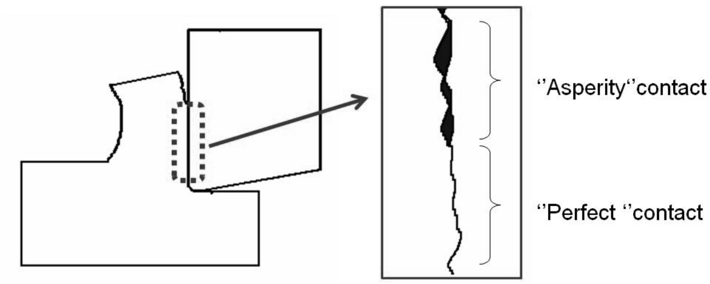

Fig. 4. Contact at the tool-workmaterial interface

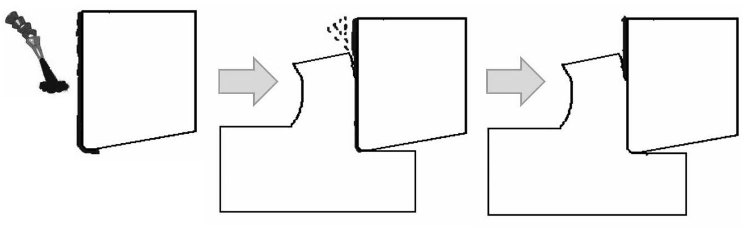

Fig. 5. Evacuation of the cutting fluid by mechanical action

Finally, without being able to prove it, a lot of authors support the idea that a cutting fluid can penetrate (or remain) the tool-chip interface for low cutting speeds only, whereas it may be vaporized at high cutting speed [18;15;1;13]. At high cutting speeds, they only consider the cooling effect of the workmaterial and of the cutting tool, as well as the flushing of chips.

So, there is an evident lack of understanding of the influence of cutting fluids along the tool-workmaterial interface. This statement leads specialists in modeling (numerical and analytical) of cutting processes to avoid the application of cutting fluids. It is only possible to mention some analytical models who have tried to introduce the influence of cutting fluids [19]. But they only consider an average friction coefficient along the tool-workmaterial interface. This assumption is far from the reality for two main reasons. First, they obtained the friction coefficient from pin on disc tests, which have been shown not to be able to simulate relevant tribological conditions. Second, as shown by [20], the local sliding velocity varies continuously along the interface and the friction coefficient varies very significantly with the sliding velocity. As an example, it varies from 0.6 (low sliding velocity) to 0.2 (high sliding velocity) in the case of a AISI4140 machined by a TiN coated carbide tool in dry conditions. So it is not possible to assume that the friction coefficient is constant along this interface.

As a consequence the objective of this paper is to quantify the influence of a cutting fluid for a large range of sliding velocity and for a high level of contact pressure in order to quantify the evolution of friction coefficient along the tool-workmaterial interface. For this purpose, a new tribometer, based on the system developed by [20], has been applied in order to simulate relevant tribological conditions. This system has been improved in term of rigidity and sliding velocity in order to cover a wider range of tribological conditions and to simulate more efficiently phenomena occurring close to the cutting edge (low sliding velocity and high contact pressure and regeneration of the contact).

The paper focuses on the machining of a AISI4140 steel (290HB) machined with a TiN coated carbide tool. Two configurations of lubrication have been considered:

- dry conditions
- lubrication with a basic straight oil

Among the cutting fluids available in the market, straight oils do not contain water. They are supposed to perform best in heavy duty machining operations where the lubrication effect is of primary importance: broaching, threading and tapping. Straight oils do not work well in high speed cutting operations because they do not dissipate heat effectively.

So the purpose of this article is to clarify and to quantify the influence of straight oils on friction coefficient for a large range of sliding velocity simulating the machining of AISI4140 steel with a TiN coated carbide steel.

