EVALUATION OF PERFORMANCES OF A DLC (DIAMOND LIKE CARBON) COATED END MILL, BY A NEW SYSTEM OF CUTTING ANALYSIS (SCCU).

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Abstract

Diamond Like Carbon (DLC) coating is a new coating with very promising performances. Dixi-polytool, manufacturer of tungsten carbide tools, intends to use this coating, if its performances are economically better than the current coating used by Dixi Polytool

Usually, a set of machining trials is needed. Nevertheless it is well known that the interpretation of machining trials isn't an easy job because the factors measured or observed are insufficient for an accurate evaluation of the efficiency of the chip formation.

This paper presents a new system of cutting analysis (SCCU, developed and patented by the Laboratoire de Machine - Outils of the HE-Arc-Ingénierie University Of Applied Sciences , Le Locle, Switzerland), which allows a better understanding of cutting conditions and machining results. Indeed, through the acquisition of cutting forces and the processing of the acquired data, the system is able to compute non-measurable factors as average and instantaneous values of friction coefficient, shear angle, power dissipated for friction on the primary friction zone and on the secondary friction zone, power used for chip formation on the shear plane . . . etc. Also, the understanding of the cutting conditions and machining results is better

In order to evaluate the performance of DLC coating, a comparative trial between an uncoated and a DLC coated tool has been made, with the SCCU system, in the case of shouldering of electrolytic copper.
The results shows the interesting properties of DLC coating observed through the capabilities of the SCCU monitoring system.
It appears also that DLC coating generates an important reduction of different components of the power dissipated, especially the power due to the friction on the primary friction zone. Moreover the paper describes the trends of different components of power during the machining.

1 Introduction

During machining of non ferrous material (N Iso class), the temperature is moderate but the trend to generate a building up edge is very high. Then a sharp edge and lower friction coefficient on tool are needed. The properties of DLC coating (High hardness, low friction coefficient) offer excellent resistance against adhesion and wear. These advantages are particularly useful during non ferrous material machining. However a lot of DLC coating lacks of coating adhesion required in hard environment of cutting tool.

These new DLC coatings represent a great interest for Dixi Polytool. Then two different DLC coatings are chosen for the tests. As a rule, the wear is measured after a given machining time. The wear is generated by a lot of parameters such chip adhesion, temperature, abrasion . . . etc.. Unfortunately the wear measurement produces a very difficult interpretation of results. The interpretation of wear mechanism could be false.

A new system of cutting analysis (SCCU) has been developed by the machines tool laboratory. It allows a very accurate analysis of cutting during machining. Indeed, a lot of unknown factors are computed such friction coefficient, shear power, friction power, etc, during non orthogonal cutting (milling).

On one hand, Dixi Polytool wants to have a better analysis of wear mechanism during a comparative test of DLC coating and on the other hand, this new system of cutting analysis has been further validated through the test campaign. Then a common project between Dixi Polytool and Machine tool Laboratory of HE-Arc has been carried out. The aim of this project was to use the SCCU system during comparative tests of DLC coatings.

2 Description of the system for the « Monitoring and analysis of the cutting » (SCCU)

The literature, and also the market, offer a large spectrum of systems based on the simulation of the cutting and the chip formation. Several laboratories and researchers developed methods for calculating cutting forces starting from the definition of the material to be cut and the cutting conditions. There are several methods, formulas and system available on the market and on the literature.

We (the “Laboratoire de Machines-Outils of HE-ARC”), moved in the opposite direction: starting from the measurement of the cutting forces we described the cutting conditions. We rebuilt a model of the chip formation starting from empirical measurements and not from analytical predictions.

The system we developed is named SCCU (“Surveillance de la coupe et caractérisation de l’usure”: “cut monitoring and wear characterisation”). Starting from the measurement of the cutting forces (obtained from dynamometric piezo tables) and from the knowledge of the tool geometry, position and cutting conditions (ae, ap, Vc, etc.), the system is able to give:

- Instantaneous and average power dissipated on the primary friction zone.
- Instantaneous and average power dissipated on the share plane.
- Instantaneous and average power dissipated on the secondary friction zone.
- Total instantaneous and average power dissipated.
- Friction angle and coefficient on the rake face

More in detail the system acts as follows:

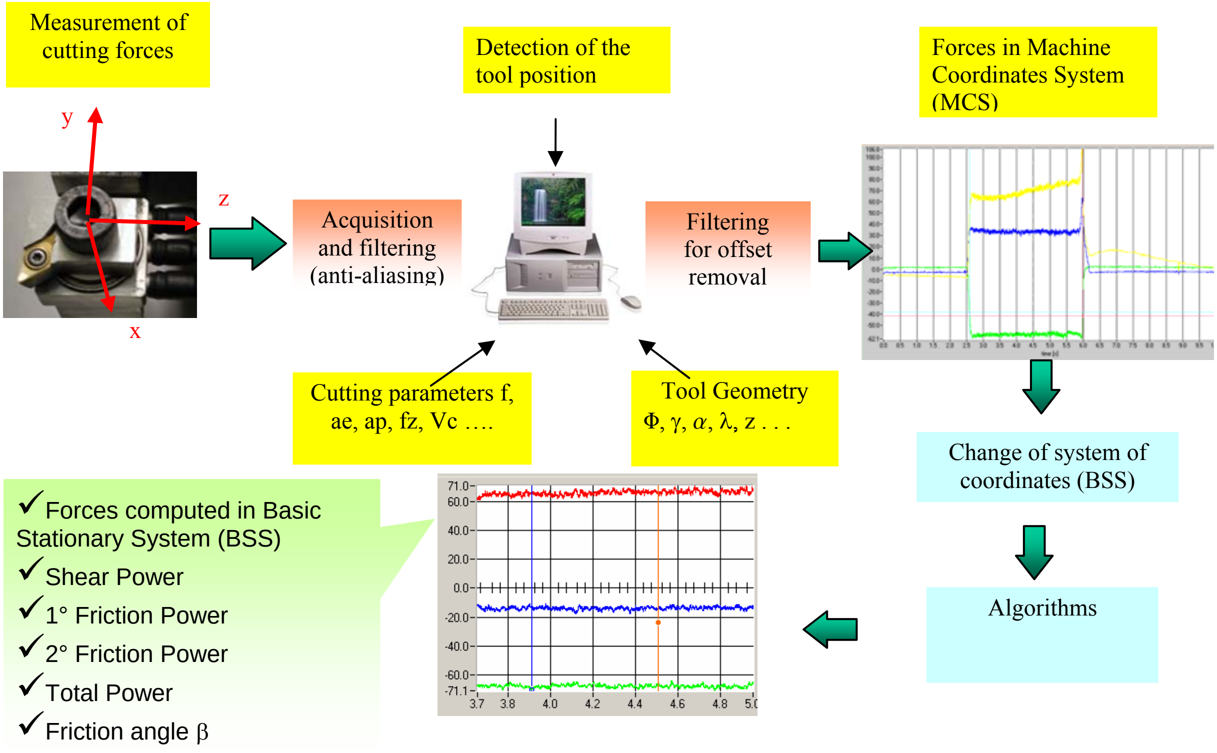


Figure 1 – General structure of the SCCU system

1) The forces are acquired at a sampling frequency until 125 KHz and filtered against aliasing. Then the offset (produced by the amplifier of the piezo sensors) is removed.

2) The components of the force are represented in the coordinates of the sensor which is oriented in order to reproduce a machine axes coordinate system (MCS).

3) The forces are translated from the MCS to a coordinate system based on the cutting edge: the Basic Stationary System (BSS). In the case of milling, the instantaneous position of the tool needs to be known for this translation. It is measured through an optical device as per the schema in the figure.

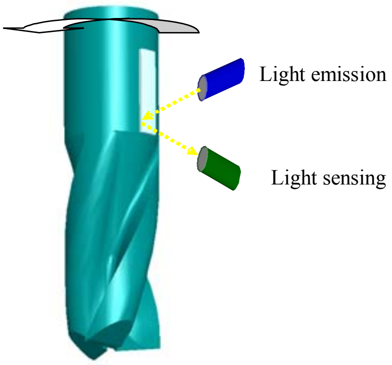


Figure 2 – detection of the tool orientation.

4) The formulas, available in the literature, allow the estimation of the velocities (on the share plane, on the rake surface . . . etc.) and in consequence we obtain the powers (Ps, Pf and Ptot).

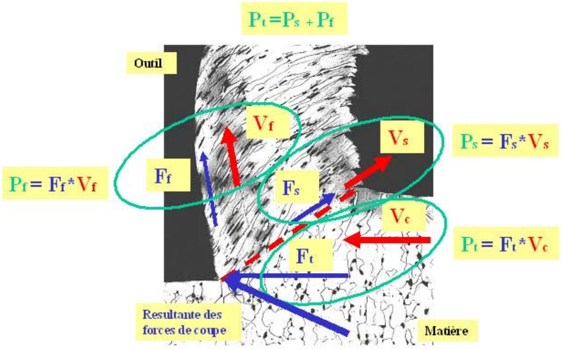


Figure 3 – Decomposition of the power

We have to point out that the total instantaneous power is computed and not calculated as sum of its components (power dissipated on the primary friction zone (Pf) and power dissipated on the share plane, (Ps)). The very first tests pointed out the fact that the total instantaneous power (Ptot) is always just a bit bigger than the sum of Ps and Pf. The difference is due to the friction on the secondary friction zone (the friction on the clearance face).

Therefore we are able to compute the power on the secondary friction zone (Pf2) as the difference:

$$P_{f\_2} = P_{Tot} - (P_S + P_F) \qquad (1)$$

The system is conceived in order to be installed closed to any machine and in an environment typical of a common shop floor.

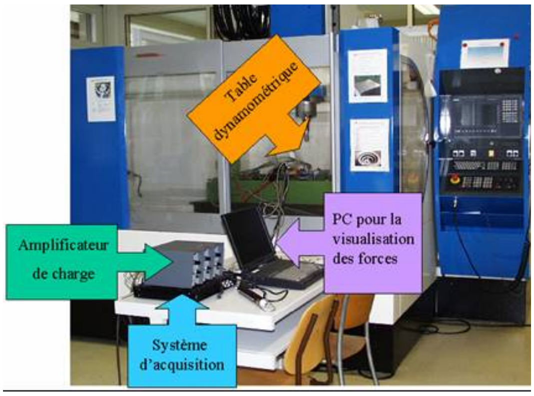


Figure 4 – SCCU system applied on a machine

3 Coating description

In the majority of case, the DLC coating properties offer a very low friction coefficient and a good hardness, but the maximal temperature of use is lower than standard PVD coating. For these reason, DLC coating are more and more proposed for the machining of non ferrous metal, which have a high trend to generate a building up edge (brass, electrolytic copper, aluminum <10% silicon). Thereto, the prices of the DLC coating are lower than polycrystalline coating. It's due to the deposition process.

Dixi Polytool SA has chosen two kind of DLC coating. The first coating (A) is obtained by a patented process based on the PVD process with pulsed and filtered method. With this process, a tetrahedral amorphous carbon layer is obtained (refer to figure 5).

The second coating (B) is obtained by a PACVD method (Plasma-Assisted Chemical Vapor Deposition). With this process, an amorphous carbon-hydrogen layer is obtained (refer to Figure 5).

The physical properties are described on the Table 1, properties of carbon based coatings.

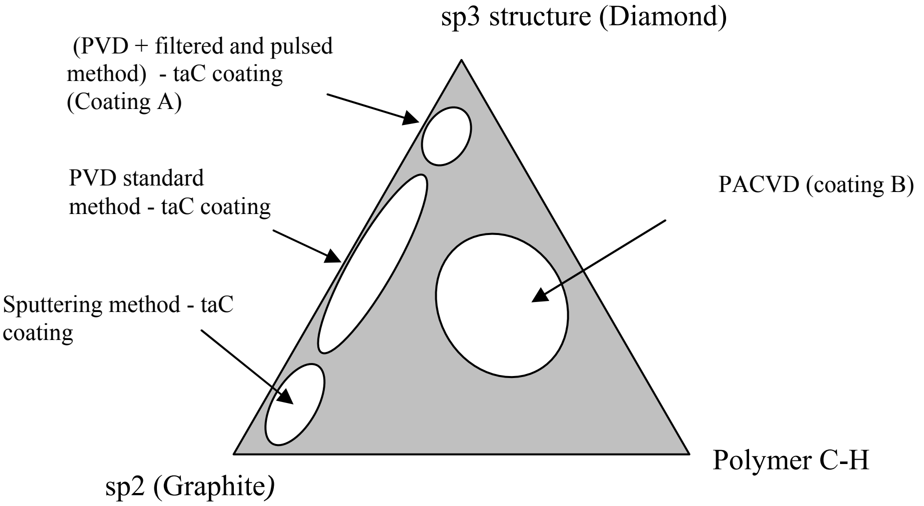


Figure 5, possible structures of carbon

Type of coating	*Diamond coating*	*Coating A*	*Coating B*
Process	*CVD*	*PVD arc+ filtered and pulsed*	*Plasma-Assisted Chemical Vapour Deposition*
Composition	*100% carbon*	*100% carbon*	*70% carbon -30% hydrogen*
% sp3	*100*	*85-95*	*40-60*
Maximal use temperature	*600*	*500*	*300*
Friction coefficient	*0.15*	*0.1*	*0.1*
Cost	*> 8x more expansive than standard PVD coating (TiAlN)*	*Similar to standard PVD coating for little diameter (∅1mm) . 2-3 more expansive than standard PVD coating for important diameter (∅8mm)*	*Similar to standard PVD coating (TiAlN)*