2. EXPERIMENTAL SET-UP

The principle of the tribometer has already been applied and validated for several previous works [8;20] already published (Fig. 6). The workmaterial is simulated through a cylindrical bar made of steel AISI 4140 (290 HB). Cutting tools are simulated through pins made of cemented carbide with a similar grade to the one used for cutting tools dedicated for AISI4140 steel machining (90% WC – 10% Co – average grain size ∼ 0.8μm).

In order to eliminate the potential influence of surface roughness, pins have been polished to reach a low surface roughness (R_a < 0.3 μm) which is coherent with a typical surface roughness on a finely ground carbide cutting tool. Pins have been coated with TiN coating deposited by (PVD – cathodic arc – ∼2μm – monolayer).

Concerning bars, after each friction test, a cutting tool refreshes the surface ploughed by the pin. A belt finishing operation is also performed in order to obtain a very low surface roughness (R_a ∼ 0.1μm) and a constant surface for each test.

Each friction test has 20 seconds duration approximately.

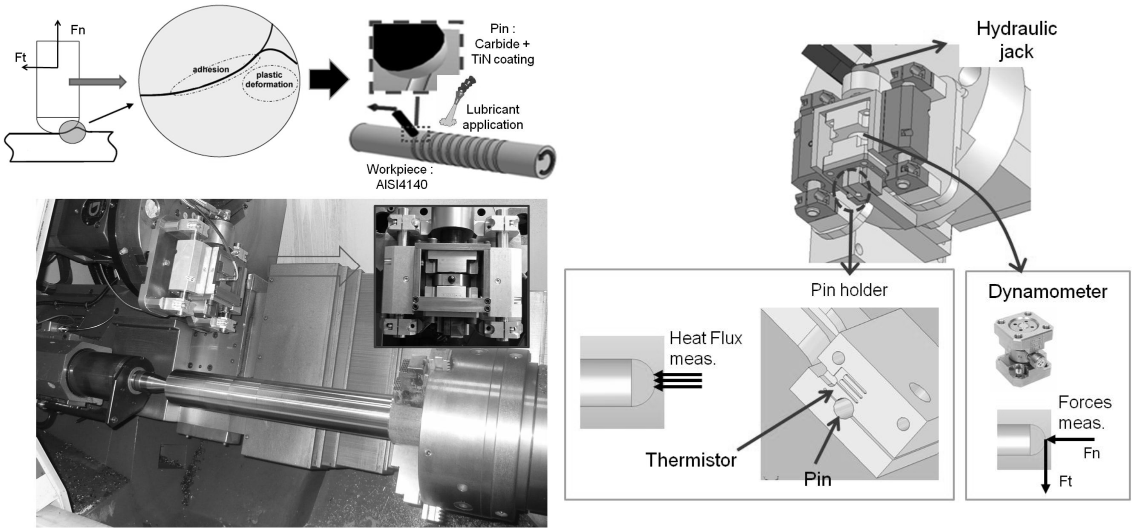

Fig. 6. Design of the tribometer developed

Compared to the tribometer developed by [8;20], the new tribometer is based on a CNC lathe instead of manual lathe (Fig. 6). The pneumatic jack is replaced by a hydraulic jack. The mechanical structure and the instrumentation of the tribometer have also been modified. The new version has much higher stiffness in order to measure friction coefficient under extreme contact pressure and very low sliding velocities. Finally, the new version enables to apply a cutting fluid under defined conditions (pressure, orientation, flow rate, temperature, etc.).

The pin is maintained by an instrumented pin-holder which is able to provide data about the instantaneous heat flow (Ø) entering into the pin. Readers interested in having details about this heat flow measuring system should read the work of [7]. The pin-holder is fixed onto a dynamometer in order to provide the normal force F_n and tangential force F_t (macroscopic forces). The apparent friction coefficient is provided by the ratio between the tangential and the normal forces, taken as an average value of the stable zone.

$$\mu_{app} = \frac{F_t}{F_n} \tag{1}$$

The term 'apparent friction coefficient' is used since it differs significantly from the 'local friction coefficient' induced by adhesion at the pin-workmaterial interface (Fig. 6). In deed the macroscopic forces measured by the tribometer include the friction phenomena (adhesion) and the plastic deformation of the workmaterial, which cannot be neglected under such severe contact conditions (F_n ~ 1000 N). As stated by [20], a pin having a diameter 9 mm lead to an average contact pressure around 3.5 GPa for a AISI4142 steel which is a similar microstructural state than the AISI4140 steel. The order of magnitude of contact pressure is coherent with typical values obtained during machining of steels (Fig. 1).

The apparent friction coefficient previously introduced (1) could be decomposed into two components [21]:

$$\mu_{app} = \frac{F_t}{F_n} = \mu_{app} + \mu_{def} \tag{2}$$

where μ_{adh} is the adhesive part and μ_{def} is the deformation part.

To extract the part of adhesion and deformation from the apparent friction coefficient, it is possible to use an analytical model developed by [21]. This model is independent of contact material properties and is based on the following hypothesis:

- The pin is considered to be infinitely rigid
- The workmaterial has a perfectly plastic behavior (no spring back)
- The contact surface is the frontal part of the hemispherical pin

3. DESIGN OF EXPERIMENTS

In this work, two variables have been investigated:

- A range of sliding velocities: from 10 to 300 m/min, corresponding to the range of sliding velocities observable during the machining of a AISI4142 steel
- The application of a straight oil

For each test, the lubrication is applied on the workmaterial before the application of the pin. At the end of the rubbing test, the pin is moved away. Then the lubrication is switched off.

Each test configuration has been replicated at least three times.

4. EXPERIMENTAL RESULTS UNDER CONTINUOUS LUBRICATION

The evolution of μ_{app} versus sliding velocity is plotted in Fig. 7. It is remarkable to see the huge difference between dry sliding and lubricated sliding.

For dry sliding, μ_{app} decreases very significantly from ~0.6 to 0.2. Adhesions are important on pins under low sliding velocities as observed in Fig. 8. This explains the large deviation of the experimental results in this range of sliding velocities. Since 60 m/min to 250 m/min, adhesions are more limited and the deviation of μ_{app} decreases. Over 300 m/min, it is no use to conduct tests because of the rapid wear of pins observed after some seconds (Fig. 8): the coating is removed. These results are in accordance with previous results already published by [20].

On the contrary, sliding tests, conducted with straight oil, lead to very low values: μ_{app} ~ 0.1. Moreover μ_{app} is constant irrespective of the sliding velocity. Adhesions on pins are very limited as shown in Fig. 8. No wear is observable even for the largest value of sliding values (300m/min). This shows that straight oil is able to penetrate the contact even if the contact pressure is very high (~2 – 2.5 GPa since [20]).