Table 1, properties of carbon based coating

4 Analysis of the tests, using the SCCU system

The purpose of these tests is to demonstrate the efficiency of DLC tools compared to uncoated tools and moreover to compare the two coatings DLC (made by the two different technologies). The used machine is a milling machine 3 axes located in the laboratory of machine tools of the HE-Arc-Ingénierie. The cutting conditions of the tests are:

ap = 4mm
ae = 2mm
Vc = 300 m/min (S = 24000 t/min)
Vf = 1000 mm/min (fz = 0.021mm)
End mill DIXI 7242 diam 4mm (z = 2)
Material: Electrolytic copper (2.0040)

The cutting parameters, the tool geometry and carbide were the same for the three tools used.

The cutting conditions involve a frequency of 800 Hz definitely below the first own frequency of the dynamometric table.

The first graph (figure 6) shows the evolution of total cutting power (Ptot) absorbed to remove material

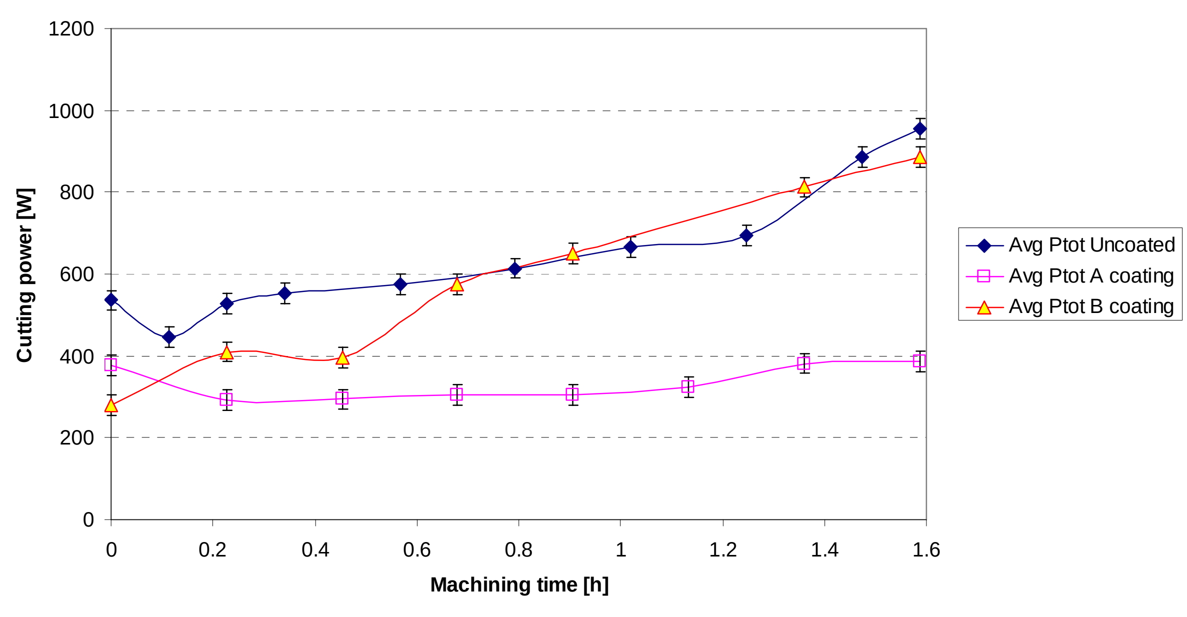


Figure 6 – Trend of the total mean power (Ptot).

The increasing total cutting power is a consequence of the increasing wear of the tool. The figure shows a big advantage offered by the A coating. Nevertheless we observe also a reduced cutting power at the beginning of the test on the B coating. After 0,7 hours of machining the B coating appears to be identical to an uncoated tool

The second graph (figure 7) shows the variation of power dissipated for friction on the primary friction zone.