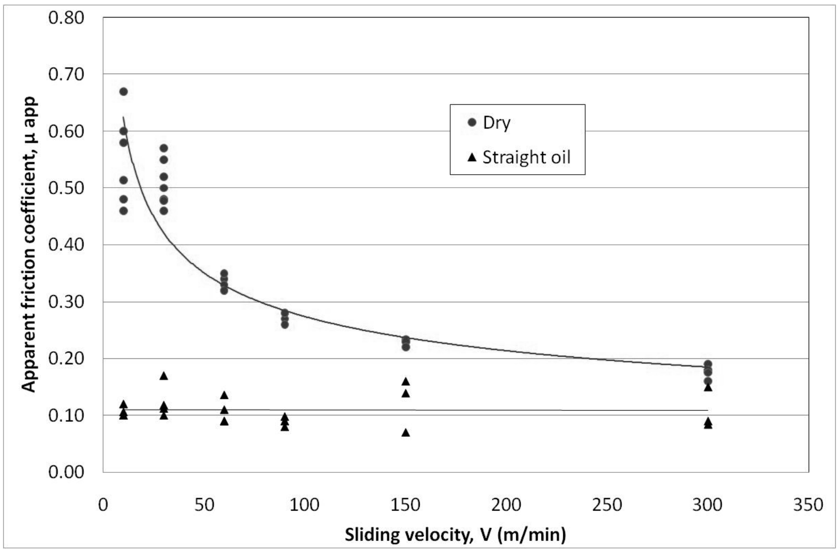

Fig. 7. Evolution of apparent friction coefficient versus sliding velocity

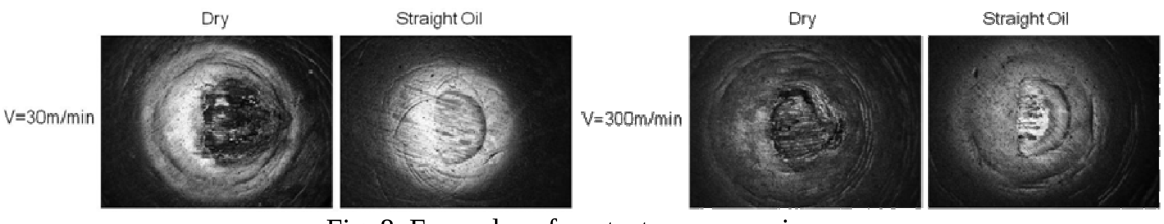

Fig. 8. Examples of contact zones on pins

As mentioned in the previous section, the adhesive friction coefficient (μ_{adh}) can be extracted from μ_{app} by applying the analytical model developed by [21]. Fig. 9 plots the evolution of the average adhesive friction coefficient versus sliding velocity. The general trend remains similar even if the values are something smaller.

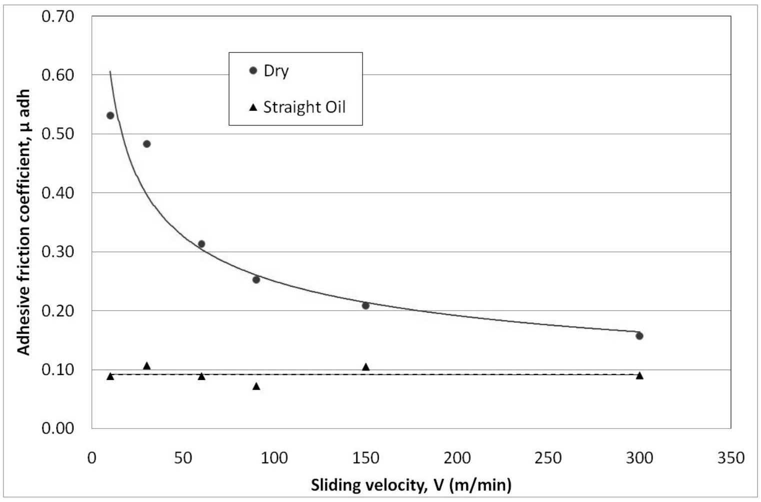

Fig. 9. Evolution of adhesive friction coefficient versus sliding velocity

During tests, the experimental set-up enables also to measure the heat flux transmitted to pins ($Ø_{pin}$). Fig.10 plots the evolution of $Ø_{pin}$ versus sliding velocity for the three lubrication conditions.

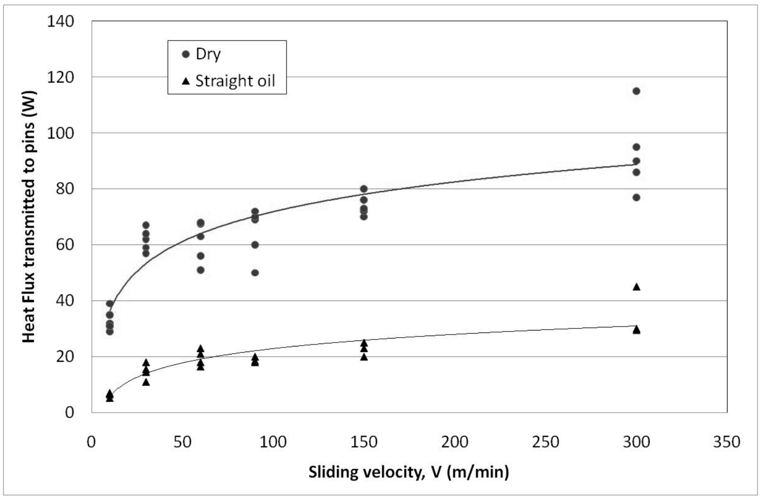

Fig. 10. Evolution of heat flux transmitted to pins versus sliding velocity

Before making some analysis of Fig. 10, it is necessary to make some statements. Indeed, $Ø_{pin}$ is only part of the total amount of energy ($Ø_{tot}$) dissipated during tests. During dry friction tests, a large amount of heat remains in the workmaterial as shown by [20]. Additionally, in the case of lubricated tests, straight oil evacuates a significant part of this heat. So, it is possible to estimate the percentage of heat transmitted to pins (α).

In a first step of analysis, it is possible to estimate the total energy $Ø_{tot}$ by:

$$Ø_{tot} = F_t \,.\, V \tag{3}$$

where F_t : tangential force (N) and V : macroscopic sliding velocity (m/s)

By assuming that all the frictional energy is fully transformed into heat, α can be estimated by:

$$\alpha = \frac{\phi_{pin}}{F_t . V} \tag{4}$$

This means that α% of the energy is transmitted to pins, whereas the workmaterial and the straight oil evacuate (1-α)% of this energy. Theoretically, in dry sliding, α depends on the effusivity of the two materials when sliding at a very low velocity (some mm/s). Unfortunately, for dynamic sliding interfaces, the standard thermal models are no more valid as shown by [8]. So, Fig. 11 reports experimental data, which are much closer to the reality.

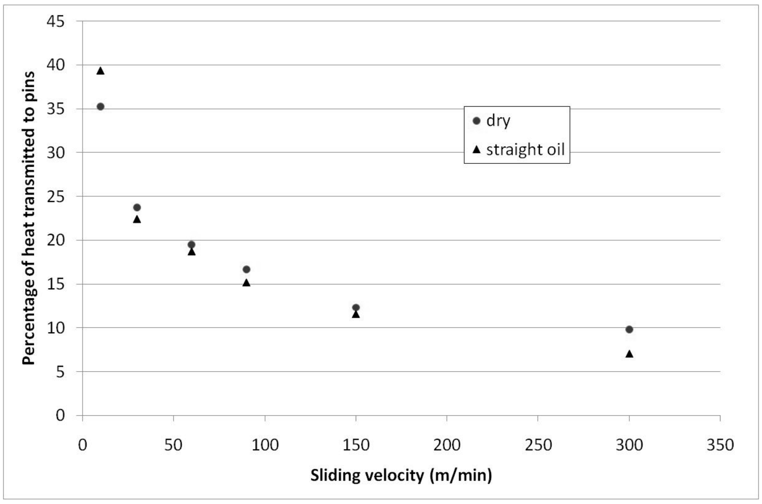

Fig. 11. Evolution of the percentage of heat transmitted to pins versus sliding velocity

Based on these statements, it is possible to analyse the experimental results. First it appears that $Ø_{pin}$ increases with sliding velocity. The curvature of the curve is not linear due to the evolution of α and μ_{adh} with sliding velocity, which contribute to limit the curvature. This result is in accordance with previous analysis made by [20] in the case of a AISI4142 steel.

Second, it appears that the deviation of the measurements is rather high. However this deviation is much smaller than the difference observed between the two configurations. Indeed, the application of a lubricant leads to a huge decrease of the heat transmitted to pins. The reason originates from two phenomena: the decrease of friction coefficient or the modification of heat partition (parameter α). As shown in Fig. 11, the evolution of the percentage of heat transmitted to pins exhibits almost no difference between dry and lubricated tests. This shows that straight oil does not modify the transmission at the interface. So the difference of heat flux highlighted in Fig. 10 is only due to a modification of friction coefficient.

Additionally, it appears that the percentage of heat transmitted to pins varies with sliding speed. This enables to conclude that heat partition coefficient along the tool-workmaterial interface has to be dependent on the local sliding velocity as shown in Fig.1

These results contribute to clarify the question of the influence of oil in metal cutting. It confirms that the influence of oil is much more important for low sliding velocities, which has already been reported in the literature [18;15;1;13]. But, it is also shown that this lubrication effect remains very significant for large sliding velocities. As observed in Fig. 7, the apparent friction coefficient μ_{app} decreases from 0.2 to 0.1 in average under a 300 m/min sliding velocity. These new quantitative data will now enable scientists to consider the influence of lubrication in numerical modeling.