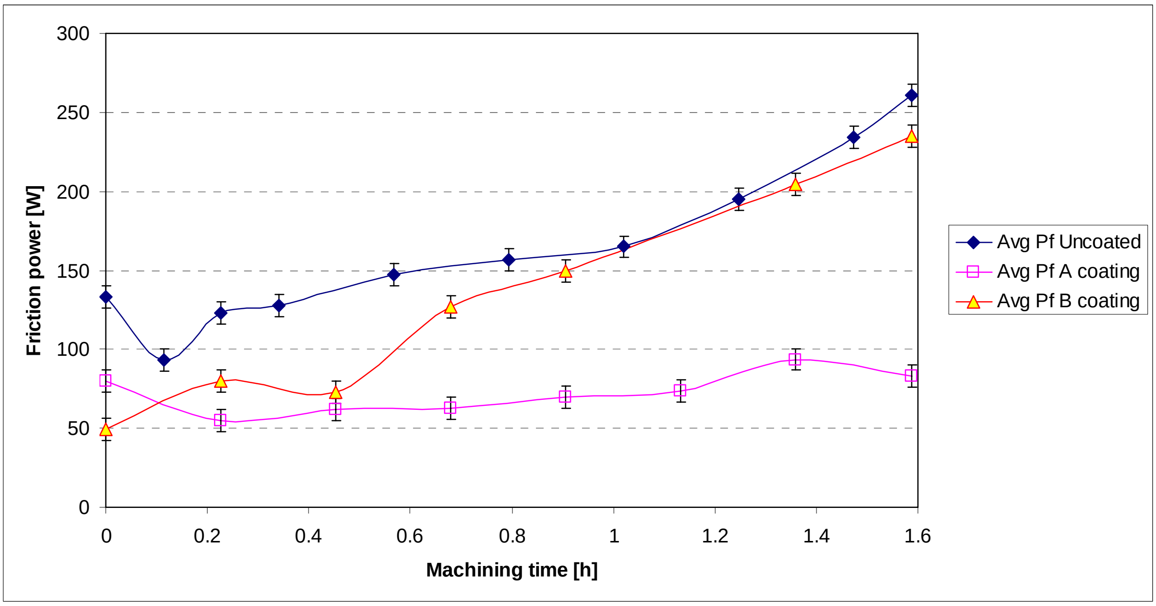


Figure 7 – Trend of the mean power dissipated for friction on the rake face (Pf).

The trend is very similar to that of the total power. This fact shows that the DLC coating B looses its tribological properties during the machining. At the opposite the A coating keeps its tribological properties during the time of machining.

The third graph (figure 8) shows the power used to shear the chip.

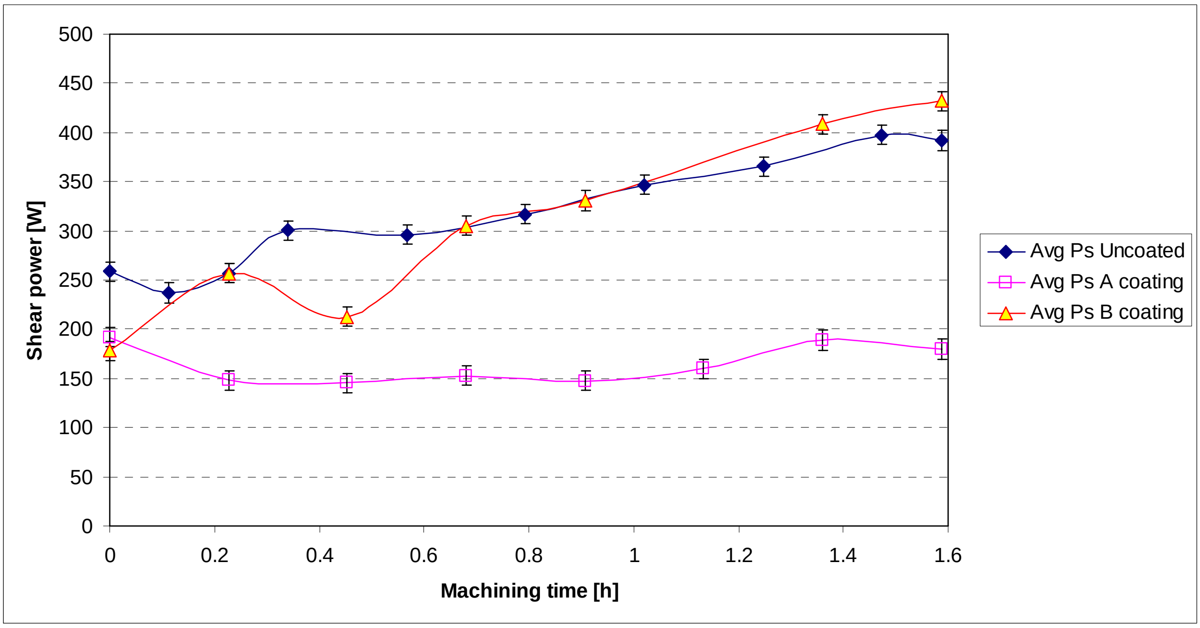


Figure 8 – Trend of the power used for the shearing of chip.