5. EXPERIMENTAL RESULTS UNDER DISCONTINUOUS LUBRICATION

However, another question remains: how fast can a lubricant penetrate in a contact? How long can he stay and act in this contact? These questions are of primary importance in metal cutting especially when comparing a continuous or discontinuous cutting operation. Fig. 12 plots the evolution of friction coefficient when adding lubrication for a very low sliding speed. It can be seen that the penetration duration is very low. Fig 13 plots the evolution of the penetration duration versus sliding speed. It reveals that the penetration duration varies between 0.6 to 0.2 s when increasing sliding speeds. This confirms that straight oil penetrates easily and rapidly into the contact.

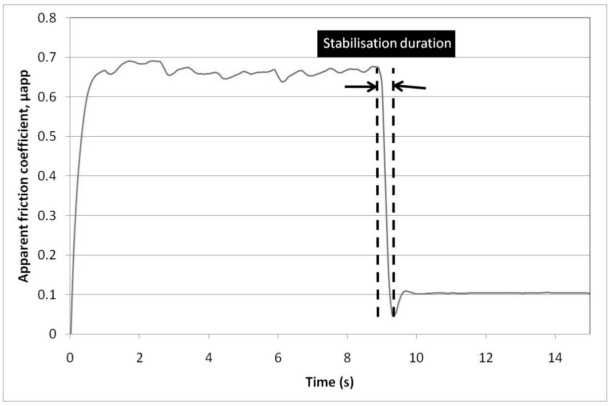

Fig. 12. Evolution of the friction coefficient when adding lubrication (V=10m/min – straight oil)

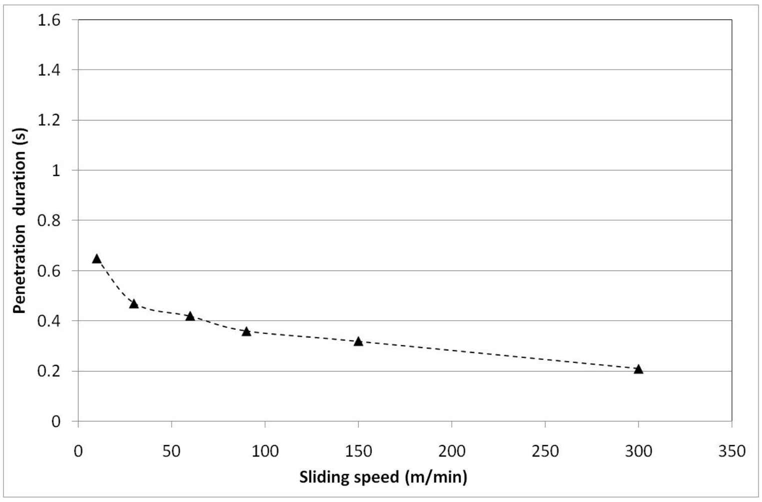

Fig. 13. Evolution of the penetration duration when adding lubrication versus sliding velocity

Fig. 14 shows the evolution of friction coefficient when stopping lubrication for the same sliding speed as in Fig. 12. It appears that friction coefficient increases rather rapidly but not suddenly. The influence of straight oil remains during more than a second. So it can be stated that oil has much more difficulty to be evacuated from the contact than to penetrate the contact. Fig. 15 plots the evacuation duration versus sliding speed. It reveals that, below 150 m/min, straight oil is able to remain in the contact. On the contrary, over 150 m/min, the evacuation duration is almost instantaneous.