At the beginning of machining, both DLC generate the same shear power. In addition the differences between the mean powers due to shear are closer than in the previous cases. In this case the difference at the beginning of the machining is 28%, against 64% in case of power due to friction).

In addition we observe that the mean power due to the shearing is rather similar in the case of uncoated tool and B coated tool, during the machining.

The reduced shear power showed by the A coated tool, is probably due to the very low wear (see images in the table 2).

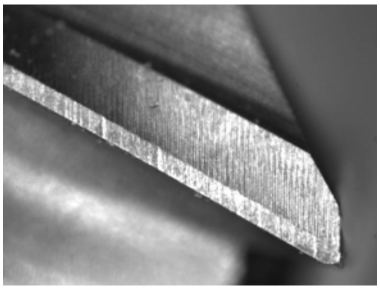
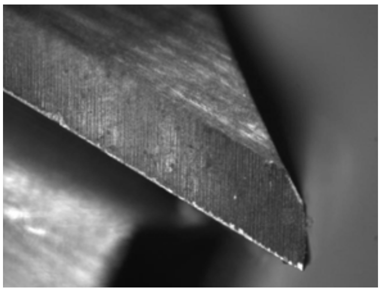
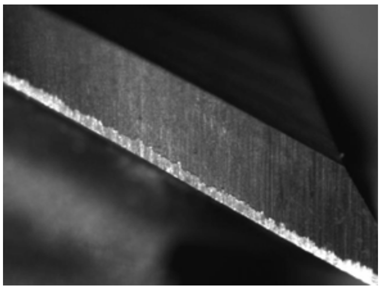
Uncoated tool	*A coated tool*	*B coated tool*
		

Table 2 – Tool wear after 1.6 hours of machining

The fourth graph (figure 9) shows the power dissipated on the secondary friction zone.

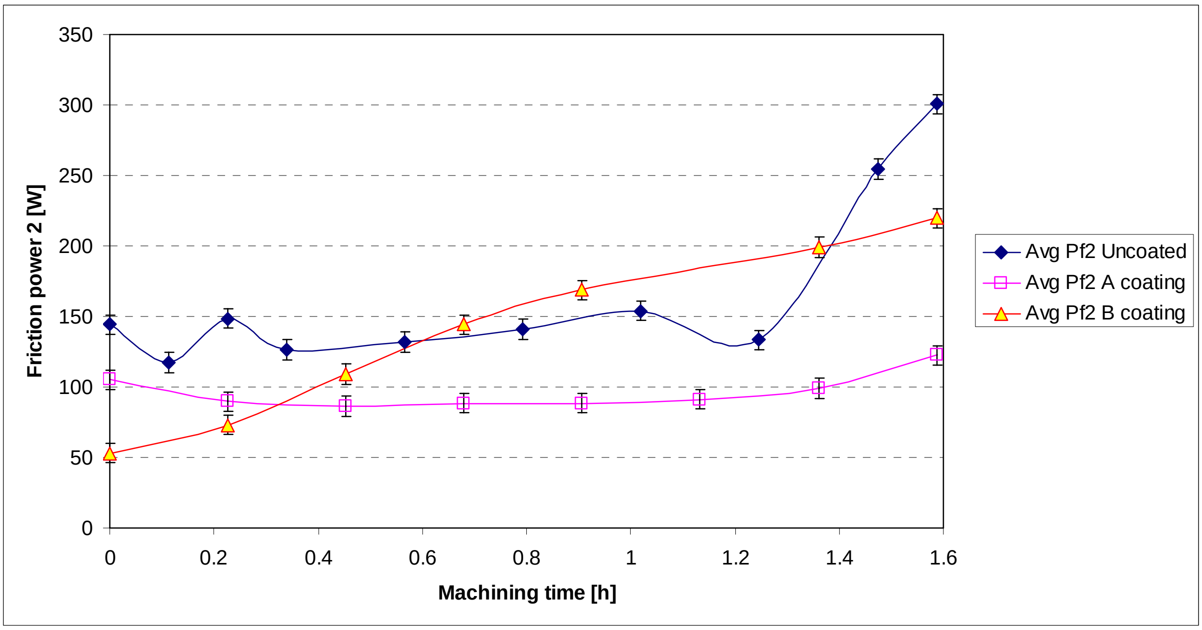


Figure 9 – Trend of the mean power dissipated for friction on the clearance face (Pf2).