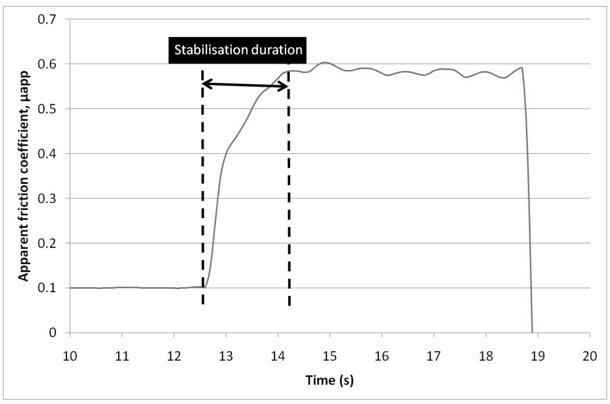

Fig. 14. Evolution of the friction coefficient when stopping lubrication (V=10m/min – straight oil)

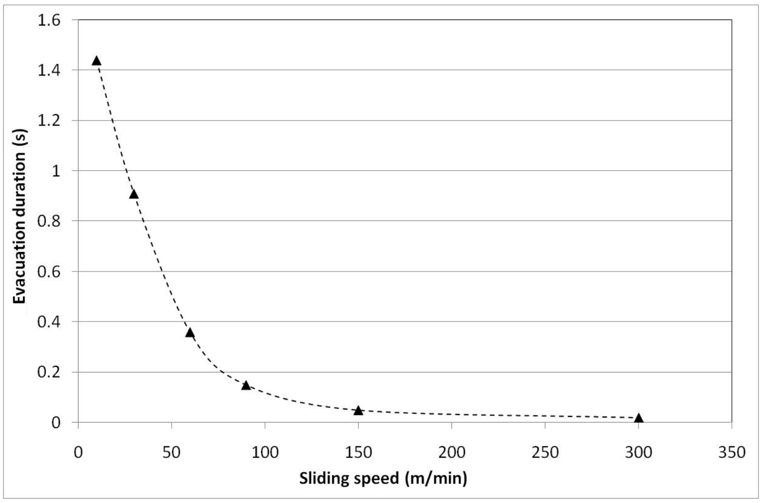

Fig. 15. Evolution of the evacuation duration when stopping lubrication versus sliding velocity

This observation shows that, when considering a continuous cutting operation such as turning, oil is not able to remain in the contact since it is evacuated within some tenth of seconds. This duration is almost negligible compared to cutting durations (several seconds). It is doubtful if straight oil can lubricate the contact as shown in introduction. However the cooling and flushing effects remain.

On the contrary, when considering interrupted cutting operations such as milling, it is possible to imagine that oil is able to remain in the contact during a large percentage of the cutting time. So the lubrication effect of straight oil can be clearly significant.

5. CONCLUSIONS

This paper has investigated the influence of a straight oil on the friction coefficient at the tool-workmaterial interface during the machining of a AISI4140 steel with a TiN coated carbide tool. The investigation is based on a new tribometer dedicated to the characterization of friction coefficients under extreme conditions relevant to the ones supported in metal cutting.

The experimental set-up has shown that friction coefficient varies from 0.5 to 0.15 in dry sliding when increasing sliding velocity from 10 to 300 m/min.

It has also been shown that a straight oil lead to huge decrease of friction coefficient under low sliding velocities (V < 150 m/min) compared to dry sliding. Moreover it has been revealed that friction coefficient under lubrication remains constant around 0.1 irrespective of sliding velocity.

Heat flux measurements have shown that the presence of oil does not modify the percentage of total heat transmitted to pins whereas it decreases very significantly the amount of heat transmitted to pins (absolute value) irrespective of sliding velocity. Additionally, it has been shown that the percentage of heat transmitted to pins varies with sliding velocity.

Finally, it has been shown that oil is able to penetrate instantaneously rapidly even if contact pressures are enormous (> 2 GPa). Then penetration duration decreases with sliding speed.

On the contrary, it has been observed that oil is able to remain approximately 1 second for low sliding velocity (< 100 m/min), whereas oil is immediately evacuated for faster values.

So this paper has contributed to provide quantitative data about the influence of a straight oil during a metal cutting operation, which is of high importance to improve numerical models in terms of friction coefficient and heat partition coefficient along the tool-workmaterial interface.

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