This power is mainly influenced by flank wear. Therefore the measurement of the power dissipated on the secondary zone gives a good indication of the flank wear. This wear is very important on the uncoated tool while the A coated tool keeps a sharp edge.

The firth graph (figure 10) shows the friction angle: β.

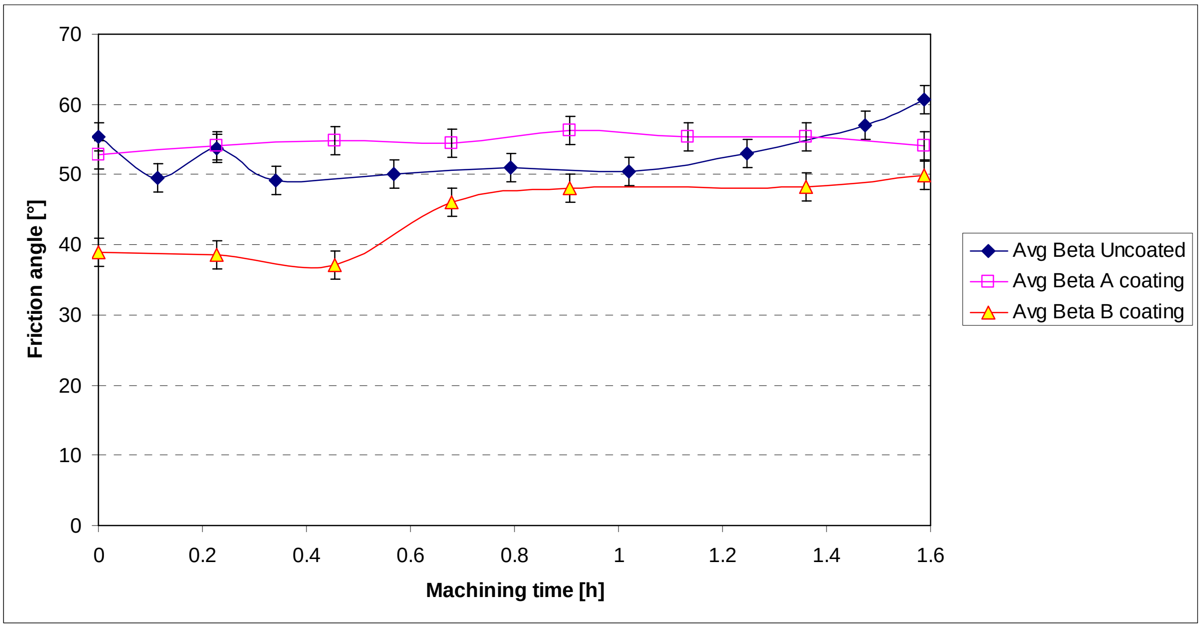


Figure 10 – Trend of the friction angle.

Even the coating A produces a reduced power compared to the B coating, the friction angle is lower for the B coated tool. (Refer to equation (2) for the friction angle)

$$\beta = Arc\tan(\mu) \qquad (2)$$

The sixth graph (figure 11) shows the angle ϕ defining the shear plane.

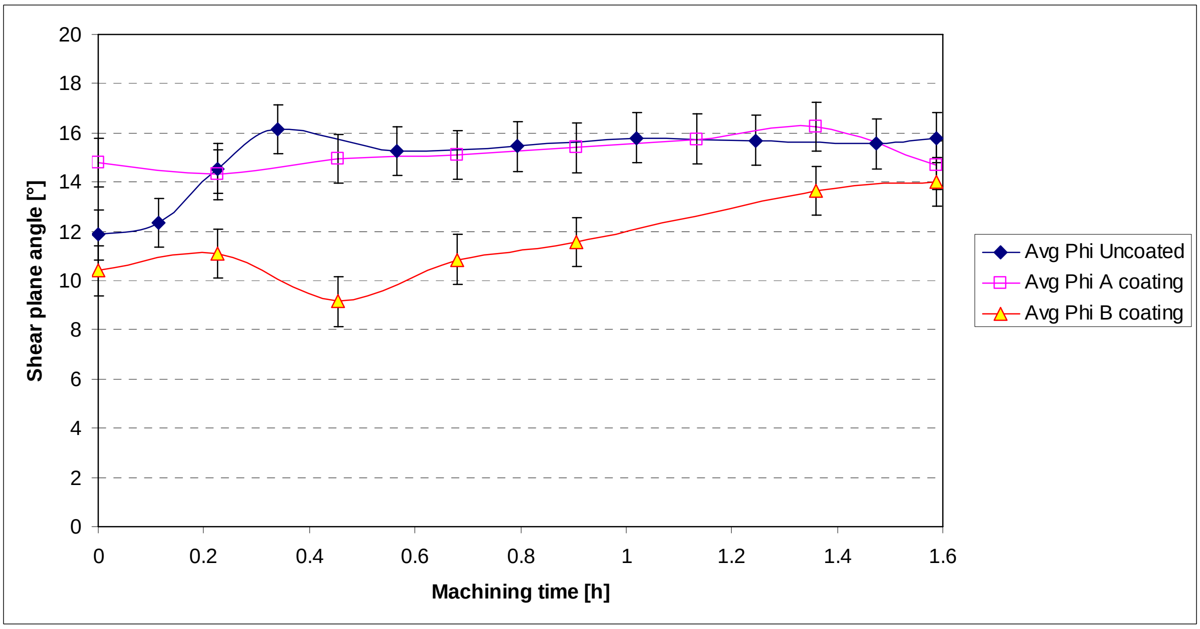


Figure 11 – Trend of the angle defining the shear plane ϕ

As well known, ideal would be at 45°. Therefore the A coating offers better results than the B coating. Notice that the values of the ϕ angle have been verified through the measurement of the depth of the chip. This measurement allows the definition of the ϕ angle through the formula (3) and (4).

$$r_c = \frac{h_0}{h_1}. \qquad (3)$$

$$\phi = \arctan\left[\frac{\cos(\eta).\cos(\gamma).recal}{\cos(\lambda) - \cos(\eta).\sin(\gamma).recal}\right] \qquad (4)$$

h0 is the undeformed chip thickness, h1 is the real chip thickness, γ is the rake angle, λ is the helix angle and η is the angle of the chip flow direction. These formulas are valid for the oblique cutting. The mean thickness of the real chip is 0.09mm (we measured chips produced different tests end we measured the mean thickness). By using the formulas (3) and (4), we find ϕ = 13.3°. This value validates the computation of the SCCU system.

An additional consideration coming from the analysis of the graphs is the following. At the beginning of the machining, we observe a decrease of different cutting power for the A coated tool. Actually the surface of this coating has s structure like the figure 12.

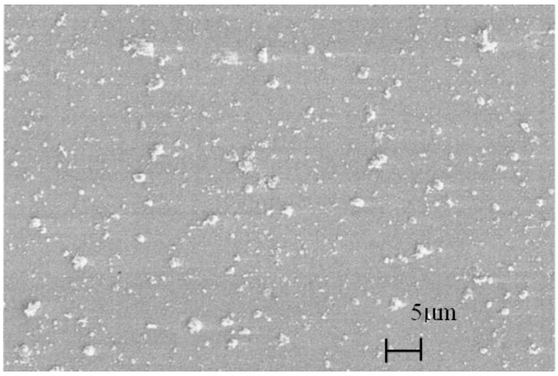


Figure 12 – Structure of surface of A coating before machining.

At the beginning of the machining, the small droplets on the surface are removed by a kind of "running-in" of the tool.

5 Conclusions

The differences between these DLC coatings are very significant. The better properties of A coating compared to the B coating are confirmed during tool life duration. The A coated tool present a flank wear, which is insignificant. The B coated tool has a flank wear two times less than the uncoated tool.

At the beginning of machining, the good friction coefficient of DLC coated tools engenders a lower cutting power compared to the uncoated tool, especially for the B coated tool. Indeed the B coated produces the lowest friction power and the lowest power due to the friction between the flank and the machined material. The shear power of the A and B coating are similar at the start of machining.

But the wear resistance of B coating isn't as good as the A coating. Every part of power increases quickly, especially the power due to friction (Pr, Pf). The different powers produced by the A coated tool are constant or increase very slowly (Ps).

The reduced power due to the friction of DLC coating produces a very smooth cutting compared to the uncoated tool. But its properties aren't useful if the wear resistance of coating isn't optimal. It's unfortunately the case for the B coating. The A coating keep its lubricant properties after 96minute of machining. We think that the A coating, with its very promising properties, can improve widely the machining of material with reduced machinability (abrasion, adhesion) if the temperature don't exceed 500°C.

Moreover this new system of cutting analysis allows a better understanding of cutting. If we observe only the cutting power graph (figure 6), it's impossible to know the reason of the cutting power increase. In regarding the different power graph, we understand that the low wear resistance of coating B generates a wide increase of the power due to friction.

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